

Polar Regions

Coordinating Lead Authors:

Michael Meredith (United Kingdom), Martin Sommerkorn (Norway/Germany)

Lead Authors:

Sandra Cassotta (Denmark), Chris Derksen (Canada), Alexey Ekaykin (Russian Federation), Anne Hollowed (USA), Gary Kofinas (USA), Andrew Mackintosh (Australia/New Zealand), Jess Melbourne-Thomas (Australia), Mônica M.C. Muelbert (Brazil), Geir Ottersen (Norway), Hamish Pritchard (United Kingdom), Edward A.G. Schuur (USA)

Contributing Authors:

Nerilie Abram (Australia), Julie Arblaster (Australia), Kevin Arrigo (USA), Kumiko Azetzu-Scott (Canada), David Barber (Canada), Inka Bartsch (Germany), Jeremy Bassis (USA), Dorothea Bauch (Germany), Fikret Berkes (Canada), Philip Boyd (Australia), Angelika Brandt (Germany), Lijing Cheng (China), Steven Chown (Australia), Alison Cook (United Kingdom), Jackie Dawson (Canada), Robert M. DeConto (USA), Thorben Dunse (Norway/Germany), Andrea Dutton (USA), Tamsin Edwards (United Kingdom), Laura Eerkes-Medrano (Canada), Arne Eide (Norway), Howard Epstein (USA), F. Stuart Chapin III (USA), Mark Flanner (USA), Bruce Forbes (Finland), Jeremy Fyke (Canada), Andrey Glazovsky (Russian Federation), Jacqueline Grebmeier (USA), Guido Grosse (Germany), Anne Gunn (Canada), Sherilee Harper (Canada), Jan Hjort (Finland), Will Hobbs (Australia), Eric P. Hoberg (USA), Indi Hodgson-Johnston (Australia), David Holland (USA), Paul Holland (United Kingdom), Russell Hopcroft (USA), George Hunt (USA), Henry Huntington (USA), Adrian Jenkins (United Kingdom), Kit Kovacs (Norway), Gita Ljubicic (Canada), Michael Loranty (USA), Michelle Mack (USA), Andrew Meijers (United Kingdom/Australia), Benoit Meyssignac (France), Hans Meltote (Denmark), Alexander Milner (United Kingdom), Pedro Monteiro (South Africa), Lawrence Mudryk (Canada), Mark Nuttall (Canada), Jamie Oliver (United Kingdom), James Overland (USA), Keith Reid (United Kingdom), Vladimir Romanovsky (USA/Russian Federation), Don E. Russell (Canada), Christina Schädel (USA/Switzerland), Lars H. Smedsrud (Norway), Julianne Stroeve (Canada/USA), Alessandro Tagliabue (United Kingdom), Mary-Louise Timmermans (USA), Merritt Turetsky (Canada), Michiel van den Broeke (Netherlands), Roderik Van De Wal (Netherlands), Isabella Velicogna (USA/Italy), Jemma Wadham (United Kingdom), Michelle Walvoord (USA), Gongjie Wang (China), Dee Williams (USA), Mark Wipfli (USA), Daqing Yang (Canada)

Review Editors:

Oleg Anisimov (Russian Federation), Gregory Flato (Canada), Cunde Xiao (China)

Chapter Scientist:

Shengping He (Norway/China), Victoria Peck (United Kingdom)

This chapter should be cited as:

Meredith, M., M. Sommerkorn, S. Cassotta, C. Derksen, A. Ekaykin, A. Hollowed, G. Kofinas, A. Mackintosh, J. Melbourne-Thomas, M.M.C. Muelbert, G. Ottersen, H. Pritchard, and E.A.G. Schuur, 2019: Polar Regions. In: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* [H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegria, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.)]. In press.

Table of contents

Executive Summary	205	3.5 Human Responses to Climate Change in Polar Regions	261
3.1 Introduction: Polar Regions, People and the Planet	209	3.5.1 The Polar Context for Responding.....	261
Box 3.1: Polar Region Climate Trends	212	3.5.2 Responses of Human Sectors	261
3.2 Sea Ice and Polar Oceans: Changes, Consequences and Impacts	212	3.5.3 Governance	268
3.2.1 Observed Changes in Sea Ice and Ocean.....	212	3.5.4 Towards Resilient Pathways	271
Box 3.2: Potential for the Polar Cryosphere to Influence Mid-latitude Weather	216	3.6 Synopsis	274
Cross-Chapter Box 7: Southern Ocean Circulation: Drivers, Changes and Implications	220	3.7 Key Knowledge Gaps and Uncertainties	275
3.2.2 Projected Changes in Sea Ice and Ocean	222	References	277
Box 3.3: Polynyas	223	Frequently Asked Questions	276
3.2.3 Impacts on Marine Ecosystems	226	FAQ 3.1 How do changes in the Polar Regions affect other parts of the world?	276
3.2.4 Impacts on Social-Ecological Systems	234		
3.3 Polar Ice Sheets and Glaciers: Changes, Consequences and Impacts	236		
3.3.1 Ice Sheet Changes.....	236		
3.3.2 Polar Glacier Changes	240		
3.3.3 Consequences and Impacts	242		
Cross-Chapter Box 8: Future Sea Level Changes and Marine Ice Sheet Instability	244		
3.4 Arctic Snow, Freshwater Ice and Permafrost: Changes, Consequences and Impacts	246		
3.4.1 Observations.....	246		
3.4.2 Projections	250		
3.4.3 Consequences and Impacts	252		
Box 3.4: Impacts and Risks for Polar Biodiversity from Range Shifts and Species Invasions Related to Climate Change	256		

Executive Summary

This chapter assesses the state of physical, biological and social knowledge concerning the Arctic and Antarctic ocean and cryosphere, how they are affected by climate change, and how they will evolve in future. Concurrently, it assesses the local, regional and global consequences and impacts of individual and interacting polar system changes, and it assesses response options to reduce risk and build resilience in the polar regions. Key findings are:

The polar regions are losing ice, and their oceans are changing rapidly. The consequences of this polar transition extend to the whole planet, and are affecting people in multiple ways.

Arctic surface air temperature has *likely*¹ increased by more than double the global average over the last two decades, with feedbacks from loss of sea ice and snow cover contributing to the amplified warming. For each of the five years since the IPCC 5th Assessment Report (AR5) (2014–2018), Arctic annual surface air temperature exceeded that of any year since 1900. During the winters (January to March) of 2016 and 2018, surface temperatures in the central Arctic were 6°C above the 1981–2010 average, contributing to unprecedented regional sea ice absence. These trends and extremes provide *medium evidence*² with *high agreement* of the contemporary coupled atmosphere-cryosphere system moving well outside the 20th century envelope. {Box 3.1; 3.2.1.1}

The Arctic and Southern Oceans are continuing to remove carbon dioxide from the atmosphere and to acidify (*high confidence*). There is *medium confidence* that the amount of CO₂ drawn into the Southern Ocean from the atmosphere has experienced significant decadal variations since the 1980s. Rates of calcification (by which marine organisms form hard skeletons and shells) declined in the Southern Ocean by 3.9 ± 1.3% between 1998 and 2014. In the Arctic Ocean, the area corrosive to organisms that form shells and skeletons using the mineral aragonite expanded between the 1990s and 2010, with instances of extreme aragonite undersaturation. {3.2.1.2.4}

Both polar oceans have continued to warm in recent years, with the Southern Ocean being disproportionately and increasingly important in global ocean heat increase (*high confidence*). Over large sectors of the seasonally ice-free Arctic, summer upper mixed layer temperatures increased at around 0.5°C per decade during 1982–2017, primarily associated with increased absorbed solar radiation accompanying sea ice loss, and the inflow of ocean heat from lower latitude increased since the 2000s (*high confidence*). During 1970–2017, the Southern Ocean south of 30°S accounted for 35–43% of the global ocean heat gain in the upper

2000 m (*high confidence*), despite occupying ~25% of the global ocean area. In recent years (2005–2017), the Southern Ocean was responsible for an increased proportion of the global ocean heat increase (45–62%) (*high confidence*). {3.2.1.2.1}

Climate-induced changes in seasonal sea ice extent and thickness and ocean stratification are altering marine primary production (*high confidence*), with impacts on ecosystems (*medium confidence*). Changes in the timing, duration and intensity of primary production have occurred in both polar oceans, with marked regional or local variability (*high confidence*). In the Antarctic, such changes have been associated with locally-rapid environmental change, including retreating glaciers and sea ice change (*medium confidence*). In the Arctic, changes in primary production have affected regional species composition, spatial distribution, and abundance of many marine species, impacting ecosystem structure (*medium confidence*). {3.2.1; 3.2.3, 3.2.4}

In both polar regions, climate-induced changes in ocean and sea ice, together with human introduction of non-native species, have expanded the range of temperate species and contracted the range of polar fish and ice-associated species (*high confidence*). Commercially and ecologically important fish stocks like Atlantic cod, haddock and mackerel have expanded their spatial distributions northwards many hundreds of kilometres, and increased their abundance. In some Arctic areas, such expansions have affected the whole fish community, leading to higher competition and predation on smaller sized fish species, while some commercial fisheries have benefited. There has been a southward shift in the distribution of Antarctic krill in the South Atlantic, the main area for the krill fishery (*medium confidence*). These changes are altering biodiversity in polar marine ecosystems (*medium confidence*). {3.2.3; Box 3.4}

Arctic sea ice extent continues to decline in all months of the year (*very high confidence*); the strongest reductions in September (*very likely* –12.8 ± 2.3% per decade; 1979–2018) are unprecedented in at least 1000 years (*medium confidence*). Arctic sea ice has thinned, concurrent with a shift to younger ice: since 1979, the areal proportion of thick ice at least 5 years old has declined by approximately 90% (*very high confidence*). Approximately half the observed sea ice loss is attributable to increased atmospheric greenhouse gas concentrations (*medium confidence*). Changes in Arctic sea ice have potential to influence mid-latitude weather on timescales of weeks to months (*low to medium confidence*). {3.2.1.1; Box 3.2}

It is *very likely* that Antarctic sea ice cover exhibits no significant trend over the period of satellite observations

¹ In this Report, the following terms have been used to indicate the assessed likelihood of an outcome or a result: Virtually certain 99–100% probability, Very likely 90–100%, Likely 66–100%, About as likely as not 33–66%, Unlikely 0–33%, Very unlikely 0–10%, and Exceptionally unlikely 0–1%. Additional terms (Extremely likely: 95–100%, More likely than not >50–100%, and Extremely unlikely 0–5%) may also be used when appropriate. Assessed likelihood is typeset in italics, e.g., *very likely* (see Section 1.9.2 and Figure 1.4 for more details). This Report also uses the term ‘*likely* range’ to indicate that the assessed likelihood of an outcome lies within the 17–83% probability range.

² In this Report, the following summary terms are used to describe the available evidence: limited, medium, or robust; and for the degree of agreement: low, medium, or high. A level of confidence is expressed using five qualifiers: very low, low, medium, high, and very high, and typeset in italics, e.g., *medium confidence*. For a given evidence and agreement statement, different confidence levels can be assigned, but increasing levels of evidence and degrees of agreement are correlated with increasing confidence (see Section 1.9.2 and Figure 1.4 for more details).

(1979–2018). While the drivers of historical decadal variability are known with *medium confidence*, there is currently *limited evidence* and *low agreement* concerning causes of the strong recent decrease (2016–2018), and *low confidence* in the ability of current-generation climate models to reproduce and explain the observations. {3.2.1.1}

Shipping activity during the Arctic summer increased over the past two decades in regions for which there is information, concurrent with reductions in sea ice extent (*high confidence*).

Transit times across the Northern Sea Route have shortened due to lighter ice conditions, and while long-term, pan-Arctic datasets are incomplete, the distance travelled by ships in Arctic Canada nearly tripled during 1990–2015 (*high confidence*). Greater levels of Arctic ship-based transportation and tourism have socioeconomic and political implications for global trade, northern nations, and economies linked to traditional shipping corridors; they will also exacerbate region specific risks for marine ecosystems and coastal communities if further action to develop and adequately implement regulations does not keep pace with increased shipping (*high confidence*). {3.2.1.1; 3.2.4.2; 3.2.4.3; 3.4.3.3.2; 3.5.2.7}

Permafrost temperatures have increased to record high levels (*very high confidence*), but there is *medium evidence* and *low agreement* that this warming is currently causing northern permafrost regions to release additional methane and carbon dioxide. During 2007–2016, continuous-zone permafrost temperatures in the Arctic and Antarctic increased by $0.39 \pm 0.15^\circ\text{C}$ and $0.37 \pm 0.10^\circ\text{C}$ respectively. Arctic and boreal permafrost region soils contain 1460–1600 Gt organic carbon (*medium confidence*). Changes in permafrost influence global climate through emissions of carbon dioxide and methane released from the microbial breakdown of organic carbon, or the release of trapped methane. {3.4.1; 3.4.3}

Climate-related changes to Arctic hydrology, wildfire and abrupt thaw are occurring (*high confidence*), with impacts on vegetation and water and food security. Snow and lake ice cover has declined, with June snow extent decreasing $13.4 \pm 5.4\%$ per decade (1967–2018) (*high confidence*). Runoff into the Arctic Ocean increased for Eurasian and North American rivers by $3.3 \pm 1.6\%$ and $2.0 \pm 1.8\%$ respectively (1976–2017; *medium confidence*). Area burned and frequency of fires (including extreme fires) are unprecedented over the last 10,000 years (*high confidence*). There has been an overall greening of the tundra biome, but also browning in some regions of tundra and boreal forest, and changes in the abundance and distribution of animals including reindeer and salmon (*high confidence*). Together, these impact access to (and food availability within) herding, hunting, fishing, forage and gathering areas, affecting the livelihood, health and cultural identity of residents including Indigenous peoples (*high confidence*). {3.4.1; 3.4.3; 3.5.2}

Limited knowledge, financial resources, human capital and organisational capacity are constraining adaptation in many human sectors in the Arctic (*high confidence*). Harvesters of renewable resources are adjusting timing of activities to changes in seasonality and less safe ice travel conditions. Municipalities

and industry are addressing infrastructure failures associated with flooding and thawing permafrost, and coastal communities and cooperating agencies are in some cases planning for relocation (*high confidence*). In spite of these adaptations, many groups are making decisions without adequate knowledge to forecast near- and long-term conditions, and without the funding, skills and institutional support to engage fully in planning processes (*high confidence*). {3.5.2, 3.5.4, Cross-Chapter Box 9}

It is *extremely likely* that the rapid ice loss from the Greenland and Antarctic ice sheets during the early 21st century has increased into the near present day, adding to the ice sheet contribution to global sea level rise. From Greenland, the 2012–2016 ice losses ($-247 \pm 15 \text{ Gt yr}^{-1}$) were similar to those from 2002 to 2011 ($-263 \pm 21 \text{ Gt yr}^{-1}$) and *extremely likely* greater than from 1992 to 2001 ($-8 \pm 82 \text{ Gt yr}^{-1}$). Summer melting of the Greenland Ice Sheet (GIS) has increased since the 1990s (*very high confidence*) to a level unprecedented over at least the last 350 years, and two-to-fivefold the pre-industrial level (*medium confidence*). From Antarctica, the 2012–2016 losses ($-199 \pm 26 \text{ Gt yr}^{-1}$) were *extremely likely* greater than those from 2002 to 2011 ($-82 \pm 27 \text{ Gt yr}^{-1}$) and *likely* greater than from 1992 to 2001 ($-51 \pm 73 \text{ Gt yr}^{-1}$). Antarctic ice loss is dominated by acceleration, retreat and rapid thinning of major West Antarctic Ice Sheet (WAIS) outlet glaciers (*very high confidence*), driven by melting of ice shelves by warm ocean waters (*high confidence*). The combined sea level rise contribution from both ice sheets for 2012–2016 was $1.2 \pm 0.1 \text{ mm yr}^{-1}$, a 29% increase on the 2002–2011 contribution and a ~700% increase on the 1992–2001 period. {3.3.1}

Mass loss from Arctic glaciers ($-212 \pm 29 \text{ Gt yr}^{-1}$) during 2006–2015 contributed to sea level rise at a similar rate ($0.6 \pm 0.1 \text{ mm yr}^{-1}$) to the GIS (*high confidence*). Over the same period in Antarctic and subantarctic regions, glaciers separate from the ice sheets changed mass by $-11 \pm 108 \text{ Gt yr}^{-1}$ (*low confidence*). {2.2.3, 3.3.2}

There is *limited evidence* and *high agreement* that recent Antarctic Ice Sheet (AIS) mass losses could be irreversible over decades to millennia. Rapid mass loss due to glacier flow acceleration in the Amundsen Sea Embayment (ASE) of West Antarctica and in Wilkes Land, East Antarctica, may indicate the beginning of Marine Ice Sheet Instability (MISI), but observational data are not yet sufficient to determine whether these changes mark the beginning of irreversible retreat. {3.3.1; Cross-Chapter Box 8 in Chapter 3; 4.2.3.1.2}

The polar regions will be profoundly different in future compared with today, and the degree and nature of that difference will depend strongly on the rate and magnitude of global climatic change³. This will challenge adaptation responses regionally and worldwide.

It is *very likely* that projected Arctic warming will result in continued loss of sea ice and snow on land, and reductions in

³ Projections for ice sheets and glaciers in the polar regions are summarized in Chapters 4 and 2, respectively.

the mass of glaciers. Important differences in the trajectories of loss emerge from 2050 onwards, depending on mitigation measures taken (*high confidence*). For stabilised global warming of 1.5°C, an approximately 1% chance of a given September being sea ice free at the end of century is projected; for stabilised warming at a 2°C increase, this rises to 10–35% (*high confidence*). The potential for reduced (further 5–10%) but stabilised Arctic autumn and spring snow extent by mid-century for Representative Concentration Pathway (RCP)2.6 contrasts with continued loss under RCP8.5 (a further 15–25% reduction to end of century) (*high confidence*). Projected mass reductions for polar glaciers between 2015 and 2100 range from $16 \pm 7\%$ for RCP2.6 to $33 \pm 11\%$ for RCP8.5 (*medium confidence*). {3.2.2; 3.3.2; 3.4.2, Cross-Chapter Box 6 in Chapter 2}

Both polar oceans will be increasingly affected by CO₂ uptake, causing conditions corrosive for calcium carbonate shell-producing organisms (*high confidence*), with associated impacts on marine organisms and ecosystems (*medium confidence*). It is *very likely* that both the Southern Ocean and the Arctic Ocean will experience year-round conditions of surface water undersaturation for mineral forms of calcium carbonate by 2100 under RCP8.5; under RCP2.6 the extent of undersaturated waters are reduced markedly. Imperfect representation of local processes and sea ice interaction in global climate models limit the ability to project the response of specific polar areas and the precise timing of undersaturation at seasonal scales. Differences in sensitivity and the scope for adaptation to projected levels of ocean acidification exist across a broad range of marine species groups. {3.2.1; 3.2.2.3; 3.2.3}

Future climate-induced changes in the polar oceans, sea ice, snow and permafrost will drive habitat and biome shifts, with associated changes in the ranges and abundance of ecologically important species (*medium confidence*). Projected shifts will include further habitat contraction and changes in abundance for polar species, including marine mammals, birds, fish, and Antarctic krill (*medium confidence*). Projected range expansion of subarctic marine species will increase pressure for high-Arctic species (*medium confidence*), with regionally variable impacts. Continued loss of Arctic multi-year sea ice will affect ice-related and pelagic primary production (*high confidence*), with impacts for whole ice-associated, seafloor and open ocean ecosystems. On Arctic land, projections indicate a loss of globally unique biodiversity as some high Arctic species will be outcompeted by more temperate species and very limited refugia exist (*medium confidence*). Woody shrubs and trees are projected to expand, covering 24–52% of the current tundra region by 2050. {3.2.2.1; 3.2.3; 3.2.3.1; Box 3.4; 3.4.2; 3.4.3}

The projected effects of climate-induced stressors on polar marine ecosystems present risks for commercial and subsistence fisheries with implications for regional economies, cultures and the global supply of fish, shellfish, and Antarctic krill (*high confidence*). Future impacts for linked human systems depend on the level of mitigation and especially the responsiveness of precautionary management approaches (*medium confidence*). Polar regions support several of the world's largest commercial fisheries. Specific impacts on the stocks and economic value in both regions will depend on future climate

change and on the strategies employed to manage the effects on stocks and ecosystems (*medium confidence*). Under high emission scenarios current management strategies of some high-value stocks may not sustain current catch levels in the future (*low confidence*); this exemplifies the limits to the ability of existing natural resource management frameworks to address ecosystem change. Adaptive management that combines annual measures and within-season provisions informed by assessments of future ecosystem trends reduces the risks of negative climate change impacts on polar fisheries (*medium confidence*). {3.2.4; 3.5.2; 3.5.4}

Widespread disappearance of Arctic near-surface permafrost is projected to occur this century as a result of warming (*very high confidence*), with important consequences for global climate. By 2100, near-surface permafrost area will decrease by 2–66% for RCP2.6 and 30–99% for RCP8.5. This is projected to release 10s to 100s of billions of tons (Gt C), up to as much as 240 Gt C, of permafrost carbon as carbon dioxide and methane to the atmosphere with the potential to accelerate climate change. Methane will contribute a small proportion of these additional carbon emissions, on the order of 0.01–0.06 Gt CH₄ yr⁻¹, but could contribute 40–70% of the total permafrost-affected radiative forcing because of its higher warming potential. There is *medium evidence* but with *low agreement* whether the level and timing of increased plant growth and replenishment of soil will compensate these permafrost carbon losses. {3.4.2; 3.4.3}

Projected permafrost thaw and decrease in snow will affect Arctic hydrology and wildfire, with impacts on vegetation and human infrastructure (*medium confidence*). About 20% of Arctic land permafrost is vulnerable to abrupt permafrost thaw and ground subsidence, which is expected to increase small lake area by over 50% by 2100 for RCP8.5 (*medium confidence*). Even as the overall regional water cycle intensifies, including increased precipitation, evapotranspiration, and river discharge to the Arctic Ocean, decreases in snow and permafrost may lead to soil drying (*medium confidence*). Fire is projected to increase for the rest of this century across most tundra and boreal regions, while interactions between climate and shifting vegetation will influence future fire intensity and frequency (*medium confidence*). By 2050, 70% of Arctic infrastructure is located in regions at risk from permafrost thaw and subsidence; adaptation measures taken in advance could reduce costs arising from thaw and other climate change related impacts such as increased flooding, precipitation, and freeze-thaw events by half (*medium confidence*). {3.4.1; 3.4.2; 3.4.3; 3.5.2}

Response options exist that can ameliorate the impacts of polar change, build resilience and allow time for effective mitigation measures. Institutional barriers presently limit their efficacy.

Responding to climate change in polar regions will be more effective if attention to reducing immediate risks (short-term adaptation) is concurrent with long-term planning that builds resilience to address expected and unexpected impacts (*high confidence*). Emphasis on short-term adaptation to specific problems will ultimately not succeed in reducing the risks and vulnerabilities to

society given the scale, complexity and uncertainty of climate change. Moving toward a dual focus of short- and long-term adaptation involves knowledge co-production, linking knowledge with decision making and implementing ecosystem-based stewardship, which involves the transformation of many existing institutions (*high confidence*). {3.5.4}

Innovative tools and practices in polar resource management and planning show strong potential in improving society's capacity to respond to climate change (*high confidence*). Networks of protected areas, participatory scenario analysis, decision support systems, community-based ecological monitoring that draws on local and indigenous knowledge, and self assessments of community resilience contribute to strategic plans for sustaining biodiversity and limit risk to human livelihoods and wellbeing. Such practices are most effective when linked closely to the policy process. Experimenting, assessing, and continually refining practices while strengthening the links with decision making has the potential to ready society for the expected and unexpected impacts of climate change (*high confidence*). {3.5.1, 3.5.2, 3.5.4}

Institutional arrangements that provide for strong multiscale linkages with Arctic local communities can benefit from including indigenous knowledge and local knowledge in the formulation of adaptation strategies (*high confidence*). The tightly coupled relationship of northern local communities and their environment provide an opportunity to better understand climate change and its effects, support adaptation and limit unintended consequences. Enabling conditions for the involvement of local communities in climate adaptation planning include investments in human capital, engagement processes for knowledge co-production and systems of adaptive governance. {3.5.3}

The capacity of governance systems in polar regions to respond to climate change has strengthened recently, but the development of these systems is not sufficiently rapid or robust to address the challenges and risks to societies posed by projected changes (*high confidence*). Human responses to climate change in the polar regions occur in a fragmented governance landscape. Climate change, new polar interests from outside the regions, and an increasingly active role played by informal organisations are compelling stronger coordination and integration between different levels and sectors of governance. The governance landscape is currently not sufficiently equipped to address cascading risks and uncertainty in an integrated and precautionary way within existing legal and policy frameworks (*high confidence*). {3.5.3, 3.5.4}

3.1 Introduction: Polar Regions, People and the Planet

This chapter provides an integrated assessment of climate change across the physical, biological and human dimensions of the polar regions, based on emerging understanding that assessing these dimensions in isolation is not sufficient or forward-looking. This offers the opportunity, for the first time in a global report, to trace cause and consequence of climate change from polar ocean and cryosphere systems to biological and social impacts, and relate them to responses to reduce risks and enhance adaptation options and resilience. To achieve this, the chapter draws on the body of literature and assessments pertaining to climate-induced dynamics and functioning of the polar regions published since the AR5, which has expanded considerably motivated in large part by growing appreciation of the importance of these regions to planetary systems and to the lives and livelihoods of people across the globe.

As integral parts of the Earth system, the polar regions interact with the rest of the world through shared ocean, atmosphere, ecological and social systems; notably, they are key components of the global climate system. This chapter therefore takes a systems approach that emphasises the interactions of cryosphere and ocean changes and their diverse consequences and impacts to assess key issues of climatic change for the polar regions, the planet and its people (Figure 3.1).

The spatial footprints of the polar regions (Figure 3.2) include a vast share of the world's ocean and cryosphere: they encompass surface areas equalling 20% of the global ocean and more than 90% of the world's continuous and discontinuous permafrost area, 69% of the world's glacier area including both of the world's ice sheets, almost all of the world's sea ice, and land areas with the most persistent winter snow cover.

Important differences in the physical setting of the two polar regions – the Arctic, an ocean surrounded by land, the Antarctic, a continent surrounded by an ocean – structure the nature and magnitude of interactions of cryosphere and ocean systems and their global linkages. The different physical settings have also led to the evolution of unique marine and terrestrial biology in each polar region and shape effects, impacts and adaptation of polar ecosystems.

It is important to recognise the existence of multiple and diverse perspectives of the polar regions, many of them overlapping. These multiple perspectives encompass the polar regions as a source of resources, a key part of the global climate system, a place for preserving intact ecosystems, a place for international cooperation and, importantly, a homeland. While many of these perspectives are equally relevant for both polar regions, only the Arctic has a population for whom the region is a permanent home: approximately four million people reside there, of whom 10% are indigenous. By contrast, the Antarctic population changes seasonally between approximately 1100 and 4400, based predominantly at research stations. When assessing knowledge relating to climate change in the context of adaptation options, limits and enhancing resilience (Cross-Chapter Box 2 in Chapter 1), such differences are important as they are linked to diverse human values, social processes, and use of resources.

Consideration of all peer-reviewed scientific knowledge is a hallmark of the IPCC assessment process. Indigenous knowledge and local knowledge are different and unique sources of knowledge that are increasingly recognised to contribute to observing, understanding, and responding to climate-induced changes (Cross-Chapter Box 4 in Chapter 1). Considering indigenous knowledge and local knowledge facilitates cooperation in the development, identification, and decision making processes for responding to climate change in communities across the Arctic, and better understanding of the challenges facing Indigenous peoples. This chapter incorporates published indigenous knowledge and local knowledge for assessing climate change impacts and responses.

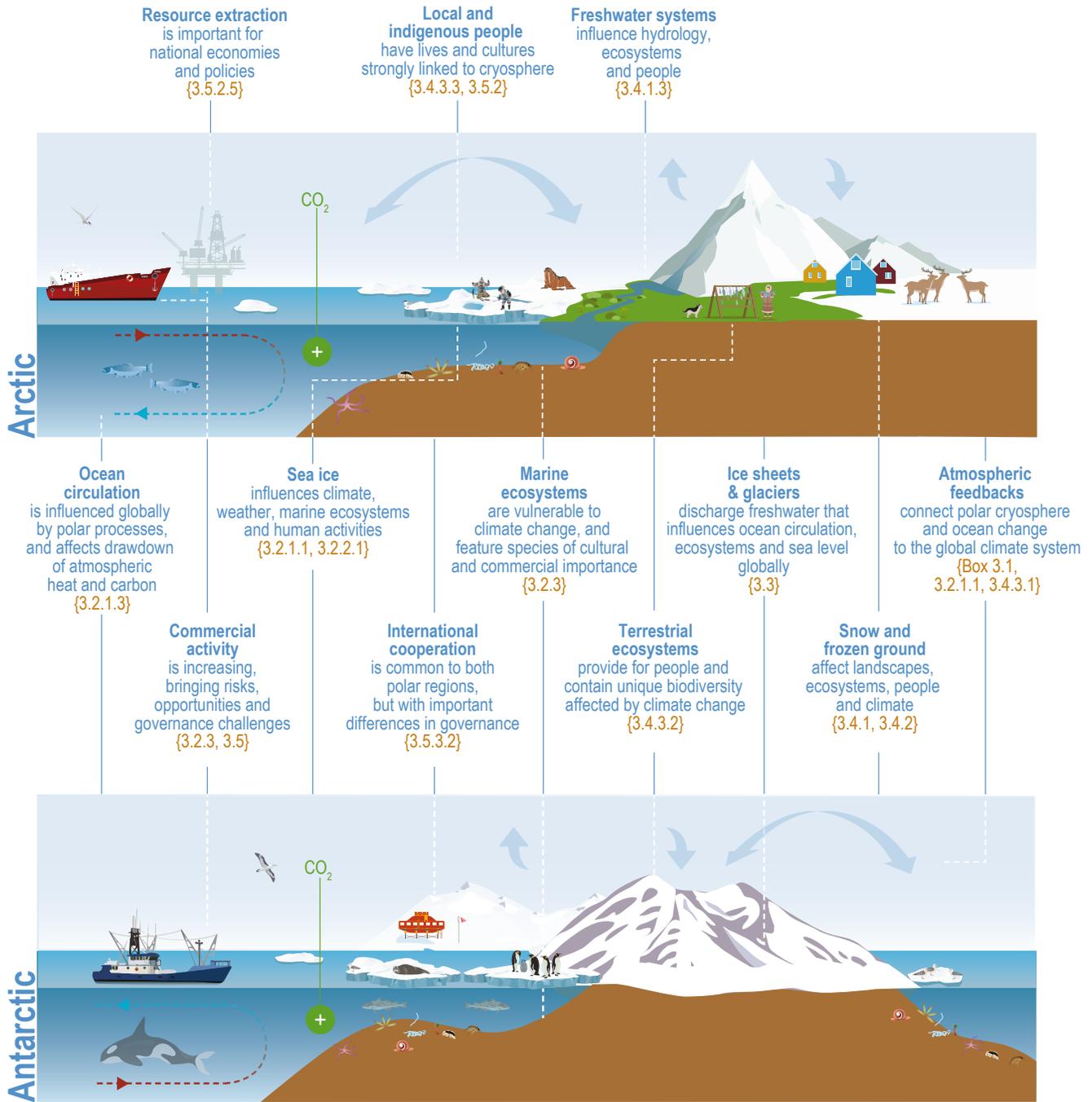


Figure 3.1 | Schematic of some of the key features and mechanisms assessed in this Chapter, and by which the cryosphere and ocean in the polar regions influence climate, ecological and social systems in the regions and across the globe. Specific elements are labelled, and section numbers given for where detailed assessment information can be found.

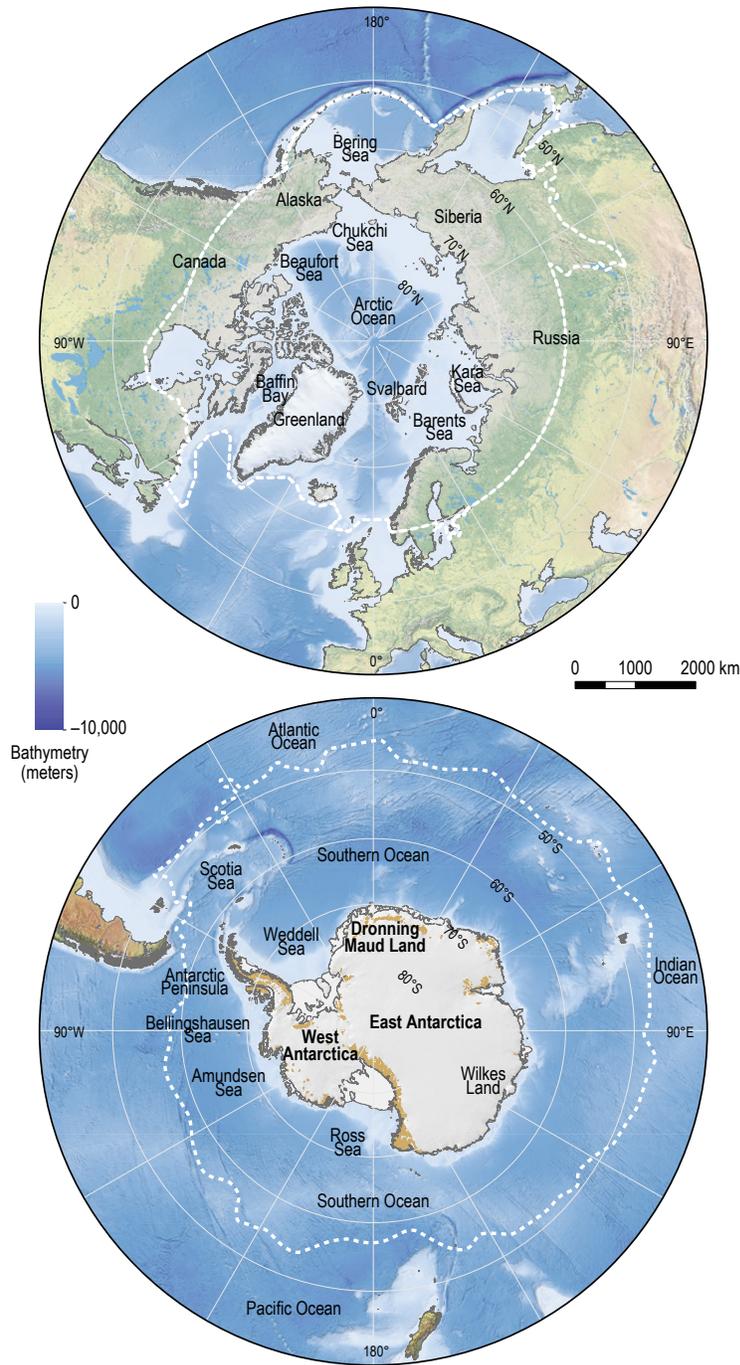


Figure 3.2 | The Arctic (top) and Antarctic (bottom) polar regions. Various place names referred to in the text are marked. Dashed lines denote approximate boundaries for the polar regions; as their spatial footprint varies in relation to particular cryosphere and ocean elements or scientific disciplines, this chapter adopts a purposefully flexible approach to their delineation. The southern polar region encompasses the flow of the Antarctic Circumpolar Current (ACC) at least as far north as the Subantarctic Front and fully encompasses the Convention for the Conservation of Antarctic Marine Living Resources Statistical Areas (CCAMLR, 2017c), the Antarctic continent and Antarctic and subantarctic islands, whilst the marine Arctic includes the areas of the Arctic Large Marine Ecosystems (PAME, 2013). The terrestrial Arctic comprises the areas of the northern continuous and discontinuous permafrost zone, the Arctic biome inclusive of glacial ice, and the parts of the boreal biome that are characterised by cryosphere elements, such as permafrost and persistent winter season snow cover.

Box 3.1 | Polar Region Climate Trends

Over the last two decades, Arctic surface air temperature has increased at more than double the global average (*high confidence*) (Notz and Stroeve, 2016; Richter-Menge et al., 2017). Attribution studies show the important role of anthropogenic increases in greenhouse gases in driving observed Arctic surface temperature increases (Fyfe et al., 2013; Najafi et al., 2015), so there is *high confidence* in projections of further Arctic warming (Overland et al., 2018a). Mechanisms for Arctic amplification are still debated, but include: reduced summer albedo due to sea ice and snow cover loss, the increase of total water vapour content in the Arctic atmosphere, changes in total cloudiness in summer, additional heat generated by newly formed sea ice across more extensive open water areas in the autumn, northward transport of heat and moisture and the lower rate of heat loss to space from the Arctic relative to the subtropics (Serreze and Barry, 2011; Pithan and Mauritsen, 2014; Goosse et al., 2018; Stuecker et al., 2018) (SM3.1.1).

A number of recent events in the Arctic indicate new extremes in the Arctic climate system. Annual Arctic surface temperature for each of the past five years since AR5 (2014–2018; relative to a 1980–2010 base line) exceeded that of any year since 1900 (Overland et al., 2018b). Winter (January to March) near-surface temperature anomalies of +6°C (relative to 1981–2010) were recorded in the central Arctic during both 2016 and 2018, nearly double the previous record anomalies (Overland and Wang, 2018a). These events were caused by a split of the tropospheric polar vortex into two cells, which facilitated the intrusion of subarctic storms (Overland and Wang, 2016). The resulting advection of warm air and moisture from the Pacific and Atlantic Oceans into the central Arctic increased downward longwave radiation, delayed sea ice freeze-up, and contributed to an unprecedented absence of sea ice. Delayed freeze-up of sea ice in subarctic seas (Chukchi, Barents and Kara) acts as a positive feedback allowing warmer temperatures to progress further toward the North Pole (Kim et al., 2017). In addition to dramatic Arctic summer sea ice loss over the past 15 years, all Arctic winter sea ice maxima of the last 4 years were at record low levels relative to 1979–2014 (Overland, 2018). Multi-year, large magnitude extreme positive Arctic temperatures and sea ice minimums (Section 3.2.1.1) since AR5 provide *high agreement* and *medium evidence* of contemporary conditions well outside the envelope of previous experience (1900–2017) (AMAP, 2017d; Walsh et al., 2017).

In contrast to the Arctic, the Antarctic continent has seen less uniform temperature changes over the past 30–50 years, with warming over parts of West Antarctica and no significant overall change over East Antarctica (Nicolas and Bromwich, 2014; Jones et al., 2016; Turner et al., 2016), though there is *low confidence* in these changes given the sparse *in situ* records and large interannual to interdecadal variability. This weaker amplified warming compared to the Arctic is due to deep ocean mixing and ocean heat uptake over the Southern Ocean (Collins et al., 2013). The Southern Annular Mode (SAM), Pacific South American mode (by which tropical Pacific convective heating signals are transmitted to high southern latitudes) and zonal-wave 3 are the dominant large-scale atmospheric circulation drivers of Antarctic surface climate and sea ice changes (SM3.1.3). Over recent decades the SAM has exhibited a positive trend during austral summer, indicating a strengthening of the surface westerly winds around Antarctica. This extended positive phase of the SAM is unprecedented in at least 600 years, according to palaeoclimate reconstructions (Abram et al., 2014; Dätwyler et al., 2017) and is associated with cooler conditions over the continent.

Consistent with AR5, it is *likely* that Antarctic ozone depletion has been the dominant driver of the positive trend in the SAM during austral summer from the late 1970s to the late 1990s (Schneider et al., 2015; Waugh et al., 2015; Karpechko et al., 2018), the period during which ozone depletion was increasing. There is *high confidence* through a growing body of literature that variability of tropical sea surface temperatures can influence Antarctic temperature changes (Li et al., 2014; Turner et al., 2016; Clem et al., 2017; Smith and Polvani, 2017) and the Southern Hemisphere mid-latitude circulation (Li et al., 2015a; Raphael et al., 2016; Turney et al., 2017; Evtushevsky et al., 2018; Yuan et al., 2018). New research suggests a stronger role of tropical sea surface temperatures in driving changes in the SAM since 2000 (Schneider et al., 2015; Clem et al., 2017).

3.2 Sea Ice and Polar Oceans: Changes, Consequences and Impacts

3.2.1 Observed Changes in Sea Ice and Ocean

3.2.1.1 Sea Ice

Sea ice reflects a high proportion of incoming solar radiation back to space, provides thermal insulation between the ocean and atmosphere, influences thermohaline circulation, and provides

habitat for ice-associated species. Sea ice characteristics differ between the Arctic and Antarctic. Expansion of winter sea ice in the Arctic is limited by land, and ice circulates within the central Arctic basin, some of which survives the summer melt season to form multi-year ice. Arctic sea ice variability and impacts on communities includes indigenous knowledge and local knowledge from across the circumpolar Arctic (Cross-Chapter Box 3 in Chapter 1). The Antarctic continent is surrounded by sea ice which interacts with adjacent ice shelves; winter season expansion is limited by the influence of the Antarctic Circumpolar Current (ACC).

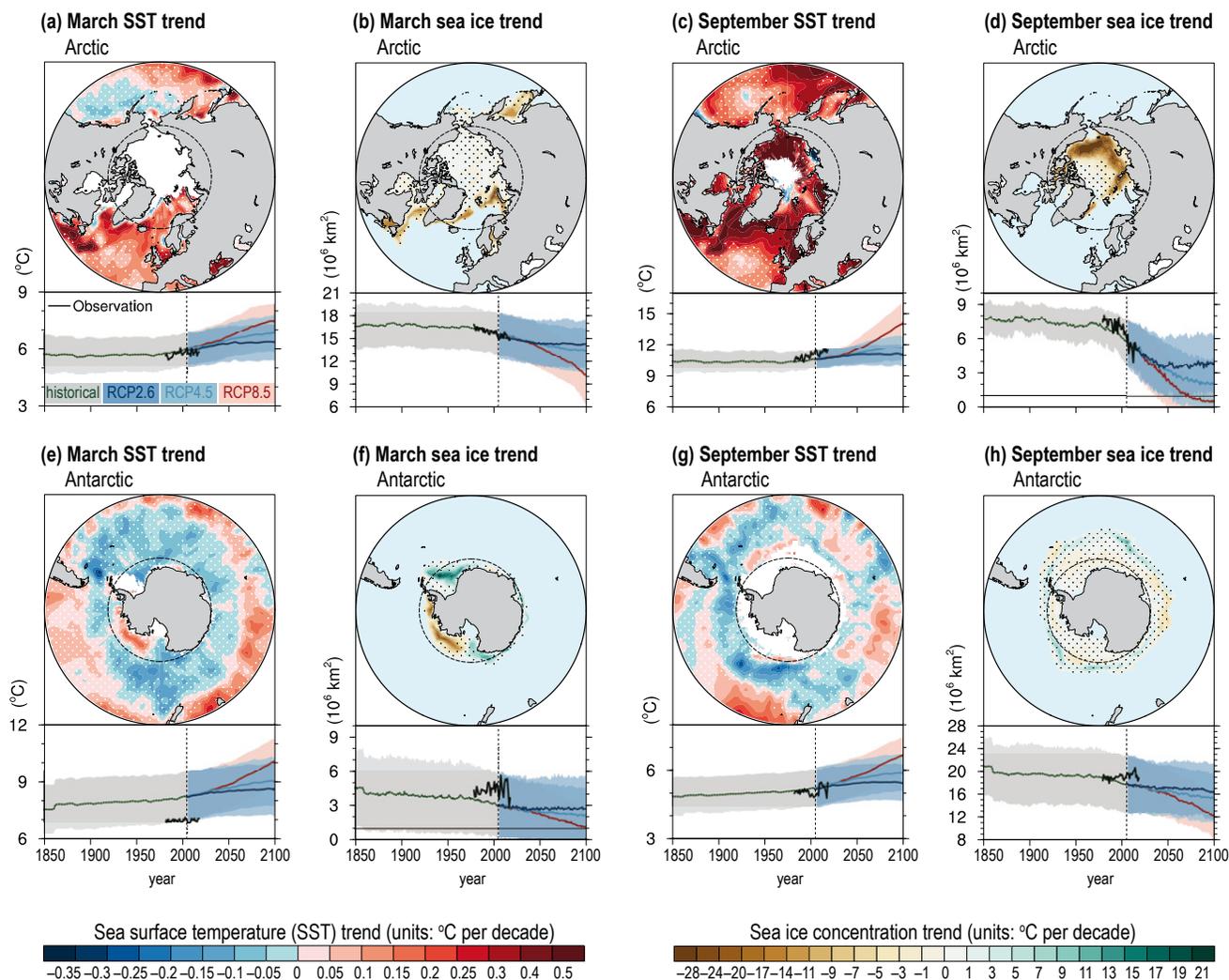


Figure 3.3 | Maps of linear trends (in $^{\circ}\text{C}$ per decade) of Arctic (a, c) and Antarctic (e, g) sea surface temperature (SST) for 1982–2017 in March (a, e) and September (c, g). (b, d, f, h) same as (a, c, e, g), but for the linear trends of sea ice concentration (in % per decade). Stippled regions indicate the trends that are statistically insignificant. Dashed circles indicate the Arctic/Antarctic Circle. Beneath each map of linear trend shows the time series of SST (area-averaged north of 40°N /south of 40°S) or sea ice extent in the northern/southern hemisphere. Black, green, blue, orange, and red curves indicate observations, Coupled Model Intercomparison Project Phase 5 (CMIP5) historical simulation, Representative Concentration Pathway (RCP)2.6, RCP4.5, and RCP8.5 projections respectively; shading indicates \pm standard deviation of multi-models. SST trend was calculated from Hadley Centre Sea Ice and Sea Surface Temperature data set (Version 1, HadISST1; Rayner, 2003). Sea ice concentration trend was calculated from the NOAA/NSIDC Climate Data Record of Passive Microwave Sea Ice Concentration, Version 3 (<https://nsidc.org/data/g02202>). The time series of observed SST are averages of HadISST1 and NOAA Optimum Interpolation SST dataset (version 2; Reynolds et al., 2002). The time series of observed sea ice extent are the averages of HadISST, the NOAA/NSIDC Climate Data Record of Passive Microwave Sea Ice Concentration, and the Global sea ice concentration reprocessing dataset from EUMETSAT (http://osisaf.met.no/p/ice/ice_conc_reprocessed.html).

3.2.1.1.1 Extent and concentration

The pan-Arctic loss of sea ice cover is a prominent indicator of climate change. Sea ice extent (the total area of the Arctic with at least 15% sea ice concentration) has declined since 1979 in each month of the year (*very high confidence*) (Barber et al., 2017; Comiso et al., 2017b; Stroeve and Notz, 2018) (Figure 3.3). Changes are largest in summer and smallest in winter, with the strongest trends in September (1979–2018; summer month with the lowest sea ice cover) of $-83,000 \text{ km}^2 \text{ yr}^{-1}$ (-12.8% per decade $\pm 2.3\%$ relative to 1981–2010 mean), and $-41,000 \text{ km}^2 \text{ yr}^{-1}$ (-2.7% per decade $\pm 0.5\%$ relative to 1981–2010 mean) for March (1979–2019; winter month with the greatest sea ice cover) (Onarheim et al., 2018). Regionally, summer ice loss is dominated by reductions in the East Siberian Sea (explains 22% of the September trend), and large declines in the Beaufort,

Chukchi, Laptev and Kara seas (Onarheim et al., 2018). Winter ice loss is dominated by reductions within the Barents Sea, responsible for 27% of the pan-Arctic March sea ice trends (Onarheim and Årthun, 2017). Summer Arctic sea ice loss since 1979 is unprecedented in 150 years based on historical reconstructions (Walsh et al., 2017) and more than 1000 years based on palaeoclimate evidence (Polyak et al., 2010; Kinnard et al., 2011; Halfar et al., 2013) (*medium confidence*).

Approximately half of the observed Arctic summer sea ice loss is driven by increased concentrations of atmospheric greenhouse gases, with the remainder attributed to internal climate variability (Kay et al., 2011; Notz and Marotzke, 2012) (*medium confidence*). The sea ice albedo feedback (increased air temperature reduces sea ice cover, allowing more energy to be absorbed at the surface, fostering more melt) is a key driver of sea ice loss (Perovich and Polashenski, 2012;

Stroeve et al., 2012b; Serreze et al., 2016) and is exacerbated by the transition from perennial to seasonal sea ice (Haine and Martin, 2017; see Section 3.2.1.1.2). Other drivers include increased warm, moist air intrusions into the Arctic during both winter (Box 3.1) and spring (Boisvert et al., 2016; Cullather et al., 2016; Kapsch et al., 2016; Mortin et al., 2016; Graham et al., 2017; Hegyi and Taylor, 2018), radiative feedbacks associated with cloudiness and humidity (Kapsch et al., 2013; Pithan and Mauritsen, 2014; Hegyi and Deng, 2016; Morrison et al., 2018), and increased exchanges of sensible and latent heat flux from the ocean to the atmosphere (Serreze et al., 2012; Taylor et al., 2018). A lack of complete process understanding limits a more definitive differentiation between anthropogenic versus internal drivers of summer Arctic sea ice loss (Serreze et al., 2016; Ding et al., 2017; Meehl et al., 2018). The unabated reduction in Arctic summer sea ice since AR5 means contributions to additional global radiative forcing (Flanner et al., 2011) have continued, with estimates of up to an additional $6.4 \pm 0.9 \text{ W/m}^2$ of solar energy input to the Arctic Ocean region since 1979 (Pistone et al., 2014).

Although Arctic ice freeze-up is occurring later (Section 3.2.1.1.3), rapid thermodynamic ice growth occurs over thin ice areas after air temperatures drop below freezing in autumn. Later freeze-up also delays snowfall accumulation on sea ice, leading to a thinner and less insulating snowpack (Section 3.2.1.1.6) (Sturm and Massom, 2016). These two negative feedbacks help to mitigate sudden and irreversible loss of Arctic sea ice (Armour et al., 2011).

Total Antarctic sea ice cover exhibits no significant trend over the period of satellite observations (Figure 3.3; 1979–2018) (*high confidence*) (Ludescher et al., 2018). A significant positive trend in mean annual ice cover between 1979 and 2015 (Comiso et al., 2017a) has not persisted, due to three consecutive years of below average ice cover (2016–2018) driven by atmospheric and oceanic forcing (Turner et al., 2017b; Kusahara et al., 2018; Meehl et al., 2019; Wang et al., 2019). The overall Antarctic sea ice extent trend is composed of near-compensating regional changes, with rapid ice loss in the Amundsen and Bellingshausen seas counteracted by rapid ice gain in the Weddell and Ross seas (Holland, 2014) (Figure 3.3). These regional trends are strongly seasonal in character (Holland, 2014); only the western Ross Sea has a trend that is statistically significant in all seasons, relative to the variance during the period of satellite observations.

Multiple factors contribute to the regionally variable nature of Antarctic sea ice extent trends (Matear et al., 2015; Hobbs et al., 2016b). Sea ice trends are closely related to meridional wind trends (*high confidence*) (Holland and Kwok, 2012; Haumann et al., 2014): poleward wind trends in the Bellingshausen Sea push sea ice closer to the coast (Holland and Kwok, 2012) and advect warm air to the sea ice zone (Kusahara et al., 2017), and the reverse is true over much of the Ross Sea. These meridional wind trends are linked to Pacific variability (Coggins and McDonald, 2015; Meehl et al., 2016; Purich et al., 2016b). Ozone depletion may also affect meridional winds (Fogt and Zbacnik, 2014; England et al., 2016), but there is *low confidence* that this explains observed sea ice trends (Landrum et al., 2017).

Coupled climate models indicate that anthropogenic warming at the surface is delayed by the Southern Ocean circulation, which transports heat downwards into the deep ocean (Armour et al., 2016). This overturning circulation (Cross-Chapter Box 7 in Chapter 3), along with differing cloud and lapse rate feedbacks (Goosse et al., 2018), may explain the weak response of Antarctic sea ice cover to increased atmospheric greenhouse gas concentrations compared to the Arctic (*medium confidence*). Because Antarctic sea ice extent has remained below climatological values since 2016, there is still potential for longer-term changes to emerge in the Antarctic (Meehl et al., 2019), similar to the Arctic.

Historical surface observations (Murphy et al., 2014), reconstructions (Abram et al., 2013b), ship records (de la Mare, 2009; Edinburgh and Day, 2016), early satellite images (Gallaher et al., 2014), and model simulations (Gagné et al., 2015) indicate a decrease in overall Antarctic sea ice cover since the early 1960s which is too modest to be separated from natural variability (Hobbs et al., 2016a) (*high confidence*).

3.2.1.1.2 Age and thickness

The proportion of Arctic sea ice at least 5 years old declined from 30% to 2% between 1979 and 2018; over the same period first-year sea ice proportionally increased from approximately 40% to 60–70% (Stroeve and Notz, 2018) (*very high confidence*) (Sections 3.2.1.1.3 and 3.2.1.1.4). Arctic sea ice has thinned through volume reductions in satellite altimeter retrievals (Laxon et al., 2013; Kwok, 2018), ocean–sea ice reanalyses (Chevallier et al., 2017) and *in situ* measurements (Renner et al., 2014; Haas et al., 2017) (*very high confidence*). Data from multiple satellite altimeter missions show declines in Arctic Basin ice thickness from 2000 to 2012 of $-0.58 \pm 0.07 \text{ m}$ per decade (Lindsay and Schweiger, 2015). Integration of data from submarines, moorings, and earlier satellite radar altimeter missions shows ice thickness declined across the central Arctic by 65%, from 3.59 to 1.25 m between 1975 and 2012 (Lindsay and Schweiger, 2015). There is emerging evidence that this sea ice volume loss may be unprecedented over the past century (Schweiger et al., 2019). New estimates of ice thickness are available for the marginal seas (up to a maximum thickness of ~1 metre) from low-frequency satellite passive microwave measurements (Kaleschke et al., 2016; Ricker et al., 2017) but data are only available since 2010. The shift to thinner seasonal sea ice contributes to further ice extent reductions through enhanced summer season melt via increased energy absorption (Nicolaus et al., 2012), and it is vulnerable to fragmentation from the passage of intense Arctic cyclones in summer and increased ocean swell conditions (Zhang et al., 2013; Thomson and Rogers, 2014).

Surface observations of Antarctic sea ice thickness are extremely sparse (Worby et al., 2008). There are no consistent long-term observations from which trends in ice volume may be derived. Calibrated model simulations suggest that ice thickness trends closely follow those of ice concentration (Massonnet et al., 2013; Holland et al., 2014) (*medium confidence*). Satellite altimeter datasets of Antarctic sea ice thickness are emerging (Paul et al., 2018) but definitive trends are not yet available.

3.2.1.1.3 Seasonality

There is *high confidence* that the Arctic sea ice melt season has extended by 3 days per decade since 1979 due to earlier melt onset, and 7 days per decade due to later freeze-up (Stroeve and Notz, 2018). This longer melt season is consistent with the observed loss of sea ice extent and thickness (Sections 3.2.1.1.1; 3.2.1.1.2). While the melt onset trends are smaller, they play a large role in the earlier development of open water (Stroeve et al., 2012b; Serreze et al., 2016) and melt pond development (Perovich and Polashenski, 2012) which enhance the sea ice albedo feedback (Stroeve et al., 2014b; Liu et al., 2015a). Observed reductions in the duration of seasonal sea ice cover are reflected in community-based observations of decreased length of time in which activities can safely take place on sea ice (Laidler et al., 2010; Eisner et al., 2013; Fall et al., 2013; Ignatowski and Rosales, 2013).

Changes in the duration of Antarctic sea ice cover over 1979–2011 largely followed the spatial pattern of sea ice extent trends with reduced ice cover duration in the Amundsen/Bellingshausen Sea region in summer and autumn owing to earlier retreat and later advance, and increases in the Ross Sea due to later ice retreat and earlier advance (Stammerjohn et al., 2012).

3.2.1.1.4 Motion

Winds associated with the climatological Arctic sea level pressure pattern drive the Beaufort Gyre (Dewey et al., 2018; Meneghello et al., 2018) and the Transpolar Drift Stream (Vihma et al., 2012), which retains sea ice within the central Arctic Basin, and exports sea ice out of the Fram Strait, respectively. There is *high confidence* that sea ice drift speeds have increased since 1979, both within the Arctic Basin and through Fram Strait (Rampal et al., 2009; Krumpfen et al., 2019), attributed to thinner ice (Spren et al., 2011) and changes in wind forcing (Olason and Notz, 2014). Fram Strait sea ice area export estimates range between 600,000 to 1 million km² of ice annually, which represents approximately 10% of the ice within the Arctic Basin (*medium confidence*) (Kwok et al., 2013; Krumpfen et al., 2016; Smedsrud et al., 2017; Zamani et al., 2019). Sea ice volume flux estimates through Fram Strait are now available from satellite altimeter datasets (Ricker et al., 2018), but they cover too short a time period for robust trend analysis. Observations of extreme Arctic sea ice deformation is attributed to the combination of decreased ice thickness and increased ice motion (Itkin et al., 2017).

Satellite estimates of sea ice drift velocity show significant trends in Antarctic ice drift (Holland and Kwok, 2012). Increased northward drift in the Ross Sea and decreased northward drift in the Bellingshausen and Weddell seas agree with the respective ice extent gains and losses in these regions, but there is only *medium confidence* in these trends due to a small number of ice drift data products derived from temporally inconsistent satellite records (Haumann et al., 2016).

3.2.1.1.5 Landfast ice

Immobile sea ice anchored to land or ice shelves is referred to as 'landfast'. The few long term surface (auger hole) records of Arctic

landfast sea ice thickness all exhibit thinning trends in springtime maximum sea ice thickness since the mid-1960s (*high confidence*): declines of 11 cm per decade in the Barents Sea (Gerland et al., 2008), 3.3 cm per decade along the Siberian Coast (Polyakov et al., 2010), and 3.5 cm per decade in the Canadian Arctic Archipelago (Howell et al., 2016). Over a shorter 1976–2007 period, winter season landfast sea ice extent from measurements across the Arctic significantly decreased at a rate of 7% per decade, with the largest decreases in the regions of Svalbard (24% per decade) and the northern coast of the Canadian Arctic Archipelago (20% per decade) (Yu et al., 2013). Svalbard and the Chukchi Sea regions are experiencing the largest declines in landfast sea ice duration (~1 week per decade) since the 1970s (Yu et al., 2013; Mahoney et al., 2014). While most Arctic landfast sea ice melts completely each summer, perennial landfast ice (also termed an 'ice-plug') occurs in Nansen Sound and the Sverdrup Channel in the Canadian Arctic Archipelago. These ice-plugs were in place continuously from the start of observations in the early 1960s, until they disappeared during the anomalously warm summer of 1998, and they have rarely re-formed since 2005 (Pope et al., 2017). The loss of this perennial sea ice is associated with reduced landfast ice duration in the northern Canadian Arctic Archipelago (Galley et al., 2012; Yu et al., 2013) and increased inflow of multi-year ice from the Arctic Ocean into the northern Canadian Arctic Archipelago (Howell et al., 2013).

Arctic landfast ice is important to northern residents as a platform for travel, hunting, and access to offshore regions (Sections 3.4.3.3, 3.5.2.2). Reports of thinning, less stable, and less predictable landfast ice have been documented by residents of coastal communities in Alaska (Eisner et al., 2013; Fall et al., 2013; Huntington et al., 2017), the Canadian Arctic (Laidler et al., 2010), and Chukotka (Inuit Circumpolar Council, 2014). The impact of changing prevailing wind forcing on local ice conditions has been specifically noted (Rosales and Chapman, 2015) including impacts on the landfast ice edge and polynyas (Box 3.3) (Gearheard et al., 2013). Long-term records of Antarctic landfast ice are limited in space and time (Stammerjohn and Maksym, 2016), with a high degree of regional variability in trends (Fraser et al., 2011) (*low confidence*).

3.2.1.1.6 Snow on ice

Snow accumulation on sea ice inhibits sea ice melt through a high albedo, but the insulating properties limit sea ice growth (Sturm and Massom, 2016) and inhibits photosynthetic light (important for in- and under-ice biota) from reaching the bottom of the ice (Mundy et al., 2007). If snow on first-year ice is sufficiently thick, it can depress the ice below the sea level surface, which forms snow-ice due to surface flooding. This process is widespread in the Antarctic (Maksym and Markus, 2008) and the Atlantic Sector of the Arctic (Merkouriadi et al., 2017), and may become more common across the Arctic (with implications for sea ice ecosystems) as the ice regime shifts to thinner seasonal ice (Olsen et al., 2017; Granskog et al., 2018) (*medium confidence*).

Despite the importance of snow on sea ice (Webster et al., 2018), surface or satellite derived observations of snowfall over sea ice, and snow depth on sea ice are lacking (Webster et al., 2014). The primary

source of snow depth on Arctic sea ice are based on observations collected decades ago (Warren et al., 1999) the utility of which are impacted by the rapid loss of multi-year ice across the central Arctic (Stroeve and Notz, 2018), and large interannual variability in snow depth on sea ice (Webster et al., 2014). Airborne radar retrievals of snow depth on sea ice provide more recent estimates, but spatial and temporal sampling is highly discontinuous (Kurtz and Farrell, 2011). Multi-source time series provide evidence of declining snow depth on Arctic sea ice (Webster et al., 2014) consistent with estimates of higher fractions of liquid precipitation since 2000 (Boisvert et al.,

2018) but there is *low confidence* because surface measurements for validation are extremely limited and suggest a high degree of regional variability (Haas et al., 2017; Rösel et al., 2018).

Although there are regional estimates of snow depth on Antarctic sea ice from satellite (Kern and Ozsoy-Çiçek, 2016), airborne remote sensing (Kwok and Maksym, 2014), field measurements (Massom et al., 2001) and ship-based observations (Worby et al., 2008), data are not sufficient in time nor space to assess changes in snow accumulation on Antarctic sea ice.

Box 3.2 | Potential for the Polar Cryosphere to Influence Mid-latitude Weather

Since AR5, understanding how observed changes in the Arctic can influence mid-latitude weather has emerged as a societally important topic because hundreds of millions of people can potentially be impacted (Jung et al., 2015). The early to middle part of the Holocene coincided with substantial decreases in net precipitation that may be due to weakening jet stream winds related to Arctic temperatures (Routson et al., 2019). There is only *low to medium confidence* in the current nature of Arctic/mid-latitude weather linkages because conclusions of recent analyses are inconsistent (National Research Council, 2014; Barnes and Polvani, 2015; Francis, 2017). The atmosphere interacts with the ocean and cryosphere through radiation, heat, precipitation and wind, but a full understanding of complex interconnected physical processes is lacking. Arctic forcing on the atmosphere from loss of sea ice and terrestrial snow is increasing, but the potential for Arctic/mid-latitude weather linkages varies for different jet stream patterns (Grotjahn et al., 2016; Messori et al., 2016; Overland and Wang, 2018a). Connectivity is reduced by the influence of chaotic internal natural variability and other tropical and oceanic forcing. Part of the scientific disagreement is due to irregular connections in the Arctic to mid-latitude linkage pathways, both within and between years (Overland and Wang, 2018b).

Considerable literature exists on the potential for sea ice loss in the Barents and Kara Seas to drive cold episodes in eastern Asia (Kim et al., 2014; Kretschmer et al., 2016), while sea ice anomalies in the Chukchi Sea and areas west of Greenland are associated with cold events in eastern North America (Kug et al., 2015; Ballinger et al., 2018; Overland and Wang, 2018a). Such connections, however, are only episodic (Cohen et al., 2018). While there is evidence of an increase in the frequency of weak polar vortex events (Screen et al., 2018), studies do not show increases in the number of mid-latitude cold events in observations or model projections (Ayarzaguena and Screen, 2016; Trenary et al., 2016). Potential Arctic/mid-latitude interactions have a more regional tropospheric pathway in November to December (Honda et al., 2009; Chen et al., 2016a; McKenna et al., 2018), whereas January to March has a more hemispheric stratospheric pathway involving migration of the polar vortex off of its usual centred location on the North Pole (Cohen et al., 2012; Nakamura et al., 2016; Zhang et al., 2018b). Overall, changes in the stratospheric polar vortex and Northern Annual Mode are not separable from natural variability, and so cannot be attributed to greenhouse gas forced sea ice loss (Screen et al., 2018).

Only a few studies have focused on the potential impact of Antarctic sea ice changes on the mid-latitude circulation (Kidston et al., 2011; Raphael et al., 2011; Bader et al., 2013; Smith et al., 2017b; England et al., 2018); these find that any impacts on the jet stream are strongly dependent on the season and model examined. England et al. (2018) suggest that the response of the jet stream to future Antarctic sea ice loss may in fact be less seasonal than the response to Arctic sea ice loss.

3.2.1.2 Ocean Properties

The Polar Oceans are amongst the most rapidly changing oceans of the world, with consequences for global-scale storage and cycling of heat, carbon and other climatically and ecologically important properties (SM3.2.1; Figure SM3.2).

3.2.1.2.1 Temperature

Ocean temperatures and associated heat fluxes have a primary influence on sea ice (e.g., Carmack et al., 2015; Steele and Dickinson, 2016). WGI AR5 (their Section 3.2.2) reported that Canada Basin surface waters warmed from 1993 to 2007, and observations over

1950–2010 show the Arctic Ocean water of Atlantic origin (i.e., the Atlantic Water Layer) warming starting in the 1970s. Warming trends have continued: August trends for 1982–2017 reveal summer mixed layer temperatures increasing at about 0.5°C per decade over large sectors of the Arctic basin that are ice-free in summer (Timmermans et al., 2017) (Figure 3.3). This is primarily the result of increased absorption of solar radiation accompanying sea ice loss (Perovich, 2016). Between 1979 and 2011, the decrease in Arctic Ocean albedo corresponded to more solar energy input to the ocean (*virtually certain*) of approximately $6.4 \pm 0.9 \text{ Wm}^{-2}$ (Pistone et al., 2014), *likely* reducing the growth of sea ice by up to 25% in both Eurasian and Canadian basins (Timmermans, 2015; Ivanov et al., 2016) (Section 3.2.1.1).

Table 3.1 | Ocean heat content trend (0–2000 m depth) during 2005–2017 and 1970–2017 for the global ocean and Southern Ocean. Ordinary Least Square (OLS) method is used; units are 10^{21} J yr^{-1} . Uncertainties denote the 90% confidence interval accounting for the reduction in the degrees of freedom implied by temporal correlations of residuals, as per Section 5.2. Values in curved brackets are percentages of heat gain by the Southern Ocean relative to the global ocean. Data sources are as per Table SM3.1. The mean proportion and its 5–95% confidence interval (1.65 times standard deviation of individual estimates) are in the last column.

OHC Trend (10^{21} J yr^{-1})	Ishii V7.2	IAP	EN4-GR10	IPRC	Scripps	JAMSTEC	Mean [5%, 95%]
Global 2005–17	10.06 ± 1.28	8.45 ± 1.04	10.57 ± 1.17	9.96 ± 1.57	8.38 ± 1.31	9.06 ± 0.67	
South of 30°S 2005–17	5.20 ± 1.03 (52%)	4.55 ± 1.00 (54%)	5.38 ± 1.30 (51%)	6.24 ± 1.80 (63%)	4.22 ± 0.70 (50%)	4.44 ± 0.63 (49%)	53% [45%, 62%]
Global 1970–2017	6.73 ± 0.55	7.02 ± 1.96	5.28 ± 1.01				
South of 30°S 1970–2017	2.42 ± 0.26 (36%)	2.78 ± 0.29 (40%)	2.18 ± 0.36 (41%)				39% [35%, 43%]

While Atlantic Water Layer temperatures appear to show less variability since 2008, total heat content in this layer continues to increase (Polyakov et al., 2017). Recent changes have been dubbed the ‘Atlantification’ of the Northern Barents Sea and Eurasian Basin (Arthun et al., 2012; Lind et al., 2018), characterised by weaker stratification and enhanced Atlantic Water Layer heat fluxes further northeast (*medium confidence*). Polyakov et al. (2017) estimate 2–4 times larger heat fluxes in 2014–2015 compared with 2007–2008. In the Canadian Basin, the maximum temperature of the Pacific Water Layer increased by $\sim 0.5^\circ\text{C}$ between 2009 and 2013 (Timmermans et al., 2014), with a doubling in integrated heat content over 1987–2017 (Timmermans et al., 2018). Over 2001–2014, heat transport associated with Bering Strait inflow increased by 60%, from around 10 TW in 2001 to 16 TW in 2014, due to increases in both volume flux and temperature (Woodgate et al., 2015; Woodgate, 2018) (*low confidence*).

The Southern Ocean is important for the transfer of heat from the atmosphere to the global ocean, including heat from anthropogenic warming (Frölicher et al., 2015; Shi et al., 2018). The Southern Ocean accounted for $\sim 75\%$ of the global ocean uptake of excess heat during 1870–1995 (Figure SM3.2; Frölicher et al., 2015), of which $\sim 43\%$ resided in the Southern Ocean with the remainder redistributed to lower latitudes. Over 1970–2017, observations show that the upper 2000 m of the ocean south of 30°S was responsible for 35–43% of the increase in global ocean heat content (Table 3.1). Both models and observations show that, relative to its size (Table SM3.1), the Southern Ocean is disproportionately important in the increase in global upper ocean heat content (*high confidence*). Multi-decadal warming of the Southern Ocean has been attributed to anthropogenic factors, especially the role of greenhouse gases but also ozone depletion (Armour et al., 2016; Shi et al., 2018; Swart et al., 2018; Irving et al., 2019) (*medium confidence*).

Surface warming during 1982–2016 was strongest along the northern flank of the ACC, contrasting with cooling further south (Figure 3.3). Interior warming was strongest in the upper 2000 m, peaking around 40°S – 50°S (Armour et al., 2016) (SM3.2.1; Figures SM3.2 and SM3.3). There is *high confidence* that this pattern of change is driven by upper-ocean overturning circulation and mixing (Cross-Chapter Box 7 in Chapter 3), whereby heat uptake at the surface by newly upwelled waters is transmitted to the ocean interior in intermediate depth layers (Armour et al., 2016). Whilst temperature trends in the

ACC itself are driven predominantly by air-sea flux changes (Swart et al., 2018), the warming on its northern side appears strongly influenced by wind-forced changes in the thickness and depth of the mode water layer (Desbruyeres et al., 2017; Gao et al., 2018) (*medium confidence*). Below the surface south of the ACC, warming extends close to Antarctica, intruding onto the continental shelf in the Amundsen-Bellinghousen Sea where temperature increases of 0.1°C – 0.3°C per decade have been observed over 1983–2012 (Schmidtke et al., 2014) (Section 3.3.1.5). This latter warming may be driven by changes in wind forcing (Spence et al., 2014), and exhibits significant decadal variability (Jenkins et al., 2018).

After around 2005, improved upper ocean heat content estimates became available via Argo profiling floats (Section 1.8.1; Section 5.2). For 2005–2017, multiple datasets show that the heat gained by the Southern Ocean south of 30°S was 45–62% of the global ocean heat gain (Table 3.1) (equivalent figures for other indicative Southern Ocean extents are in Table SM3.2). This accords with Roemmich et al. (2015), who found that during 2006–2013 the ocean south of 20°S accounted for 67–98% of total heat gain in the upper 2000 m of the global ocean. (The smaller proportion for 2005–2017 c.f. 2006–2013 is due to comparatively greater warming in the earlier part of the common period). The recent Southern Ocean heat gain is thus larger than its long-term trend over either the preceding several decades (1970–2004, 30–51%, Table SM3.3) or the full period 1970–2017 (35–43%; Table 3.1 and above). There is *high confidence* that the Southern Ocean has increased its role in global ocean heat content in recent years compared with the past several decades. Attribution of this increased role is currently lacking.

The ocean below 2000 m globally stores $\sim 19\%$ of the excess anthropogenic heat in the Earth system, with a large fraction (6% of global total heat excess) located in the deep Southern Ocean south of 30°S (Frölicher et al., 2015; Talley et al., 2016) (*medium confidence*). The WGI AR5-quantified warming of these waters was recently updated (Desbruyeres et al., 2017) to an equivalent heat uptake of 0.07 ± 0.06 W m^{-2} below 2000 m since the beginning of the century, resulting in an extra 34 ± 14 TW south of 30°S from 1980 to 2012 (Purkey and Johnson, 2013). Antarctic Bottom Water volume is decreasing (Purkey and Johnson, 2012), resulting in a deepening of density surfaces and driving much of the warming on depth surfaces below 2000 m (Desbruyeres et al., 2017). This reduction in

bottom water volume is suggestive of a decrease in its production (Purkey and Johnson, 2013). In the Indian and Pacific basins close to Antarctica, bottom water is freshening (Purkey and Johnson, 2013; Menezes et al., 2017) consistent with the uptake of enhanced Antarctic ice shelf and glacial melt (Purkey and Johnson, 2013).

3.2.1.2.2 Salinity

Salinity is the dominant determinant of polar ocean density, and exerts major controls on stratification, circulation and mixing. Salinity changes are induced by freshwater runoff to the ocean (rivers and land ice), net precipitation, sea ice, and advection of mid-latitude waters, with the potential to impact water mass formation and circulation (e.g., Thornalley et al., 2018; see also Section 6.7.1).

Updating WGI AR5 (their Section 3.3.3.3), recent Arctic-wide estimates yield a freshwater increase (relative to salinity of 34.8 on the Practical Salinity Scale, used throughout this chapter) of $600 \pm 300 \text{ km}^3 \text{ yr}^{-1}$ over 1992–2012, with about two-thirds concomitant with decreasing salinity, and the remainder with a thickening of the freshwater layer (*medium confidence*) (Rabe et al., 2014; Haine et al., 2015; Carmack et al., 2016). The Beaufort Gyre region has increased its freshwater by ~40% (6600 km^3) over 2003–2017; this, and the Gyre's strengthening, have been attributed to dominance of clockwise wind patterns over the Canadian Basin over 1997–2016 and freshwater accumulation from sea ice-melt (Krishfield et al., 2014; Proshutinsky et al., 2015). Freshwater decreases in the East Siberian, Laptev, Chukchi and Kara seas are estimated to be $\sim 180 \text{ km}^3$ over 2003–2014 (Armitage et al., 2016). During the 2000s, freshwater content in the upper 100 m of the northern Barents Sea declined by about 32%, from a mean of $\sim 2.5 \text{ m}$ (relative to a salinity of 35) in 1970–1999, to 1.7 m in 2010–2016 (Lind et al., 2018). An increasing trend of $30 \pm 20 \text{ km}^3 \text{ yr}^{-1}$ in freshwater flux through Bering Strait, primarily due to increased volume flux, was measured from 1991 to 2015, with record maximum freshwater influx in 2014 of around 3500 km^3 in that year (Woodgate, 2018). Freshwater fluxes from rivers are also increasing (Section 3.4.1.2.2), and there have been observed increases in discharge of glacial ice from Greenland (Section 3.3.1.3).

Observed Southern Ocean freshening trends are consistent with WGI AR5; subsequent studies have increased confidence in their magnitude and sign, and also attributed them to anthropogenic influences (Swart et al., 2018). Changes over 1950–2010 show persistent surface water freshening over the whole Southern Ocean, with subsducted mode/intermediate waters carrying trends of $0.0002\text{--}0.0008 \text{ yr}^{-1}$ to below 1500 m (Skirris et al., 2014), whilst de Lavergne et al. (2014) observe a circumpolar freshening south of the ACC of $0.0011 \pm 0.0004 \text{ yr}^{-1}$ in the upper 100 m since the 1960s (*medium confidence*). This intensifies over the Antarctic continental shelves (except along the Western Antarctic Peninsula), where freshening of up to 0.01 yr^{-1} is observed (Schmidtke et al., 2014). Freshening may be driven by increases in precipitation, but while models (Pauling et al., 2016) and observations suggest an increase may have occurred over the last 60 years, uncertainty is presently too high to quantify its net impact (Skirris et al., 2014). Recently, there has been increased recognition of the importance of sea ice in driving Southern Ocean salinity changes, with Haumann et al. (2016) demonstrating that wind driven

sea ice export has increased by $20 \pm 10\%$ from 1982 to 2008, and that this may have driven freshening of $0.002 \pm 0.001 \text{ yr}^{-1}$ in the surface and intermediate waters. Separately, the central role of sea ice in driving water mass transformations in the Southern Ocean has been highlighted (Abernathy et al., 2016; Pellichero et al., 2018; Swart et al., 2018), hence such changes have the potential to affect overturning circulation (Cross-Chapter Box 7 in Chapter 3). Freshwater input to the ocean from the Antarctic Ice Sheet also has the potential to affect the properties and circulation of Southern Ocean water masses; see Section 3.3.3.

3.2.1.2.3 Stratification

See Supplementary Material (SM3.2.2).

3.2.1.2.4 Carbon and ocean acidification

Various elements of marine biogeochemistry and geochemistry in the polar regions are of global importance. Here we focus on aspects relevant to carbon and ocean acidification; others (e.g., changes in dissolved oxygen) are assessed in Section 5.2.2. Compiled datasets on observed trends in ocean acidification from different observational platforms can be found in Table SM5.3.

About a quarter of carbon dioxide (CO_2) released by human activities is taken up by the ocean (WGI AR5, their Section 3.8). This dissolves in surface water to form carbonic acid, which, upon dissociation, causes a decrease in pH (acidification) and carbonate ion (CO_3^{2-}) concentration. This can affect organisms that form shells and skeletons using calcium carbonate (CaCO_3 , aragonite and calcite as dominant mineral forms). Since AR5, new observations have demonstrated the spatial and temporal variability of ocean acidification and controlling mechanisms of carbon systems in different regions (Bellerby et al., 2018).

Robbins et al. (2013) showed aragonite undersaturation for about 20% of surface waters in the Canada and Makarov Basins, where substantial sea ice melt occurred. Qi et al. (2017) reported that aragonite undersaturation has expanded northward by at least 5° of latitude, and deepened by $\sim 100 \text{ m}$ between the 1990s and 2010 primarily due to increased Pacific Winter Water transport. In the East Siberian Arctic Shelf, extreme aragonite undersaturation was driven by the degradation of terrestrial organic matter and runoff of Arctic river water with elevated CO_2 concentrations, reflecting pH changes in excess of those projected in this region for 2100 (Semiletov et al., 2016) (*high confidence*); this was also observed along the continental margin and traced in the deep Makarov and Canada Basins (Anderson et al., 2017a). The variable buffering capacities of rivers flowing through watersheds with different bedrock geology also influenced the state of ocean acidification in coastal regions (Tank et al., 2012; Azetsu-Scott et al., 2014).

The dissolved inorganic carbon (DIC) concentration increased in subsurface waters (150–1400 m) in the central Arctic between 1991 and 2011 (Ericson et al., 2014). The rate of increase was $0.6\text{--}0.9 \mu\text{mol kg}^{-1} \text{ yr}^{-1}$ in the Arctic Atlantic Water and $0.4\text{--}0.6 \mu\text{mol kg}^{-1} \text{ yr}^{-1}$ in the upper Polar Deep Water due to anthropogenic CO_2 , while no trend was observed in nutrient

concentrations. In waters below 2000 m, no significant trend was observed for DIC and nutrient concentrations. Observation-based estimates (MacGilchrist et al., 2014) revealed a net summertime pan-Arctic export of $231 \pm 49 \text{ TgC yr}^{-1}$ of DIC across the Arctic Ocean gateways to the North Atlantic; at least $166 \pm 60 \text{ TgC yr}^{-1}$ of this was sequestered from the atmosphere (*medium confidence*). Similar to other regions (Table SM5.3), observed changes in the carbonate chemistry of the Arctic are indicative of ongoing ocean acidification (*high confidence*).

Studies covering seasonal-to-decadal variability in the Arctic are limited, with most conducted in ice-free or low ice periods during summer to autumn. However, it has been demonstrated that biological processes, respiration and photosynthesis, control the CaCO_3 saturation states in Chukchi Sea bottom water (Yamamoto-Kawai et al., 2016). Sea ice formation and melt influence the dynamics of ikaite (CaCO_3 precipitation trapped in sea ice during brine rejection), and therefore local carbonate chemistry (Rysgaard et al., 2013; Bates et al., 2014; Geilfus et al., 2016; Fransson et al., 2017). Although the increase of pH and saturation states by biological carbon fixation that consumes DIC in surface water is well documented (Azetsu-Scott et al., 2014; Yamamoto-Kawai et al., 2016) (*high confidence*), it has been shown that long photoperiods in Arctic summers sustain high pH in kelp forests, slowing ocean acidification (Krause-Jensen et al., 2016).

Since AR5, there are new constraints on the seasonal-to-decadal variability in the Southern Ocean CO_2 flux (McNeil and Matear, 2013; Landschützer et al., 2014; Landschützer et al., 2015; Gregor et al., 2017; Ritter et al., 2017; Keppler and Landschützer, 2019) (Figure SM3.4), with mean annual flux anomalies varying from $0.3 \pm 0.1 \text{ Pg C yr}^{-1}$ in 2001–2002 to $-0.4 \text{ Pg C yr}^{-1}$ in 2012 (Landschützer et al., 2015); this can affect the magnitude of the global CO_2 sink (Section 5.2.2). A weakening CO_2 sink during the 1990s (Le Quéré et al., 2007) reversed in the 2000s as part of a decadal cycle (Landschützer et al., 2015; Munro et al., 2015; Williams et al., 2017) (SM3.2.3; Figure SM3.4), with a weakening again since 2011 (Keppler and Landschützer, 2019). While the weakening sink during the 1990s was explained as a response to changes in the circumpolar winds over the Southern Ocean enhancing the outgassing of natural CO_2 , the subsequent changes appear due to a combination of changes in regional winds, temperature and circulation (Landschützer et al., 2015; Gregor et al., 2017; Keppler and Landschützer, 2019). Data scarcity, especially in winter, remains a challenge (Ritter et al., 2017; Fay et al., 2018; Gruber et al., 2019b); recent data from pH-enabled floats highlighted the potential role for winter outgassing south of the Polar Front (Williams et al., 2017; Gray et al., 2018). Overall, there is *medium confidence* that the Southern Ocean CO_2 sink has experienced significant decadal variations since the 1980s.

Southern Ocean carbon storage is affected by changes in overturning circulation (Cross-Chapter Box 7 in Chapter 3), with the storage of anthropogenic and natural carbon being both variable and out of phase on decadal timescales (DeVries et al., 2017; Tanhua et al., 2017) (Table SM3.4). Mode and intermediate waters are strongly involved in changing storage, also showing high sensitivity to shifts in winds (Swart et al., 2014; Swart et al., 2015a; Tanhua et al., 2017; Gruber et al., 2019a). Zonal basin differences in the uptake and

storage of anthropogenic carbon are not well resolved and there is weak agreement between reanalysis products and Coupled Model Intercomparison Project Phase 5 (CMIP5) models (Swart et al., 2014). The presence of subduction hotspots suggest that basin-wide studies may be underestimating the importance of mode water subduction as a principal storage mechanism (Langlais et al., 2017).

Strengthening impacts of Southern Ocean acidification are illustrated by the $3.9 \pm 1.3\%$ decrease in derived calcification rates (1998–2014) (Freeman and Lovenduski, 2015). These have strong regional character, with decreases in the Indian and Pacific sectors (7.5–11.6%) and increases in the Atlantic ($14.3 \pm 5.1\%$). There have also been changes in the seasonality of pCO_2 linked to decreasing buffer capacity (McNeil and Sasse, 2016) (SM3.2.4) or adjustments to primary production (Conrad and Lovenduski, 2015); seasonal changes are discussed further in Section 5.2.2.

3.2.1.3 Ocean Circulation

The major elements of Southern Ocean circulation are assessed in Cross-Chapter Box 7 in Chapter 3; Arctic Ocean circulation is considered here. Arctic processes, such as discharge of freshwater from the Greenland Ice Sheet, have the potential to impact on the formation of the headwaters of the Atlantic Meridional Overturning Circulation (Section 6.7.1), and can impact on the structure and function of the marine ecosystem with implications for commercially-harvested species (Sections 3.2.3, 3.2.4).

Satellite data indicate a general strengthening of the surface geostrophic currents in the Arctic basin (Armitage et al., 2017). Between 2003 and 2014, the strength of some currents in the Beaufort Gyre approximately doubled (Armitage et al., 2017). Over 2001–2014, annual Bering Strait volume transport from the Pacific to the Arctic Ocean increased from $0.7 \times 10^6 \text{ m}^3\text{s}^{-1}$ to $1.2 \times 10^6 \text{ m}^3\text{s}^{-1}$ (Woodgate et al., 2015). Mesoscale eddies are characterised by horizontal scales of $\sim 10 \text{ km}$ in the Arctic, and are important components of the ocean system. Increased wind power input to the Arctic Ocean system can in principle be compensated by the production of eddy kinetic energy; analysis of observations in the Beaufort Gyre region suggest this is *about as likely as not* (Meneghello et al., 2017). Data of sufficiently high resolution is limited in the boundary regions of the Arctic Ocean, precluding estimates of eddy variability on a basin-wide scale. In the central basin regions, a statistically significant higher concentration of eddies was sampled in the Canadian Basin compared to the Eurasian Basin between 2003 and 2014; further, a medium correspondence was found between eddy activity in the Beaufort Gyre region and intensified gyre flow (Zhao et al., 2014; Zhao et al., 2016).

In contrast to the Southern Ocean (Cross-Chapter Box 7 in Chapter 3), there is comparatively little knowledge on changing Arctic frontal positions and current cores since AR5. An exception is that the Beaufort Gyre expanded to the northwest between 2003 and 2014, contemporaneous with changes in its freshwater accumulation and alterations in wind forcing, resulting in increased proximity to the Chukchi Plateau and Mendeleev Ridge (Armitage et al., 2017; Regan et al., 2019) (Section 3.2.1.2.2).

Cross-Chapter Box 7 | Southern Ocean Circulation: Drivers, Changes and Implications

Authors: Michael P. Meredith (UK), Robert Hallberg (US), Alessandro Tagliabue (UK), Andrew Meijers (UK/Australia), Jamie Oliver (UK), Andrew Hogg (Australia)

Horizontal Circulation and Movement of Fronts

The Southern Ocean is disproportionately important in global climate and ecological systems, being the major connection linking the Atlantic, Pacific and Indian Oceans in the global circulation. The horizontal circulation in the circumpolar Southern Ocean is comprised of an eastward-flowing mean current concentrated in a series of sinuous, braided jets exhibiting strong meandering variability and shedding small-scale transient eddies (Figure CB7.1). The mean flow circumnavigates Antarctica as the world's largest ocean current, the Antarctic Circumpolar Current (ACC), transporting approximately $173.3 \pm 10.7 \times 10^6 \text{ m}^3 \text{ s}^{-1}$ (Donohue et al., 2016) of water eastward in a geostrophic balance set up by the contrasting properties of waters around Antarctica and those inside the subtropical gyres to the north of ACC. This contrast is maintained by a combination of strong westerly winds and ocean heat loss south of the ACC.

Trends in the atmospheric forcing of the Southern Ocean are dominated by a strengthening of westerly winds in recent decades (Swart et al., 2015a), but there is no evidence that this enhanced wind stress has significantly altered the ACC transport. While the annual mean value of transport is stable in the instrumental period (Chidichimo et al., 2014; Koenig et al., 2014; Donohue et al., 2016) it is difficult to resolve changes in barotropic transport; overall there is *medium confidence* that ACC transport is only weakly sensitive to changes in winds. This is consistent with longer-term analyses that find only minimal changes in ACC transport since the last glaciation (McCave et al., 2013). Theoretical predictions and high-resolution ocean modelling suggest that the weak sensitivity of the ACC to changes in wind stress is a consequence of eddy saturation (Munday et al., 2013), whereby the time-mean state of the ocean remains close to a marginal condition for eddy instability and hence additional energy input from stronger winds cascades rapidly into the smaller-scale eddy field. Satellite measurements of eddy kinetic energy over the last two decades are consistent with this, showing a statistically significant upward trend in eddy energy in the Pacific and Indian Ocean sectors of the Southern Ocean (Hogg et al., 2015) (*medium confidence*). This is supported by eddy-resolving models, which also show a marked regional variability (Patara et al., 2016), and there is evidence that local hotspots in eddy energy, especially downstream of major topographic features including the Drake Passage, Kerguelen Plateau, Campbell Plateau and the East Pacific Rise, may dominate the regional fields (Thompson and Naveira Garabato, 2014).

Working Group I (WGI) of the IPCC's 5th Assessment Report (AR5) assessed that there was *medium confidence* that the mean position of the ACC had moved southwards in response to a contraction of the Southern Ocean circumpolar winds. Such movements can in principle have profound effects on marine ecosystems via, e.g., changing habitat ranges for different species (e.g., Cristofari et al., 2018; Meijers et al., 2019) (Section 3.2.3.2). Since AR5, however, substantial contrary evidence has emerged. While winds have strengthened over the Southern Ocean, reanalysis products show no significant shift in the annual mean latitude of zonal wind jets between 1979–2009 (Swart et al., 2015a). Similarly, a variety of methods applied to satellite data have found no long-term trend and no statistically significant correlation of ACC position with winds (Gille, 2014; Chapman, 2017; Chambers, 2018). The discrepancy between these studies and those assessed in WGI AR5 appears to be caused by issues associated with using a fixed sea surface height contour as a proxy for frontal position in the presence of strongly eddying fields (Chapman, 2014) and large-scale increases in sea surface height consistent with mean global trends in sea level rise (Gille, 2014). The increase in sea surface height is ascribed largely to warming-driven steric expansion in the upper ocean, but the mechanism driving such warming is still uncertain (Gille, 2014). These recent findings do not preclude more local changes in frontal position, but it is now assessed as *unlikely* that there has been a statistically significant net southward movement of the mean ACC position over the past 20 years.

Overturning Circulation and Water Mass Formation

The Southern Ocean is the key region globally for the upwelling of interior ocean waters to the surface, enabling waters that were last ventilated in the pre-industrial era to interact with the industrial-era atmosphere and the cryosphere. New water masses are produced that sink back into the ocean interior. Such export of both extremely cold and dense Antarctic Bottom Water and the lighter mode and intermediate waters (Figure CB7.1) represents important pathways for surface properties to be sequestered from the atmosphere for decades to millennia. This upwelling and sinking constitutes a two-limbed overturning circulation, by which much of the global deep ocean is renewed.

The Southern Ocean overturning circulation plays a strong role in mediating climate change via the transfer of heat and carbon (including that of anthropogenic origin) with the atmosphere (Sections 3.2.1.2; 5.2.2.2); it also has an impact on sea ice extent and concentration, with implications for climate via albedo (Section 3.2.1.1). It acts to oxygenate the ocean interior

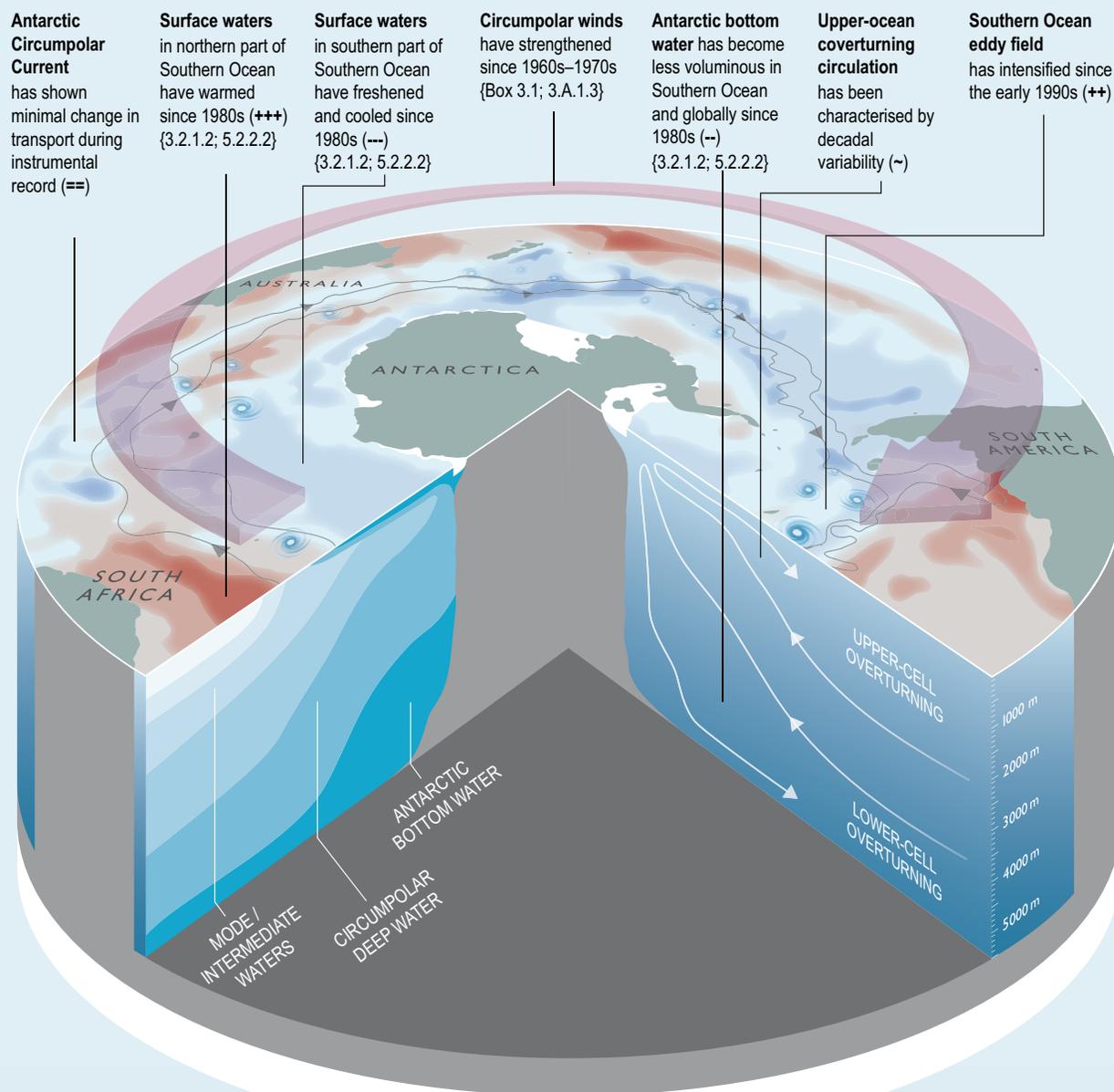


Figure CB7.1 | Schematic of some of the major Southern Ocean changes assessed in this Box and in Chapters 3 and 5. Assessed changes are marked as positive (+), neutral (=), negative (–), or dominated by variability (~). The number of symbols used indicates confidence, from *low* (1) through *medium* (2) to *high* (3). Section numbers indicate the links to further information outside this box.

and sequesters nutrients that ultimately end up supporting a significant fraction of primary production in the rest of the world ocean (Section 5.2.2.2). The upwelling waters in the overturning bring heat to the Antarctic shelf seas, with consequences for ice shelves, marine-terminating glaciers and the stability of the Antarctic Ice Sheet (AIS) (Section 3.3.1). The lower limb of this overturning circulation supplies Antarctic Bottom Water that forms the abyssal layer of much of the world ocean (Section 3.2.1.2; 5.2.2.2).

It is challenging to measure the Southern Ocean overturning directly, and misinterpretation of Waugh et al. (2013) led to AR5 erroneously reporting the upper cell to have slowed (AR5 WGI, Section 3.6.4). However, additional indirect estimates since AR5 provide support for the increase in the upper ocean overturning proposed by Waugh et al. (2013). Waugh (2014) and Ting and Holzer (2017) suggest that over the 1990s–2000s water mass ages changed in a manner consistent with an increase in upwelling and overturning. However, inverse analyses suggest that such overturning experiences significant inter-decadal variability in response

Cross-Chapter Box 7 (continued)

to wind forcing, with reductions in 2000–2010 relative to 1990–2000 (DeVries et al., 2017). This variability, combined with the indirect nature of observational estimates, means that there is *low confidence* in assessments of long-term changes in upper cell overturning.

Available evidence indicates that the volume of Antarctic Bottom Water in the global ocean has decreased (Purkey and Johnson, 2013; Desbruyeres et al., 2017) (*medium confidence*), thinning at a rate of 8.1 m yr^{-1} since the 1950s (Azaneu et al., 2013); recently updated analyses confirm this trend to present day (Figure 5.4). This suggests that the production and export of this water mass has probably slowed, though direct observational evidence is difficult to obtain. The large-scale impacts of Antarctic Bottom Water changes include a potential modulation to the strength of the Atlantic Meridional Overturning Circulation (e.g., Patara and Böning, 2014; see also Section 5.2.2.2.1).

Projections

Projections of future trends in the Southern Ocean are dominated by the potential for a continued strengthening of the westerly winds (Bracegirdle et al., 2013), as well as a combination of warming and increased freshwater input from both increased net precipitation and changes in sea ice export (Downes and Hogg, 2013). Dynamical considerations and numerical simulations indicate that, if further increases in the westerly winds are sustained, then it is *very likely* that the eddy field will continue to grow in intensity (Morrison and Hogg, 2013; Munday et al., 2013), with potential consequences for the upper-ocean overturning circulation and transport of tracers (Abernathey and Ferreira, 2015) (including heat, carbon, oxygen and nutrients), and *likely* that the mean position and strength of the ACC will remain only weakly sensitive to winds.

The considerable Coupled Model Intercomparison Project Phase 5 (CMIP5) inter-model variations in Southern Ocean time-mean circulation projections reported in WGI AR5 (Meijers et al., 2012; Downes and Hogg, 2013) remain largely unchanged. Some of the differences in projected changes have been found to be correlated with biases in the various models' ability to simulate the historical state of the Southern Ocean, such as mixed layer depth (Sallée et al., 2013a) and westerly wind jet latitude (Bracegirdle et al., 2013). This suggests that bias reduction against observed historical metrics (Russell et al., 2018) in future generations of coupled models (e.g., Coupled Model Intercomparison Project Phase 6 (CMIP6)) should lead to improved confidence in aspects of projected Southern Ocean changes. CMIP5 models suggest that the subduction of mode and intermediate water will increase (Sallée et al., 2013b), which will affect oxygen and nutrient transports, and the overall transport of the Southern Ocean upper overturning cell will increase by up to 20% (Downes and Hogg, 2013), but model performance is limited by the inability to explicitly resolve eddy processes (Gent, 2016; Downes et al., 2018). The formation and export of Antarctic Bottom Water is predicted to continue decreasing (Heuzé et al., 2015) due to warming and freshening of surface source waters near the continent. These are, however, some of the most poorly represented processes in global models. Further uncertainty derives from increased meltwater from the AIS not being considered in the CMIP5 climate models, despite its potential for significant impact on Southern Ocean dynamics and the global climate, and its potential for positive feedbacks (Bronse laer et al., 2018). Due to these uncertainties, *low confidence* is therefore ascribed to the CMIP5-based model projections of future Southern Ocean circulation and watermasses.

3.2.2 Projected Changes in Sea Ice and Ocean

3.2.2.1 Sea Ice

The multi-model ensemble of historical simulations from CMIP5 models identify declines in total Arctic sea ice extent and thickness (Sections 3.2.1.1.1; 3.2.1.1.2; Figure 3.3) which agree with observations (Massonnet et al., 2012; Stroeve et al., 2012a; Stroeve et al., 2014a; Stroeve and Notz, 2015). There is a range in the ability of individual models to simulate observed sea ice thickness spatial patterns and sea ice drift rates (Jahn et al., 2012; Stroeve et al., 2014a; Tandon et al., 2018). Reductions in Arctic sea ice extent scale linearly with both global temperatures and cumulative CO₂ emissions in simulations and observations (Notz and Stroeve, 2016), although aerosols influenced historical sea ice trends (Gagné et al., 2017). The uncertainty in sea ice sensitivity (ice extent loss per unit of warming)

is quite large (Niederdrenk and Notz, 2018) and the model sensitivity is too low in most CMIP5 models (Rosenblum and Eisenman, 2017). Emerging evidence suggests, however, that internal variability, including links between the Arctic and lower latitude, strongly influences the ability of models to simulate observed reductions in Arctic sea ice extent (Swart et al., 2015b; Ding et al., 2018).

CMIP5 models project continued declines in Arctic sea ice through the end of the century (Figure 3.3) (Notz and Stroeve, 2016) (*high confidence*). There is a large spread in the timing of when the Arctic may become ice free in the summer, and for how long during the season (Massonnet et al., 2012; Stroeve et al., 2012a; Overland and Wang, 2013) as a result of natural climate variability (Notz, 2015; Swart et al., 2015b; Screen and Deser, 2019), scenario uncertainty (Stroeve et al., 2012a; Liu et al., 2013), and model uncertainties related to sea ice dynamics (Rampal et al., 2011; Tandon et al., 2018)

and thermodynamics (Massonnet et al., 2018). Internal climate variability results in an uncertainty of approximately 20 years in the timing of seasonally ice-free conditions (Notz, 2015; Jahn, 2018), but the clear link between summer sea ice extent and cumulative CO₂ emissions provides a basis for when consistent ice-free conditions may be expected (*high confidence*). For stabilised global warming of 1.5°C, sea ice in September is *likely* to be present at end of century with an approximately 1% chance of individual ice-free years (Notz and Stroeve, 2016; Sanderson et al., 2017; Jahn, 2018; Sigmond et al., 2018); after 10 years of stabilised warming at a 2°C increase, more frequent occurrence of an ice-free summer Arctic is expected (around 10–35%) (Mahlstein and Knutti, 2012; Jahn et al., 2016; Notz and Stroeve, 2016). Model simulations show that a temporary temperature overshoot of a warming target has no lasting impact on ice cover (Armour et al., 2011; Ridley et al., 2012; Li et al., 2013).

CMIP5 models show a wide range of mean states and trends in Antarctic sea ice (Turner et al., 2013; Shu et al., 2015). The ensemble mean across multiple models show a decrease in total Antarctic sea ice extent during the satellite era, in contrast to the lack of any observed trend (Figure 3.3; Section 3.2.1.1.1). Interannual sea ice variability in the models is larger than observations (Zunz et al., 2013), which may mask disparity between models and observations. Internal variability (Polvani and Smith, 2013; Zunz et al., 2013), and

model sensitivity to warming (Rosenblum and Eisenman, 2017) are also important sources of uncertainty. During the historical period, regional trends of Antarctic sea ice are not captured by the models, particularly the decrease in the Bellingshausen Sea and the expansion in the Ross Sea (Hobbs et al., 2015). There is a very wide spread of model responses in the Weddell Sea (Hobbs et al., 2015; Ivanova et al., 2016), a region with complex ocean-sea ice interactions that many models do not replicate (de Lavergne et al., 2014).

There is *low confidence* in projections of Antarctic sea ice because there are multiple anthropogenic forcings (ozone and greenhouse gases) and complicated processes involving the ocean, atmosphere, and adjacent ice sheet (Section 3.2.1.1.). Model deficiencies are related to stratification (Sallée et al., 2013a), freshening by ice shelf melt water (Bintanja et al., 2015), atmospheric processes including clouds (Schneider and Reusch, 2015; Hyder et al., 2018), and wind and ocean driven processes (Purich et al., 2016a; Purich et al., 2016b; Schroeter et al., 2017; Purich et al., 2018; Zhang et al., 2018a). Uncertainty in sea ice projections reduces confidence in projections of Antarctic Ice Sheet surface mass balance because sea ice affects Antarctic temperature and precipitation trends (Bracegirdle et al., 2015), and impacts projected changes in the Southern Hemisphere westerly jet (Bracegirdle et al., 2018; England et al., 2018) with implications for the Southern Ocean overturning circulation (Cross-Chapter Box 7 in Chapter 3).

Box 3.3 | Polynyas

Arctic Coastal Polynyas

Arctic polynyas (areas of open water surrounded by sea ice) are important because they ventilate the Arctic Ocean. The polynyas induce bottom reaching convection on shallow shelves (Damm et al., 2018) because the warm and exposed ocean surface creates very high heat fluxes and new sea ice formation during winter, releasing brine and creating dense water (Barber et al., 2012). On the shallow Siberian shelves, the ocean surface waters are dominated by river runoff which is rich with sediments (Damm et al., 2018), which end up both in the dense bottom water and in new sea ice (Bauch et al., 2012; Janout et al., 2015). This process maintains the Arctic Ocean halocline (Bauch et al., 2011), which insulates the sea ice cover from the heat of the underlying Atlantic-derived waters.

Polynyas are projected to change in different ways depending on regional ice conditions and ice formation processes. Further reductions in sea ice are projected for Arctic shelf seas which have already lost ice in recent decades (Barnhart et al., 2015; Onarheim et al., 2018) so polynyas will cease to exist where seasonal sea ice disappears or evolve to become part of the marginal sea ice zone due to changes in ice dynamics (i.e., the North Water polynya and the Circumpolar Flaw Lead); new or enlarged polynyas could result in regions where thinner ice becomes more effectively advected offshore, or where marine terminating glaciers increase land ice fluxes to the marine system (*medium confidence*). The reduced survival rate of sea ice in the Transpolar Drift interrupts the transport of sediment-laden ice produced from Siberian shelf polynyas (Krumpfen et al., 2019), with consequences for the associated biogeochemical matter and gas fluxes (Damm et al., 2018) (*medium confidence*).

Projected changes to polynyas are important because the spring phytoplankton bloom starts early as the ocean is often well-ventilated and nutrient rich, so the entire biological range from phytoplankton to seabirds to marine mammals thrive in polynya waters (*high confidence*) (Stirling, 1997; Arrigo and van Dijken, 2004; Karnovsky et al., 2009). Secondary production and upper food web processes are typically adapted to the early availability of energy to the system with arrival of higher trophic species (Asselin et al., 2011). Because of the abundance of marine food resources including seals, whales and fish in and around polynyas, Arctic peoples have hunted regularly in these areas for thousands of years (Barber and Massom, 2007). Recent implementation of Inuit-led marine management areas acknowledge the Inuit knowledge of polynyas, and recognise the potential for development of fisheries and other resources in polynya systems, provided these activities minimise harm on the environment and wildlife. The Inuit Circumpolar Council's Pikialasorsuaq Commission is an example of a proposal to develop an Inuit management area in the North Water Polynya (Cross-Chapter Box 3 in Chapter 1).

Antarctic Coastal Polynyas

The Antarctic continent is surrounded by coastal polynyas, which form from the combined effects of winds and landfast ice in the lee of coastal features that protrude into the westward coastal current (Nihashi and Ohshima, 2015; Tamura et al., 2016). Intense ice growth within these polynyas contributes to the production of Antarctic Bottom Water, the densest and most voluminous water mass in the global ocean (Jacobs, 2004; Nicholls et al., 2008; Orsi and Wiederwohl, 2009; Ohshima et al., 2013). Sea ice production is greatest in Ross and Weddell sea polynyas and around East Antarctica (Drucker et al., 2011; Nihashi and Ohshima, 2015; Tamura et al., 2016) (*high confidence*).

Antarctic coastal polynyas are biological hot-spots that support high rates of primary production (Ainley et al., 2015; Arrigo et al., 2015) due to a combination of both high light (Park et al., 2017) and high nutrient levels, especially iron (Gerringa et al., 2015). Basal ice shelf melt is the primary supplier of iron to coastal polynyas (Arrigo and van Dijken, 2015) although sea ice melt and intrusions of Circumpolar Deep Water are significant in the Ross Sea (McGillicuddy et al., 2015; Hatta et al., 2017). As ice shelves retreat, the polynyas created in their wake also increase local primary production: the new polynyas created after the collapse of the Larsen A and B ice shelves are as productive as other Antarctic shelf regions, *likely* increasing organic matter export and altering marine ecosystem evolution (Cape et al., 2013). The recent calving of Mertz Glacier Tongue in East Antarctica has altered sea ice and ocean stratification (Fogwill et al., 2016) such that polynyas there are now twice as productive (Shadwick et al., 2017).

The productivity associated with these polynyas is a critical food source for some of the most abundant top predators in Antarctic waters, including penguins, albatross and seals (Raymond et al., 2014; Malpress et al., 2017) (Section 3.2.3.2.4). However, only a fraction of the carbon fixed by phytoplankton in coastal polynyas is consumed by upper trophic levels. The rest sinks to the seafloor where it is re-mineralised or sequestered (Shadwick et al., 2017), or is advected off the shelf (Lee et al., 2017b). Given the high amount of residual macronutrients in polynya surface waters, there is evidence that future changes in ice shelf melt rates could increase water column productivity (Gerringa et al., 2015; Rickard and Behrens, 2016; Kaufman et al., 2017), influencing Antarctic coastal ecosystems and increasing the ability of continental shelf waters to sequester atmospheric carbon dioxide (Arrigo and van Dijken, 2015).

The Weddell Polynya

The Weddell Polynya is a large area of open water within the winter ice pack of the Weddell Sea close to the Maud Rise seamount (at approximately 65°S, 3°E), and has importance on a global scale for deep water ventilation. The polynya opens intermittently, and remained open from 1974 to 1976, with an area of 0.2–0.3 million km² (Carsey, 1980). A similar polynya appeared in spring 2017, with a smaller area in 2016, but did not occur in 2018 (Campbell et al., 2019; Jena et al., 2019). Based on these recent events, there is *medium confidence* in the drivers of Weddell Polynya formation; it forms over deep water and appears connected to sea ice divergence created by ocean eddies (Holland, 2001) or strong winds (Campbell et al., 2019; Francis et al., 2019; Wilson et al., 2019). Around Maud Rise, the ocean is weakly stratified, and winter sea ice formation causes brine release and the related deepening mixed layer brings warmer deep waters towards the surface. This causes heat loss to the atmosphere above 200 W m⁻² (Campbell et al., 2019). These polynya formation processes cause deep ocean convection that releases heat from the deep ocean to the atmosphere (Smedsrud, 2005), and may contribute to the uptake of anthropogenic carbon (Bernardello et al., 2014).

In some CMIP5 models, phases of Weddell polynya activity appear for decades or centuries at a time, and then cease for a similar period (Reintges et al., 2017). The observational era is not sufficiently long to rule out this behaviour. Models indicate that under anthropogenic climate change, surface freshening caused by increased precipitation reduces the occurrence of the Weddell polynya (de Lavergne et al., 2014). There are systematic biases in modelled ocean stratification resulting in *low confidence* in future Weddell Polynya projections (Reintges et al., 2017).

3.2.2.2 Physical Oceanography

Consistent with the projected sea ice decline, there is *high confidence* that the Arctic Ocean will warm significantly towards the end of this century at the surface and in the deeper layers. Most CMIP5 models capture the seasonal changes in surface heat and freshwater fluxes for the present day climate, and show that the excess summer solar heating is used to melt sea ice, in a positive ice albedo feedback (Ding et al., 2016). Using RCP8.5, Vavrus et al. (2012) found that the Atlantic layer is projected to warm by 2.5°C at around 400 m depth at the end of the century, but only by 0.5°C in the surface mixed layer.

Consistent results for lower Atlantic Water layer warming were found by Koenig and Brodeau (2014) for RCP2.5 (0.5°C), RCP4.5 (1.0°C) and RCP8.5 (2.0°C).

Poleward ocean heat transport contributes to Arctic Ocean warming (*medium confidence*). Comparing 20 CMIP5 simulations for RCP8.5, Nummelin et al. (2017) found a 2°C–6°C range in Arctic amplification of surface air temperature north of 70°N, consistent with increased ocean heat transport. Comparing 26 different CMIP5 simulations for RCP4.5, Burgard and Notz (2017) found that ocean heat transport changes explain the Arctic Ocean multi-model mean warming, but

that differences between models are compensated by changes in surface fluxes. Increased ocean heat transport into the Barents Sea beyond 2020 appears as a probable mechanism with continued warming (Koenigk and Brodeau, 2014; Årthun et al., 2019). Based on four CMIP5 models, the Barents Sea is projected to become ice-free during winter beyond 2050 under RCP8.5 (Onarheim and Årthun, 2017), to which the main response is an increased ocean-to-atmosphere heat flux and related surface warming (Smetsrud et al., 2013). The ocean heat transport increases in all Arctic gateways, but is dominated by the Barents Sea, and when winter sea ice disappears here the heat loss cannot increase further and the excess ocean heat continues into the Arctic Basin (Koenigk and Brodeau, 2014).

The surface mixed layer of the Arctic Ocean is expected to freshen in future because an intensified hydrological cycle will increase river runoff (Haine et al., 2015) (*medium confidence*). The related increase in stratification has the potential to contribute to the warming of the deep Atlantic Water layer, as upward vertical mixing will be reduced (Nummelin et al., 2016). There are, however, biases in salinity of ~ 1 across the Arctic Basin for the present day climate (Ilicak et al., 2016) in forced global ice-ocean models with configurations comparable to CMIP5, suggesting limited predictive skill for the Arctic freshwater cycle.

CMIP5 projections (Figure 3.3) indicate that observed Southern Ocean warming trends will continue under RCP4.5 and RCP8.5 scenarios, leading to 1°C – 3°C warming by 2100 mostly in the upper ocean (Sallée et al., 2013a). Projections demonstrate a similar distribution of heat storage to historical observations, notably focused in deep pools north of the Subantarctic Front (e.g., Armour et al., 2016). Antarctic Bottom Water becomes coherently warmer by up to 0.3°C by 2100 across the model ensemble under RCP8.5 (Heuzé et al., 2015). The upper ocean also becomes considerably fresher (salinity decrease of approximately 0.1) (Sallée et al., 2013b) with an overall increase in stratification and a shallowing of mixed layers (Sallée et al., 2013a). Although the sign of model changes appear mostly robust, there is *low confidence* in magnitude due to the large inter-model spread in projections and significant warm biases in historical water mass properties (Sallée et al., 2013a) and sea surface temperature, which may be up to 3°C too high in the historical runs (Wang et al., 2014).

Projections of changes in Southern Ocean circulation are discussed in Cross-Chapter Box 7 in Chapter 3.

3.2.2.3 Carbon and Ocean Acidification

The Arctic and Southern Ocean have a systemic vulnerability to aragonite undersaturation (Orr et al., 2005). For the RCP8.5 scenario, the entire Arctic and Southern Ocean surface waters will *very likely* be typified by year-around conditions corrosive for aragonite minerals for 2090–2100 (Figure 3.4) (Hauri et al., 2015; Sasse et al., 2015), whilst under RCP2.6 the extent of undersaturated waters are reduced markedly. At a basin/circumpolar scale, there is *high confidence* in these projections due to our robust understanding of the driving mechanisms. However, there is *medium confidence* for the response of specific locations, due to the need for improved resolution of the local circulation, interactions with sea ice, and other processes that modulate the rate of acidification.

Under RCP8.5, melting ice causes the greatest declining rate of pH and CaCO_3 saturation state in the Central Arctic, Canadian Arctic Archipelago and Baffin Bay (Popova et al., 2014). In the Canada Basin, projections using RCP8.5 show reductions in mean surface pH from approximately 8.1 in 1986–2005 to 7.7 by 2066–2085, and aragonite saturation from 1.52–0.74 during the same period (Steiner et al., 2014). A shoaling of the aragonite saturation horizon of approximately 1200 m, a large increase in area extent of undersaturated surface waters, and a pH change in the surface water of -0.19 are projected using the SRES A1B scenario (broadly comparable to RCP6.0) in the Nordic Sea from 2000 to 2065 (Skogen et al., 2014). Under the same scenario, aragonite undersaturation is projected to occur in the bottom waters over the entire Kara Sea shelf by 2040 and over most of the Barents and East Greenland shelves by 2070 due to the accumulation of anthropogenic CO_2 (Wallhead et al., 2017).

Under RCP8.5, the rate of CO_2 uptake by the Southern Ocean is projected to increase from the contemporary $0.91 \text{ Pg C yr}^{-1}$ to $2.38 (1.65\text{--}2.55) \text{ Pg C yr}^{-1}$ by 2100, but the growth in uptake rate will slow and likely stop around 2070 ± 10 corresponding to cumulative CO_2 emissions of 1600 Gt C (Kessler and Tjiputra, 2016;

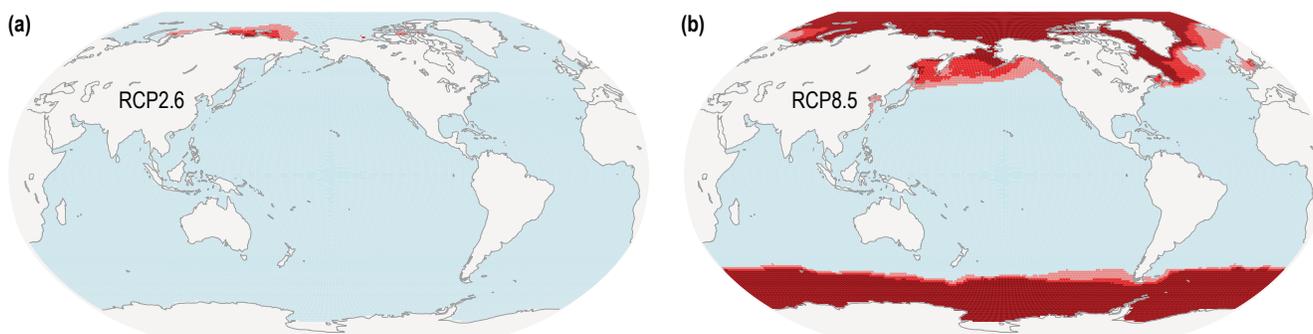


Figure 3.4 | The upper ocean (0–10 m) at end of this century (2081–2100), characterised by year-around undersaturated conditions for aragonite for the Representative Concentration Pathway (RCP)8.5 (a) and RCP2.6 (b) scenarios in the Coupled Model Intercomparison Project Phase 5 (CMIP5). The medium red shade denotes the area for which the multi-model annual mean of aragonite saturation is < 1 ; the lighter and darker red shades denote the same conditions but calculated using the -90% and $+90\%$ confidence intervals for the aragonite saturation state, respectively. Shaded regions are plotted over each other. Blue regions are those without year-around aragonite saturation states < 1 . Aragonite saturation states are averaged and confidence intervals calculated at each geographic location across the CNRM-CM5, HadGEM2-ES, GFDL-ESM2G, GFDL-ESM2G, IPSL-CM5-LR, IPSL-CM5-MR, MPI-LR, MPI-MR and NCAR-CESM1 models.

Wang et al., 2016b). This halt in the increase in the uptake rate of CO₂ is linked to the combined feedbacks from well-understood reductions in buffering capacity and warming, as well as the increased upwelling rate of carbon-rich Circumpolar Deep Water (Hauck and Volker, 2015) (Cross-Chapter Box 7 in Chapter 3). Although there is *high agreement* amongst models, contemporary biases in the fluxes of CO₂ in CMIP5 models in the Southern Ocean (Mongwe et al., 2018) suggest *medium confidence* levels for these projections.

Alongside the mean state changes, Southern Ocean aragonite saturation is also affected by the seasonal cycle of carbonate as well as by the impact of reduced buffering capacity (SM3.2.4) on the seasonal cycle of CO₂ (Sasse et al., 2015; McNeil and Sasse, 2016). This leads to an amplification of the seasonal variability of pCO₂ (Hauck and Volker, 2015; McNeil and Sasse, 2016; Landschützer et al., 2018) and the hydrogen ion concentration that accelerates the onset of hypercapnia (i.e., high pCO₂ levels; pCO₂ > 1000 µatm) to nearly 2 decades (~2085) ahead of anthropogenic CO₂ forcing (McNeil and Sasse, 2016). The seasonal cycles of pH and aragonite saturation will be attenuated (Kwiatkowski and Orr, 2018) (Section 5.2.2.3), however when the mean state changes are combined with the changes in seasonality, the onset of undersaturation is brought forward by 10–20 years (Table SM3.5). Model projections remain uncertain and affected by the resolution of local ocean physics, which leads to overall *medium confidence* in the timing of undersaturation and hypercapnia.

3.2.3 Impacts on Marine Ecosystems

3.2.3.1 Arctic

Climate change has, and is projected to continue to have, significant implications for Arctic marine ecosystems, with consequences at different trophic levels both in the pelagic, benthic, and sympagic (sea ice related) realms (Figure 3.5). Specifically, climate change is projected to alter the distribution and properties of Arctic marine habitats with associated implications for species composition, production and ecosystem structure and function (Frainer et al., 2017; Kaartvedt and Titelman, 2018; Moore et al., 2018). The rate and severity of ecosystem impacts will be spatially heterogeneous and dependent on future emission scenarios.

In the few Arctic regions where data is sufficient to assess trends in biodiversity, the ecosystem level responses appear to be products of multiple interacting physical, chemical and biological processes (Frederiksen, 2017) (*medium confidence*). Climate change impacts on vertical fluxes and stratification (Sections 3.2.1.2.3, 3.2.2.2) will contribute to changes in benthic-pelagic-sympagic coupling. For instance, projected climate driven changes in ocean properties and hydrography (Section 3.2.2.2) and the abundance of pelagic grazers (Box 3.4) could alter the export of organic matter to the sea floor with associated impacts on the benthos in some Arctic shelf ecosystems (Moore and Stabeno, 2015; Stasko et al., 2018) (*low confidence*). Projected future reductions in summer sea ice (Section 3.2.1.1), increased stratification in summer, shifting currents and fronts and increased ocean temperatures (Section 3.2.2.2) and ocean

acidification (Section 3.2.2.3) are all expected to impact the future production and distribution of several marine fish and invertebrates (*high confidence*).

Ocean acidification (Section 3.2.2.3) will affect several key Arctic species (*medium confidence*). The effects of current and projected levels of acidification have been examined for a broad suite of species groups (bivalves, cephalopods, echinoderms, crustaceans, corals and fishes) and these studies reveal species-specific differences in sensitivity, as well as differences in the scope for, and energetic cost of, adaptation (Luckman et al., 2014; Howes et al., 2015; Falkenberg et al., 2018).

3.2.3.1.1 Plankton and primary production

There is evidence that the combination of loss of sea ice, freshening, and regional stratification (Sections 3.2.1.1 and 3.2.1.2) has affected the timing, distribution and production of primary producers (Moore et al., 2018) (*high confidence*). Satellite data show that the decline in ice cover has resulted in a >30% increase in annual net primary production (NPP) in ice-free Arctic waters since 1998 (Arrigo and van Dijken, 2011; Bélanger et al., 2013; Arrigo and van Dijken, 2015; Kahru et al., 2016), a phenomenon corroborated by both *in situ* data (Stanley et al., 2015) and modelling studies (Vancoppenolle et al., 2013; Jin et al., 2016). Ice loss has also resulted in earlier phytoplankton blooms (Kahru et al., 2011) with blooms being dominated by larger-celled phytoplankton (Fujiwara et al., 2016). The longer open water season in the Arctic has also increased the incidence of autumn blooms, a phenomenon previously rarely observed in Arctic waters (Ardyna et al., 2017).

Thinner Arctic sea ice cover has led to the appearance of intense phytoplankton blooms that develop beneath first-year sea ice (*medium confidence*). Blooms of this size (1000s of km²) and intensity (peaks of approximately 30 mg Chl-a-m⁻³) were previously thought to be restricted to the marginal ice zone and the open ocean where ample light reaches the surface ocean for rapid phytoplankton growth (Arrigo et al., 2012). Evidence shows that these blooms can thrive beneath sea ice in areas of reduced thickness, increased coverage of melt ponds (Arrigo et al., 2014; Zhang et al., 2015; Jin et al., 2016; Horvat et al., 2017), first-year ridges at the snow-ice interface (Fernández-Méndez et al., 2018), and a large number of cracks (high lead fractions) in the ice (Assmy et al., 2017), although the latter has not changed significantly in the last three decades (Wang et al., 2016a). Local features including snow-free or thin snow, hummocks and ridges commonly found on multi-year ice also provide habitat for ice algae (Lange et al., 2017).

The reduction in sea ice area and thickness in the Arctic Ocean appears to be indirectly impacting rates of NPP through increased exposure of the surface ocean to atmospheric forcing (*medium confidence*) and these indirect impacts will possibly increase in the future (*low confidence*). Greater wind stress has been shown to increase upwelling of nutrients at the shelf break both over ice-free waters (Williams and Carmack, 2015) and a partial ice cover (Schulze and Pickart, 2012), leading to more new production (Williams and Carmack, 2015). At the same time, enhanced vertical stratification

(Section 3.2.1.2.2, SM3.2.2) and decreased upwelling of nutrients into surface waters (Capotondi et al., 2012; Nummelin et al., 2016) may reduce Arctic NPP in the future, especially in the central basin (Ardyna et al., 2017). It could also impact phytoplankton community composition and size structure, with small-celled phytoplankton, which require less nutrients, becoming more dominant as nutrient concentrations in surface waters decline (Yun et al., 2015).

In addition to its impact on phytoplankton bloom dynamics, the decline in the proportion of multi-year sea ice and proliferation of a thinner first year sea ice cover may favour growth of microalgae within the ice due to increased light availability (*medium confidence*). Recent studies suggest that the contribution of sea ice algae to total Arctic NPP is higher now than values measured previously (Song et al., 2016), accounting for nearly 10% of total NPP (ice plus water) and as much as 60% in places like the central Arctic (Fernández-Méndez et al., 2015).

Ongoing changes in NPP will impact the biogeochemistry and ecology of large parts of the Arctic Ocean (*high confidence*). In areas of enhanced nutrient availability and greater NPP, dominance by larger-celled microalgae increases vertical export efficiency from the surface downwards in both ice covered (Boetius et al., 2013; Lalande et al., 2014; Mäkelä et al., 2017) and open ocean (Le Moigne et al., 2015) areas. However, because exported biomass production may be increasing in some areas but declining in others, the net impact may be small (Randelhoff and Guthrie, 2016) (Sections 3.2.3.1.2, 5.3.6, SM3.2.6). Phytoplankton may have the capacity to compensate for ocean acidification under a range of temperatures and pH values (Hoppe et al., 2018).

Increased water temperatures (Section 3.2.1) and shifts in the spatial pattern and timing of the ice algal and phytoplankton blooms, have impacted the phenology, magnitude and duration of zooplankton production with associated changes in the zooplankton community composition (*medium confidence*). Negative effects of reductions in ice algae on zooplankton may be partially offset by predicted increases in water column phytoplankton production in the Bering Sea (Wang et al., 2015). Changes in sea ice coverage and thickness may alter the phenology, abundance and distribution of zooplankton in the future. Projected changes will initially have the most pronounced impact on sympagic amphipods, but will subsequently affect food web functioning and carbon dynamics of the pelagic system (Kohlbach et al., 2016).

At the more southern boundaries of the Arctic such as the southeastern Bering Sea, warm conditions have led to reduced production of large copepods and euphausiids (*medium confidence*) (Sigler et al., 2017; Kimmel et al., 2018). On more northern shelves, the increased open water period has led to increases in large copepods over a 60 year period within the Chukchi Sea (Ershova et al., 2015) and in recent years also the Beaufort Sea (Smoot and Hopcroft, 2017), while in the Central Basins zooplankton biomass in general has increased (Hunt et al., 2014; Rutzen and Hopcroft, 2018) (*medium confidence*).

There are inconsistent findings concerning the future development of copepods in the Arctic. Coupled biophysical model results suggest

that sea ice loss will increase primary production and that will primarily be consumed pelagically by zooplankton grazers such as *Calanus hyperboreus*; increasing their abundances in the central Arctic (Kvile et al., 2018). Feng et al. (2018) concluded that *C. glacialis* should continue to benefit from a warmer Arctic Ocean. On the other hand, in the transition zone between Arctic and Atlantic water masses, *C. glacialis* may face increasing competition from the more boreal *C. finmarchicus* (Dalpadado et al., 2016). Renaud et al. (2018) found the lipid content of *Calanus* spp. was related to size and not species. This suggests that climate driven shifts in dominant *Calanus* species may, because of overlap in size spectrum and contrary to earlier assumptions, not negatively impact their consumers in the Barents Sea.

The effects of ocean acidification on Arctic zooplankton and pteropods (small pelagic molluscs) have been examined for only a few species and these studies reveal that the severity of effects is dependent on emission scenarios and the species sensitivity and adaptive capacity. The copepod *C. glacialis* exhibits stage-specific sensitivities to ocean acidification with some stages being relatively insensitive to decreases in pH and other stages exhibiting substantial reductions in scope for growth (Bailey et al., 2017; Thor et al., 2018). Although there is strong evidence that pteropods are sensitive to the effects of ocean acidification (Manno et al., 2017) recent studies indicate they may exhibit some ability to adapt (Peck et al., 2016; Peck et al., 2018). However, the metabolic costs of adaptation may be constraining, especially during periods of low food availability (Lischka and Riebesell, 2016).

3.2.3.1.2 Benthic communities

There is evidence that earlier spring sea ice retreat and later autumn sea ice formation (Section 3.2.1.1) are changing the phenology of primary production with cascading effects on Arctic benthic community biodiversity and production (Link et al., 2013) (*medium confidence*). In the Barents Sea, evidence suggests that factors directly related to climate change (sea ice dynamics, ocean mixing, bottom-water temperature change, ocean acidification, river/glacier freshwater discharge; Sections 3.2.1.1, 3.2.1.2) are impacting the benthic species composition (Birchenough et al., 2015). Other human influenced activities, such as commercial bottom trawling and the introduction of non-native species are also regarded as major drivers of observed and expected changes in benthic community structure (Johannesen et al., 2017), and may interact with climate impacts.

Rapid and extensive structural changes in the rocky-bottom communities of two Arctic fjords in the Svalbard Archipelago during 1980–2010 have been documented and linked to gradually increasing seawater temperature and decreasing sea ice cover (Kortsch et al., 2012; Kortsch et al., 2015). Also, there are indications of declining benthic biomass in the northern Bering Sea (Grebmeier and Cooper, 2016) and southern Chukchi Sea (Grebmeier et al., 2015). It is unclear whether these rapid ecosystem changes will be tipping points for local ecosystems (Chapter 6, Table 6.1; Wassmann and Lenton, 2012). However, biomass of kelps have increased considerably in the intertidal to shallow subtidal in Arctic regions over the last two decades, connected to reduced physical impact by ice scouring

and increased light availability as a consequence of warming and concomitant fast-ice retreat (Kortsch et al., 2012; Paar et al., 2016) (*medium confidence*) (see Section 5.3.3 and SM3.2.6 for further information on kelp).

The growth, early survival and production of commercially important crab stocks in the Bering Sea are influenced by time-varying exposure to multiple interacting drivers including bottom temperature, larval advection, predation, competition and fishing (Burgos et al., 2013; Long et al., 2015; Ryer et al., 2016). In Newfoundland and Labrador waters and on the western Scotian Shelf, snow crab (*Chionoecetes opilio*) productivity has declined (Mullowney et al., 2014; Zisseron and Cook, 2017). Contrary to this, snow crabs have expanded their distribution in the Barents Sea and commercial harvesting increased (Hansen, 2016; Lorentzen et al., 2018) (*high confidence*).

Bering sea crabs exhibit species-specific sensitivities to reduced pH (Long et al., 2017; Swiney et al., 2017; Long et al., 2019). However, current pH levels do not appear to have negatively impacted crab production in the Bering or Barents Seas (Mathis et al., 2015; Punt et al., 2016).

3.2.3.1.3 Fish

Since AR5, additional evidence shows climate-induced physical and biogeochemical changes are impacting, and will continue to impact, the distribution and production of marine fish (*medium confidence*). Changes in the spatial distribution and production of Arctic fish are best documented for ecologically and commercially important stocks in the Bering and Barents Seas (Box 3.4; Figure 3.5), while data is severely limited in other Arctic shelf regions and the Central Arctic Ocean (CAO).

Higher temperature and changes in the quality and distribution of prey is already affecting marine fish (Wassmann et al., 2015; Dalpadado et al., 2016; Hunt et al., 2016; Section 3.2.3.1) (*high confidence* for detection, *medium confidence* for attribution). In the northern Barents Sea, Atlantic Sector, higher temperatures (Section 3.2.1.2) have expanded suitable feeding areas for boreal/subarctic species (Box 3.4) and has contributed to increased Atlantic cod (*Gadus morhua*) production (Kjesbu et al., 2014). In contrast, Arctic species like polar cod (*Boreogadus saida*) are expected to be affected negatively by a shortened ice covered season and reduced sea ice extent through loss of spawning habitat and shelter, increased predatory pressure, reduced prey availability (Christiansen, 2017),

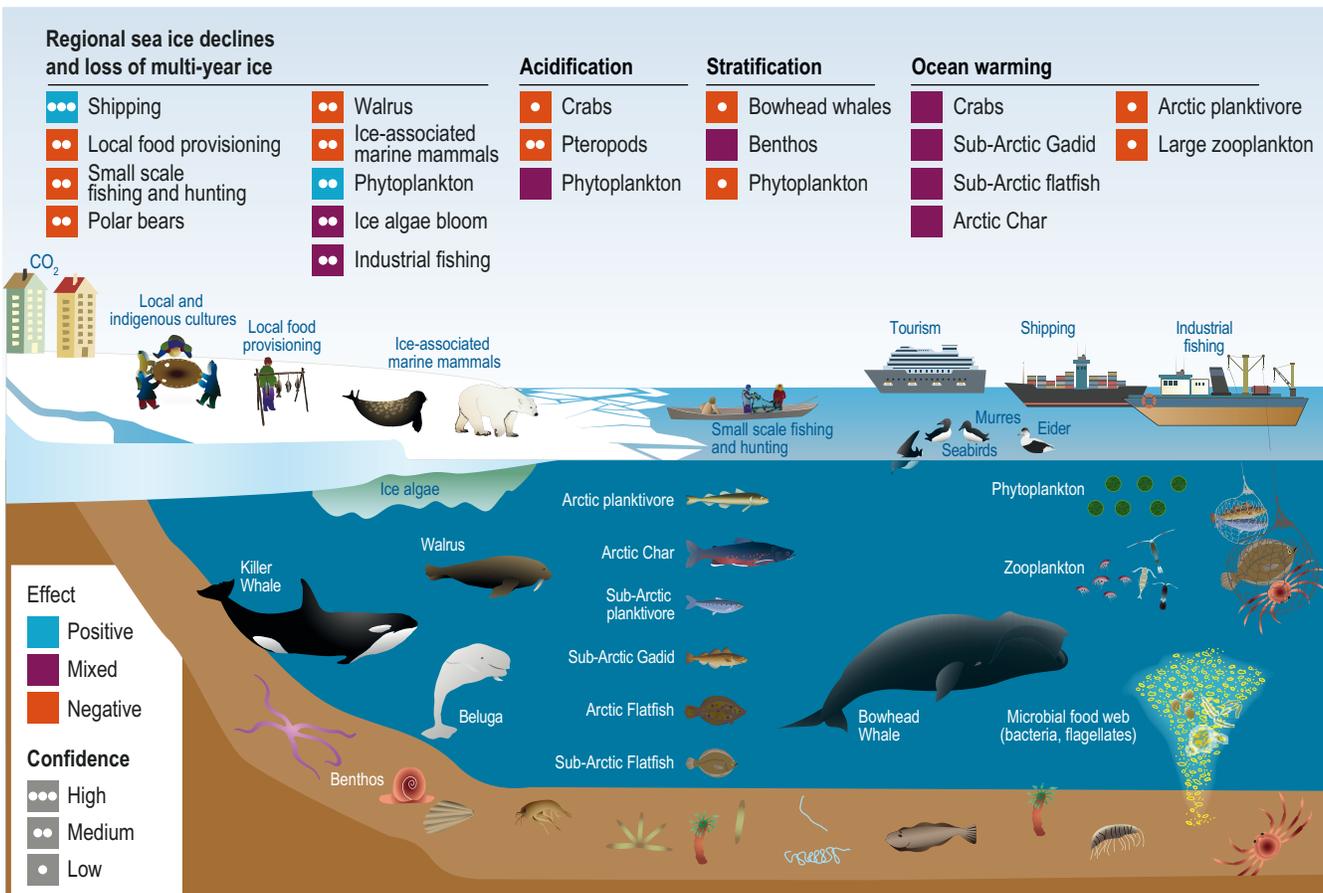


Figure 3.5 | Schematic summary of key drivers that are causing, or are projected to cause, direct effects on Arctic marine ecosystems (Section 3.2.1.2). Effects presented here are described in the main text (Sections 3.2.3.1; 3.2.4.1.1; 3.2.4.2; 3.2.4.3) with associated confidence levels and citations. For mixed effects, no confidence level is given (see main text for details on how multiple drivers cause interacting positive and negative effects). Projected effects are conceptual representations based on high emission scenarios (Section 3.2.1.2). The cross-sectional view of the Arctic ecosystem shows the association of key functional groups (marine mammals, birds, fish, zooplankton, phytoplankton and benthic assemblages) with Arctic marine habitats. Species depicted in the fishing net are not a comprehensive depiction of all target species.

and impaired growth and reproductive success (Nahrgang et al., 2014). These changes may cause structural changes in food webs, with large piscivorous and semipelagic boreal fish species replacing small bodied Arctic benthivores (Box 3.4; Fossheim et al., 2015; Frainer et al., 2017).

Time series on responses of anadromous fish (including salmon) in the high Arctic are limited, although these stocks will also be exposed to a wide range of future stressors (Reist et al., 2016). There is some evidence that environmental variability influences the production of anadromous species such as Arctic char (*Salvelinus alpinus*), brown trout (*Salmo trutta*), and Atlantic salmon (*Salmo salar*) through its influence on growth and winter survival (Jensen et al., 2018).

The scope for adaptation of marine fish to a changing ocean conditions is uncertain, but knowledge is informed by previous biogeographic studies (Chernova, 2011; Lynghammar et al., 2013). The present niche partitioning between subarctic and Arctic pelagic fish species is expected to become more diffuse with potential negative impacts on cold adapted species such as polar cod (Laurel et al., 2017; Alabia et al., 2018; Logerwell et al., 2018) (*low confidence*). Winter ocean conditions in the high Arctic are projected to remain cold in most regions (Section 3.2.3.1), limiting the immigration of subarctic species that spawn in positive temperatures onto the high Arctic shelves (Landa et al., 2014). Projected increases in summer temperature may open gateways to subarctic pelagic foragers in summer, particularly in the inflow regions of the Kara and Chukchi Seas, and the shelf regions of east and west Greenland (Mueter et al., 2017; Joli et al., 2018). For example, the pelagic capelin (*Mallotus villosus*) are capable of entering the CAO, but may be restricted in winter by availability of suitable spawning areas and lack of antifreeze proteins (Hop and Gjørseter, 2013; Christiansen, 2017).

Regional climate scenarios, derived from down-scaled global climate scenarios, have been used to drive environmentally linked fish population models (Hermann et al., 2016; Holsman et al., 2016; Ianelli et al., 2016; Hermann et al., 2019). Hermann et al. (2019) contrasted future production of copepods and euphausiids in the eastern Bering Sea under scenarios derived from projected downscaled high spatial and temporal resolution ocean habitats under RCP4.5 and RCP8.5. Consistent with AR5, these updated scenarios project future declines in the abundance of large copepods under RCP8.5, a result that has been shown to negatively impact production of walleye pollock, Pacific cod (*Gadus microcephalus*) and arrowtooth flounder (*Atheresthes stomias*) (Sigler et al., 2017; Kimmel et al., 2018) (*medium confidence*). Hedger et al. (2013) predicts increases in Atlantic salmon abundance in northern Norway (river Alta around 70°N) with future warming (*low confidence*). Under end of century RCP8.5 projections, ocean acidification and higher ocean temperatures are expected to reduce production of Barents Sea cod (Stiasny et al., 2016; Koenigstein et al., 2018) (*low confidence*).

3.2.3.1.4 Seabirds and marine mammals

Environmental alterations caused by global warming are resulting in phenological, behavioural, physiological, and distributional changes in Arctic marine mammal and seabird populations (Gilg et al., 2012; Laidre et al., 2015; Gall et al., 2017) (*high confidence*). These changes include altered ecological interactions as well as direct responses to habitat degradation induced especially via loss of sea ice. Population responses to warming have not all been linear, some have been particularly strong and abrupt due to environmental regime shifts, as seen in black-legged kittiwakes (*Rissa tridactyla*). A steep population decline in kittiwake colonies distributed throughout their breeding range coincided with an abrupt warming of sea-surface temperature in the 1990s, while their population dynamics did not seem to be affected during periods of more gradual warming (Descamps et al., 2017).

Seabirds and marine mammals are mobile animals that respond to changes in the distribution of their preferred habitats and prey, by shifting their range, altering the timing or pathways for migration or prey shifting when this is feasible (Post et al., 2013; Hamilton et al., 2019) (*very high confidence*). However, some species display strong site fidelity that can be maladaptive in a changing climate and Arctic endemic marine mammals (all of which are ice-affiliated for breeding) in general have little scope to move northward in response to warming (Kovacs et al., 2012; Hamilton et al., 2015). Changes in the location or availability of polar fronts, polynyas, tidal glacier fronts or ice edges have impacted where Arctic sea birds and marine mammals concentrate because of the influence these physical features have on productivity; traditionally these areas have been key foraging sites for top predators in the Arctic (deHart and Picco, 2015; Hamilton et al., 2017; Hunt et al., 2018).

In some species, shifts in distribution in response to changes in suitable habitat have been associated with increased mortality. Increased mortality rates of walrus (*Odobenus rosmarus*) calves have been observed during on-shore stampedes of unusually large herds, because Pacific walrus females are no longer able to haul out on ice over the shelf in summer due to the retraction of the southern ice edge into the deep Arctic Ocean (Kovacs et al., 2016). Shifts in the temporal and spatial distribution and availability of suitable areas of sea ice for ice-breeding seals have occurred (Bajzak et al., 2011; Øigård et al., 2013) with increases in strandings and pup mortality in years with little ice (Johnston et al., 2012c; Soulen et al., 2013; Stenson and Hammill, 2014).

Climate impacts that reduce the availability of prey resources can negatively impact marine mammals (Asselin et al., 2011; Øigård et al., 2014; Choy et al., 2017) (*very high confidence*). Sea ice changes have increased the foraging effort of ringed seals (*Pusa hispida*) in the marginal ice zone north of Svalbard (Hamilton et al., 2015), also causing diet shifts (Lowther et al., 2017). Ringed seals in Svalbard are using terrestrial haul out sites during summer for the first time in observed history, following major declines in sea ice (Lydersen et al., 2017), an example of an adaptive behavioural response to extreme habitat changes. Sea ice related changes in the export of production to the benthos (Section 3.3.3.1) and associated changes in the benthic community (Section 3.4.1.1.2) may impact marine

mammals dependent on benthic prey (e.g., walruses and gray whales, *Eschrichtius robustus*) (Brower et al., 2017; Udevitz et al., 2017; Szpak et al., 2018).

Changes in the timing, distribution and thickness of sea ice and snow (Sections 3.2.1.1, 3.4.1.1) have been linked to phenological shifts, and changes in distribution, denning, foraging behaviour and survival rates of polar bears (*Ursus maritimus*) (Andersen et al., 2012; Hamilton et al., 2017; Escajeda et al., 2018) (*high confidence*). Less ice is also driving polar bears to travel over greater distances and swim more than previously both in offshore and in coastal areas, which can be particularly dangerous for young cubs (Durner et al., 2017; Pilfold et al., 2017; Lone et al., 2018). Cumulatively, changes in sea ice patterns are driving demographic changes in polar bears, including declines in some populations (Lunn et al., 2016; McCall et al., 2016), while others are stable or increasing (Voorhees et al., 2014; Aars et al., 2017). This is because protective management measures have been successful in allowing severely depleted populations to recover or because new food sources, such as carrion, are becoming available to polar bears in some regions (Galicia et al., 2016; Stapleton et al., 2016). Changes in the spatial distribution of polar bears and killer whales can have top-down effects on other marine mammal prey populations (Øigård et al., 2014; Breed et al., 2017; Smith et al., 2017a).

Several studies from different parts of the Arctic show evidence that changing temperatures impact seabird diets (Dorresteijn et al., 2012; Divoky et al., 2015; Vihtakari et al., 2018), reproductive success and body condition (Gaston et al., 2012; Provencher et al., 2012; Gaston and Elliott, 2014) (*high confidence*). Recent studies also show that changes in sea surface temperature and sea ice dynamics have impacts on the distribution and abundance of seabird prey with cascading impacts on seabird community composition (Gall et al., 2017), nutritional stress and decreased reproductive output (Dorresteijn et al., 2012; Divoky et al.; Kokubun et al., 2018) and survival (Renner et al., 2016; Hunt et al., 2018).

3.2.3.2 Southern Ocean

Marine ecosystem dynamics in the Antarctic region are dominated by the ACC and its frontal systems (Cross-Chapter Box 7 in Chapter 3), subpolar gyres, polar seasonality, the annual advance and retreat of sea ice (Section 3.2.1.1) and the supply of limiting micronutrients for productivity (most commonly iron) (Section 5.2.2.5). Antarctic krill (*Euphausia superba*) play a central role in Southern Ocean foodwebs as grazers and as prey items for fish, squid, marine mammals and seabirds (Schmidt and Atkinson, 2016; Trathan and Hill, 2016) (SM3.2.6). This is due in part to the high abundance and circumpolar distribution of Antarctic krill, although the abundance and importance of this species varies between different regions of the Southern Ocean (Larsen et al., 2014; Siegel, 2016; McCormack et al., 2017). Recent work has characterised the nature of habitat change for Southern Ocean biota at regional and circumpolar scales (Constable et al., 2014; Gutt et al., 2015; Constable et al., 2016; Hunt et al., 2016; Gutt et al., 2018), and the direct responses of biota to these changes (Constable et al., 2014) (summarised in Figure 3.6). These findings indicate that overlapping changes in

key ocean and sea ice habitat characteristics (temperature, sea ice cover, iceberg scour, mixed layer depth, aragonite undersaturation; Sections 3.2.1, 3.2.2) will be important in determining future states of Southern Ocean ecosystems (Constable et al., 2014; Gutt et al., 2015) (*medium confidence*). However, there is a need to better characterise the nature and importance of indirect responses to physical change using models and observations. Important advances have also been made since AR5 in (i) identifying key variables to detect and attribute change in Southern Ocean ecosystems, as part of long-term circumpolar modelling designs (Constable et al., 2016), and (ii) refining methods for using sea ice projections from global climate models in ecological studies and ecosystem models for the Southern Ocean (Cavanagh et al., 2017).

3.2.3.2.1 Plankton and pelagic primary production

Changes in column-integrated phytoplankton biomass for the Southern Ocean are coupled with changes in the spatial extent of ice-free waters, suggesting little overall change in biomass per area at the circumpolar scale (Behrenfeld et al., 2016). Arrigo et al. (2008) also report no overall trend in remotely-sensed column-integrated primary production south of 50°S from 1998 to 2006. At a regional scale, local-scale forcings (e.g., retreating glaciers, topographically steered circulation and sea ice duration) and associated changes in stratification are key determinants of phytoplankton bloom dynamics at coastal stations on the West Antarctic Peninsula (Venables et al., 2013; Schofield et al., 2017; Kim et al., 2018; Schofield et al., 2018) (*medium confidence*). For example, a shallowing trend in mixed layer depth in the southern part of the Peninsula (as opposed to no trend in the north) associated with changes in sea ice duration over a 24-year period (from 1993 to 2017) has been linked to enhanced phytoplankton productivity (Schofield et al., 2018). The phenology of Southern Ocean phytoplankton blooms in this region may also be shifting to earlier in the growth season (Arrigo et al., 2017a). However, the effect of climate change on Southern Ocean pelagic primary production is difficult to determine given that the length of time series data is insufficient (less than 30 years) to enable the climate change signature to be detected and attributed; and that, even when records are of sufficient length, data trends are often reported as being driven by climate change when they are due to a combination of climate change and variability.

Recent studies on the ecological effects of acidification in coastal waters near the Antarctic continent indicate a detrimental effect of acidification on primary production and changes to the structure and function of microbial communities (Hancock et al., 2017; Deppeler et al., 2018; Westwood et al., 2018) (*medium confidence*). Trimborn et al. (2017) report that Southern Ocean diatoms are more sensitive to ocean acidification and changes in irradiance than the prymnesiophyte *Phaeocystis antarctica*, which may have implications for biogeochemical cycling because diatoms and prymnesiophytes are generally considered key drivers of these cycles. Both laboratory manipulations and *in situ* experiments indicate that sea ice algae are tolerant to acidification (McMinn, 2017) (*medium confidence*). Model projections of trends in primary production in the Southern Ocean due to climate change from Leung et al. (2015) are summarised in Table 3.2.

Table 3.2 | Model projections of trends due to climate change driven alteration of phytoplankton properties under RCP8.5 from 2006 to 2100 across three zones of the Southern Ocean, from Leung et al. (2015). There is *low confidence* in predicted zonal changes in phytoplankton biomass due to *low confidence* regarding future changes in iron supply in the Southern Ocean (Hutchins and Boyd, 2016). Acidification was not reported as an important driver in this modelling experiment.

Zonal Band	Predicted change in phytoplankton biomass	Drivers	Mechanisms
40°S–50°S	↑	Higher mean underwater irradiance More iron supply	Shallowing of the summertime mixed layer depth Change in iron supply mechanism
50°S–65°S	↓	Lower mean underwater irradiance	Deeper summertime mixed layer depth Decreased summertime incident radiation (increased cloud fraction)
South of 65°S	↑	More iron supply Higher mean underwater irradiance Temperature	Melting of sea ice Warming ocean

Previously reported declines in Antarctic krill abundance in the South Atlantic Sector (Atkinson et al., 2004) cited in WGII AR5 (Larsen et al., 2014) may not represent a long-term, climate driven, regional-scale decline (Fielding et al., 2014; Kinzey et al., 2015; Steinberg et al., 2015; Cox et al., 2018) (*medium confidence*) but could reflect a sudden, discontinuous change following an episodic period of anomalous peak abundance for this species (Loeb and Santora, 2015) (*low confidence*). Recent analyses have not detected trends in long-term krill abundance in the South Atlantic Sector in acoustic surveys (Fielding et al., 2014; Kinzey et al., 2015), net-based surveys (Steinberg et al., 2015) or reanalysis of historical data (Cox et al., 2018). Nevertheless, the spatial distribution and size composition of Antarctic krill may already have changed in association with change in the sea ice environment (Atkinson et al., 2019) (*medium confidence*) and may result in different regional trends in numerical krill abundance (Cox et al., 2018; Atkinson et al., 2019) (*medium confidence*).

The distribution of Antarctic krill is expected to change under future climate change because of changes in the location of the optimum conditions for growth and recruitment (Melbourne-Thomas et al., 2016; Piñones and Fedorov, 2016; Meyer et al., 2017; Murphy et al., 2017; Klein et al., 2018). The optimum conditions for krill are predicted to move southwards, with the decreases most apparent in the areas with the most rapid warming (Hill et al., 2013; Piñones and Fedorov, 2016) (Section 3.2.1.2.1) (*medium confidence*). The greatest projected reductions in krill due to the effects of warming and ocean acidification are predicted for the southwest Atlantic/Weddell Sea region (Kawaguchi et al., 2013; Piñones and Fedorov, 2016) (*low confidence*), which is the area of highest current krill concentrations, contains important foraging grounds for krill predators, and is also the main area of operation of the krill fishery. Modelled effects of warming on krill growth in the Scotia Sea and northern Antarctic Peninsula (AP) region resulted in reductions in total krill biomass under both RCP2.6 and RCP8.5 (Klein et al., 2018). Projections from a food web model for the West Antarctic Peninsula under simple scenarios for change in open water and sea ice-associated primary production from 2010 to 2050 (6, 15, and 41% increases in phytoplankton production with equivalent percentage decreases in ice algal production) indicate a decline in krill biomass with contemporaneous increases in the biomass of gelatinous salps (Suprenand and Ainsworth, 2017).

Current understanding of climate change effects on Southern Ocean zooplankton is largely based on observations and predictions from

the South Atlantic and the West Antarctic Peninsula. Comparison of the mesozooplankton community in the southwestern Atlantic Sector between 1926–1938 and 1996–2013 showed no evidence of change despite surface ocean warming (Tarling et al., 2018). These results suggest that predictions of distributional shifts based on temperature niches may not reflect the actual levels of thermal resilience of key taxa. Sub-decadal cycles of macrozooplankton community composition adjacent to the West Antarctic Peninsula are strongly linked to climate indices, with evidence of increasing abundance for some species over the period from 1993 to 2013 (Steinberg et al., 2015). Pteropods are vulnerable to the effects of acidification, and new evidence indicates that eggs released at high CO₂ concentrations lack resilience to ocean acidification in the Scotia Sea region (Manno et al., 2016) (*medium confidence*).

3.2.3.2.2 Benthic communities

Carbon uptake and storage by Antarctic benthic communities is predicted to increase with sea ice losses, because across-shelf growth gains from longer algal blooms outweigh ice scour mortality in the shallows (Barnes, 2017). Benthic-pelagic coupling and vertical energy flux will also influence Southern Ocean ecosystem responses to climate change (Jansen et al., 2017). Benthic communities in shallow water habitats mostly consist of dark-adapted invertebrates and rely on sea ice to create low-light marine environments. Increases in the amount of light reaching the shallow seabed under climate change may result in ecological regime shifts, in which invertebrate-dominated communities are replaced by macroalgal beds (Clark et al., 2015; Clark et al., 2017) (*low confidence*) (Table 6.1). Griffiths et al. (2017a) modelled distribution changes for 963 benthic invertebrate species in the Southern Ocean under RCP8.5 for 2099. Their results suggest that 79% of Antarctica's endemic species will face a reduction in suitable temperature habitat (an average 12% reduction) over the current century. Predicted reductions in the number of species are most pronounced for the West Antarctic Peninsula and the Scotia Sea region (Griffiths et al., 2017a).

3.2.3.2.3 Fish

Many Antarctic fish have a narrow thermal tolerance as a result of physiological adaptations to cold water (Pörtner et al., 2014; Mintenbeck, 2017), which makes them vulnerable to the effects of increasing temperatures (Mueller et al., 2012; Beers and Jayasundara, 2015). Increasing water temperatures may displace

icefish (family *Channichthyidae*) in marginal habitats (e.g., shallow regions around subantarctic islands) as they lack haemoglobin and are unable to adjust blood parameters to an increasing oxygen demand (Mintenbeck et al., 2012) (*low confidence*). Future warming may also reduce the planktonic duration and increase egg and larval mortality for fish species, which is predicted to affect dispersal patterns, with implications for population connectivity and the ability of fish species to adapt to ongoing environmental change (Young et al., 2018). The Antarctic silverfish (*Pleuragramma antarctica*) is an important prey species in some regions of the Southern Ocean, and has an ice-dependent life cycle (Mintenbeck et al., 2012; Vacchi et al., 2012). Documented declines in the abundance of this species in some parts of the West Antarctic Peninsula may have consequences for associated food webs (Parker et al., 2015; Mintenbeck and Torres, 2017) (*low confidence*).

Myctophids and toothfish are important fish groups from both a food web (myctophids) and fishery (toothfish) perspective. Species distribution models for *Electrona antarctica*, a dominant myctophid species in the Southern Ocean, project habitat loss for this species under RCP4.5 ($6.2 \pm 6.0\%$ loss) and RCP8.5 ($13.1 \pm 10.2\%$ loss) by 2090, associated with increased sea surface temperature (Freer et al., 2018). There have been no observed effects of climate change on the two species of toothfish that are found in the Southern Ocean: Patagonian and Antarctic toothfish (*Dissostichus eleginoides* and *D. mawsoni*), but recruitment is inversely correlated with sea surface temperature for Patagonian toothfish at South Georgia (Belchier and Collins, 2008). Given differences in temperature tolerances for Patagonian toothfish (with a wide temperature tolerance) and Antarctic toothfish (limited by a low tolerance for water temperatures above 2°C), the latter may be faced with reduced habitat and potential competition with southward-moving Patagonian toothfish under climate change (Mintenbeck, 2017) (*very low confidence*).

3.2.3.2.4 Seabirds and marine mammals

Since AR5, there has been an increasing body of evidence of climate-induced changes in populations of some Antarctic higher predators such as seabirds and marine mammals. These changes vary between different regions of the Southern Ocean and reflect differences in key drivers (Bost et al., 2009; Gutt et al., 2015; Constable et al., 2016; Hunt et al., 2016; Gutt et al., 2018), particularly sea ice extent and food availability (*high confidence*) across regions (Sections 3.2.1.1.1, 5.2.3.1, 5.2.3.2, 5.2.4). The predictability of foraging grounds and ice cover are associated with variations in climate (Dugger et al., 2014; Youngflesh et al., 2017; Abrahms et al., 2018) (Section 3.2.1.1) and are the main drivers of observed population changes of Southern Ocean higher predators (*high confidence*) (Descamps et al., 2015; Jenouvrier et al., 2015; Sydeman et al., 2015; Abadi et al., 2017; Bjørndal et al., 2017; Fluhr et al., 2017; Hinke et al., 2017a; Hinke et al., 2017b; Pardo et al., 2017). The suitability of breeding habitats and the location of environmental features that facilitate the aggregation of prey are also influenced by climate change, and in turn influence the distribution in space and time of marine mammals and birds (Bost et al., 2015; Kavanaugh et al., 2015; Hindell et al., 2016; Santora et al., 2017) (*medium confidence*). Finally, biological parameters (reproductive

success, mortality, fecundity and body condition), life history traits, morphological, physiological and behavioural characteristics of top predators in the Southern Ocean, as well as their patterns of activity (migration, distribution, foraging and reproduction) are also changing as a result of climate change (Braithwaite et al., 2015a; Whitehead et al., 2015; Seyboth et al., 2016; Hinke et al., 2017b) (*high confidence*).

Trends of populations of Antarctic penguins affected by climate change include both increases for gentoo penguins, (*Pygoscelis papua*) (Lynch et al., 2013; Dunn et al., 2016; Hinke et al., 2017a), and decreases for Adélie (*P. adeliae*), chinstrap (*P. antarctica*), king (*Aptenodytes patagonicus*) and Emperor (*A. forsteri*) penguins (Trivelpiece et al., 2011; LaRue et al., 2013; Jenouvrier et al., 2014; Bost et al., 2015; Southwell et al., 2015; Younger et al., 2015; Cimino et al., 2016) (*high confidence*). Yet population shifts in Adélie penguins (Youngflesh et al., 2017) may have resulted from strong interannual environmental variability in good and bad years for prey and breeding habitat rather than climate change (*low confidence*). New evidence suggests that present Emperor penguin population estimates should be evaluated with caution based on the existence of breeding colonies yet to be discovered/confirmed (Ancel et al., 2017) as well as studies that draw conclusions based on trend estimates from single colonies (Kooyman and Ponganis, 2017).

Evidence for climate change impacts on Antarctic flying birds indicates that contraction of sea ice (seasonally and in specific regions), increases in sea surface temperatures, extreme events (snowstorms) and wind regime shifts can reduce breeding success and population growth rates in some species: southern fulmars (*Fulmarus glacialis*), Antarctic petrels (*Thalassoica antarctica*) and black-browed albatrosses (*Thalassarche melanophris*) (Descamps et al., 2015; Jenouvrier et al., 2015; Pardo et al., 2017) (*low confidence*). Poleward population shifts with increased intensity and frequency of westerly winds affect functional traits, demographic rates, foraging range, rates of travel and flight speeds of flying birds (Weimerskirch et al., 2012; Jenouvrier et al., 2018) but also increase overlap with fisheries activities thus increasing the risk of bycatch and the need for mitigation measures (Krüger et al., 2018) (*medium confidence*).

Changes in local- and regional-scale oceanographic features (Section 3.2.1.2) together with bathymetry control prey aggregation and distribution, and affect the ecological responses and biological traits of higher predators (particularly marine mammals) in the Southern Ocean (Lyver et al., 2014; Bost et al., 2015; Jenouvrier et al., 2015; Whitehead et al., 2015; Cimino et al., 2016; Hinke et al., 2017a; Pardo et al., 2017) (*medium confidence*) and *likely* explain most of the observed population shifts (Kavanaugh et al., 2015; Hindell et al., 2016; Gurarie et al., 2017; Santora et al., 2017). Decadal climate cycles affect access to mesopelagic prey by southern elephant seals (*Mirounga leonina*) in the Indian Sector of the Southern Ocean and breeding females are excluded from highly productive continental shelf waters in years of increased sea ice extent and duration (Hindell et al., 2016) (*medium confidence*). To date there is no unified global estimate of the abundance of Antarctic pack ice seal species (Ross seals (*Ommatophoca rossi*), crabeater seals (*Lobodon carcinophaga*),

leopard seals (*Hydrurga leptonyx*) and Weddell seals (*Leptonychotes weddellii*) as a reference point for understanding climate change impacts on these species (Southwell et al., 2012; Bester et al., 2017), although some regional population estimates for pack ice seals are available (Gurarie et al., 2017 and references therein). Analysis of long-term data suggests a genetic component to adaptation to climate change (*low confidence*) in Antarctic fur seals (*Arctocephalus gazella*, Forcada and Hoffman (2014)) and pigmy blue whales (*Balaenoptera musculus brevicauda*, Attard et al. (2015)).

Population trends of migratory baleen whales have been associated with krill abundance in the Atlantic and Pacific sectors of the Southern Ocean which is reflected in increased reproductive success, body condition and energy allocation (milk availability and transfer) to calves (Braithwaite et al., 2015a; Braithwaite et al., 2015b; Seyboth et al., 2016) (*high confidence*). There have been predictions of negative future impacts of climate change on krill and all whale species, although the magnitude of impacts differs among populations (Tulloch et al., 2019) as for other higher predators (Section 5.2.3). Pacific blue (Tulloch et al., 2019) (*Balaenoptera musculus*), fin (*B. physalus*) and southern right whales (*Eubalaena australis*) are the most at risk but humpback whales (*Megaptera novaeangliae*) are also at risk, as consequence of reduced prey and increasing interspecific competition. Importantly, climate-related risks for whale populations are a product of environmental conditions and connectivity between whale foraging grounds (Southern Ocean) and breeding grounds (lower latitudes) (Section 5.2.3.1).

3.2.3.2.5 Pelagic foodwebs and ecosystem structure

This section assesses the impacts of ocean and sea ice changes on pelagic foodwebs and ecosystem structure. The ecological impacts of loss of ice shelves and retreat of coastal glaciers around Antarctica are assessed in Section 3.3.3.4. Recent syntheses of Southern Ocean ecosystem structure and function recognise the importance of at least two dominant energy pathways in pelagic foodwebs – a short trophic pathway transferring primary production to top predators via krill, and at least one other pathway that moves energy from smaller phytoplankton to top predators via copepods and small mesopelagic fishes – and indicate that the relative importance of these pathways will change under climate change (Murphy et al., 2013; Constable et al., 2016; Constable et al., 2017; McCormack et al., 2017) (*medium confidence*). Using an ecosystem model, Klein et al. (2018) found that the effects of warming on krill growth off the AP and in the Scotia Sea translated to increased risks of declines in krill predator populations, particularly penguins, under both RCP2.6 and RCP8.5. The relative importance of different energy pathways in Southern Ocean foodwebs has important implications for resource management, in particular the management of krill and toothfish fisheries by the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) (Constable et al., 2016; Constable et al., 2017) (Sections 3.2.4.1.2, 3.5.3.2.2).

In summary, advances in knowledge regarding the impacts of climate change on Antarctic marine ecosystems since AR5 are consistent with the impacts described in Larsen et al. (2014) (also summarised in Figure 3.6). These advances include further descriptions of local-scale, climate-related influences (sea ice and stratification)

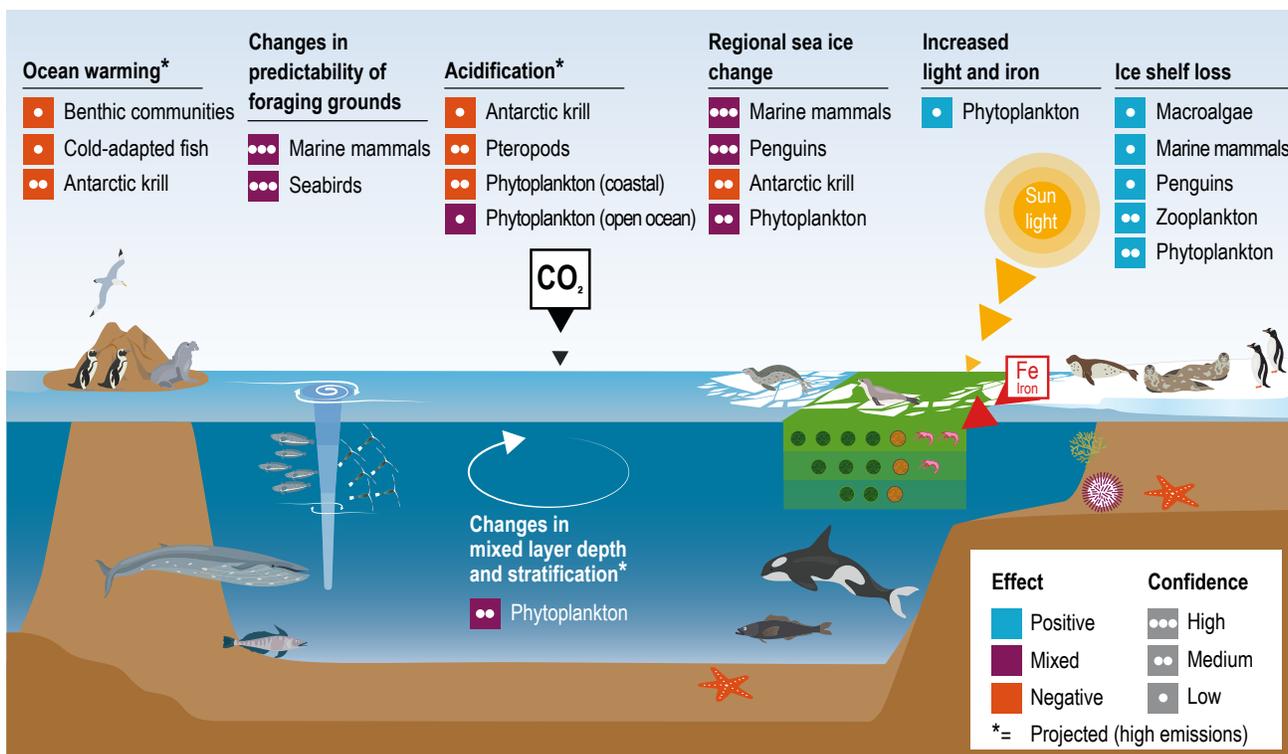


Figure 3.6 | Schematic summary of key drivers that are causing or are projected to cause direct effects on Southern Ocean marine ecosystems. Effects presented here are described in the main text (Sections 3.2.3.2, 3.3.3.4), with associated confidence levels and citations. Projected changes (indicated by an asterisk) are for high emissions scenarios. The cross-sectional view of the Southern Ocean ecosystem shows the association of key functional groups (marine mammals, birds, fish, zooplankton, phytoplankton and benthic assemblages) with Southern Ocean habitats. The configuration of the Southern Ocean foodweb is described in SM3.2.6.

on primary productivity, particularly in the West Antarctic Peninsula region (Section 3.2.3.2.1) (*medium confidence*). At the circumpolar scale, primary production is projected to increase in regions south of 65°S over the period from now to 2100 under RCP8.5 (Leung et al., 2015) (*low confidence*). However, ocean acidification may have a detrimental effect on coastal phytoplankton communities around the Antarctic continent (Section 3.2.3.2.1) (*medium confidence*). Increased information is also available regarding climate-driven changes in Antarctic krill populations in the south Atlantic, including the observed southward shift in the spatial distribution of krill in this region (Atkinson et al., 2019) (*medium confidence*) but evidence of a long-term trend in overall abundance in the region is equivocal (Section 3.2.3.2.1). Further habitat contraction for Antarctic krill is predicted in the future (*medium confidence*) (references detailed in Section 3.2.3.2.1). Under high emissions scenarios the majority of Antarctic seafloor species are projected to be negatively impacted by the end of the century (Griffiths et al., 2017a) (*low confidence*). Observed changes in the geography of ice-associated habitats (sea ice, ice shelves and polynyas) have both positive and negative effects on seabirds and marine mammals, and will interact with ice dependent changes in Antarctic krill populations to compound the impacts on krill dependent predators (Klein et al., 2018) (Sections 3.2.3.2.1, 3.2.3.2.4) (*medium confidence*).

3.2.4 Impacts on Social-Ecological Systems

3.2.4.1 Fisheries

3.2.4.1.1 Arctic

Arctic fisheries are important economically and societally. Large commercial fisheries exist off the coasts of Greenland and in the Barents and Bering Seas (Holsman et al., 2018; Peck and Pinnegar, 2018). First-wholesale value for commercial harvest of all species in 2017 in the Eastern Bering Sea was 2.68 billion USD, and for the Barents Sea around 1 billion USD to Norwegian fishers alone. The target species for these commercial fisheries include gadoids, flatfish, herring, red fish (*Sebastes* sp.), salmonids, and capelin. Fisheries in other Arctic regions are relatively small-scale, locally operated, and target a limited number of species (Reist, 2018). Still, these fisheries are of considerable cultural, economic and subsistence importance to local communities (Section 3.5.2.1).

Climate change will affect the spatial distribution and productivity of some commercially important marine fish and shellfish under most RCPs (Section 3.2.3.1) with associated impacts on the distribution and economic viability of commercial fisheries (*high confidence*). Past performance suggests that high latitude fisheries have been resilient to changing environmental and market drivers. For example, the Norwegian cod fishery has exported dried cod over an unbroken period of more than a thousand years (Barrett et al., 2011), reflecting the resilience of the northern Norwegian cod fisheries to historic climate variability (Eide, 2017). Also, model projections indicate that expansions in suitable habitat for subarctic species and increased production of planktonic prey due to increasing temperatures and ice retreat, will continue to support commercially important fisheries

(Lam et al., 2016; Eide, 2017; Haug et al., 2017; Peck and Pinnegar, 2018) (Section 3.2.3.1.3, Box 3.4) (*medium confidence*).

However, recent studies in the Bering Sea suggest that future fish production will also depend on how climate change and ocean acidification will alter the quality, quantity and availability of suitable prey; the thermal stress and metabolic demands of resident fish; and species interactions (Section 3.2.3.1.3), suggesting that the future of commercial fisheries in Arctic regions is uncertain (Holsman et al., 2018). It is also uncertain whether future autumn and winter ocean conditions will be conducive to the establishment of resident overwintering spawning populations that are large enough to support sustainable commercial fishing operations at higher latitude Arctic shelf regions (Section 3.2.3.1) (*medium confidence*).

Projecting the impacts of climate change on marine fisheries is inextricably intertwined with response scenarios regarding risk tolerance in future management of marine resources, advancements in fish capture technology, and markets drivers (e.g., local and global demand, emerging product lines, competition, processing efficiencies and energy costs) (Groeneveld et al., 2018). Seasonal and interannual variability in ocean conditions influences product quality and costs of fish capture (Haynie and Pfeiffer, 2012) (Table 3.4). Further, past experience suggests that barriers to diversification may limit the portfolio of viable target fisheries available to small-scale fisheries (Ward et al., 2017) (*low confidence*).

3.2.4.1.2 Southern Ocean

This section examines climate change impacts on Southern Ocean fisheries for Antarctic krill and finfish. Management of these fisheries by CCAMLR and responses to climate change are discussed in Section 3.5.2.1. The main Antarctic fisheries are for Antarctic krill, and for Antarctic and Patagonian toothfish; in 2016 the reported catches for these species were approximately 260 thousand tons for krill (CCAMLR, 2017b) and 11 thousand tons for Antarctic and Patagonian toothfish combined (CCAMLR, 2017a). The mean annual wholesale value of the Antarctic krill fishery was 69.5 USD million yr⁻¹ for the period from 2011 to 2015, and 206.7 million USD yr⁻¹ for toothfish fisheries (combined) over the same period (CCAMLR, 2016b). The fishery for Antarctic krill in the southern Atlantic Sector and the northern West Antarctic Peninsula (together the current area of focus for the fishery) has become increasingly concentrated in space over recent decades, which has raised concern regarding localised impacts on krill predators (Hinke et al., 2017a). The krill fishery has also changed its peak season of operation. In the early years of the fishery, most krill were taken in summer and autumn, with lowest catches being taken in spring. In recent years the lowest catches have occurred over summer, catches have peaked in late autumn, and very little fishing activity has occurred in spring (Nicol and Foster, 2016). Some of these temporal and spatial shifts in the fishery over time have been attributed to reductions in winter sea ice extent in the region (Kawaguchi et al., 2009) (*low confidence*). Recent increases in the use of krill catch to produce krill oil (as a human health supplement) has also led to vessels concentrating on fishing in autumn and winter when krill are richest in lipids (Nicol and Foster, 2016). Available evidence regarding future changes to Antarctic krill populations

(Section 3.2.3.2.1) indicates that the impacts of climate change will be most pronounced in the areas that are currently most important for the Antarctic krill fishery: the Scotia Sea and the northern tip of the AP. Major future changes in the krill fishery itself are expected to be driven by global issues external to the Southern Ocean, including conservation decision making and socioeconomic drivers.

There is limited understanding of the consequences of climate change for Southern Ocean finfish fisheries. Lack of recovery of mackerel icefish (*Champscephalus gunnari*) after cessation of fishing in 1995 has been related to anomalous water temperatures (~2°C increase related to a strong El Niño) in the subantarctic Indian Ocean and to availability of krill prey in the Atlantic region (Mintenbeck, 2017) (*low confidence*). Differences in temperature tolerance of Patagonian and Antarctic toothfish described in Section 3.2.3.2.3 may have implications for future fisheries of these two species.

3.2.4.2 Tourism

Reductions in sea ice have facilitated an increase in marine and cruise tourism opportunities across the Arctic related to an increase in accessibility (Dawson et al., 2014; Johnston et al., 2017) (*high confidence*). While not exclusively 'polar', Alaska attracts the highest number of cruise passengers annually at just over one million; Svalbard attracts 40,000–50,000; Greenland 20,000–30,000; and Arctic Canada 3,500–5,000 (Johnston et al., 2017). Compared to a decade ago, there are more cruises on offer, ships travel further in a single season, larger vessels with more passenger berths are in operation, more purpose-built polar cruise vessels are being constructed, and private pleasure craft are appearing in the Arctic more frequently (Lasserre and Têtu, 2015; Johnston et al., 2017; Dawson et al., 2018). In Antarctica, almost 37,000 (predominantly shipborne) tourists visited in 2016–2017, with 51,707 during 2017–2018; there were 6700 tourists in 1992–1993 (the first year of record) (ATCM, 2018). Due to accessibility and convenience, these tourism operations are mostly based around the few ice-free areas of Antarctica, concentrated on the AP (Perterra et al., 2017).

Canada's Northwest Passage (southern route), which only saw occasional cruise ship transits in the early 2000s is now reliably accessible during the summer cruising season, and as a result has experienced a doubling and quadrupling of cruise and pleasure craft activity over the past decade (Johnston et al., 2017; Dawson et al., 2018). There is *high confidence* that demand for Arctic cruise tourism will continue to grow over the coming decade (Johnston et al., 2017). The anticipated implications of future climate change have become a driver for polar tourism. A niche market known as 'last chance tourism' has emerged whereby tourists explicitly seek to experience vanishing landscapes or seascapes, and natural and social heritage in the Arctic and Antarctic, before they disappear (Lemelin et al., 2010; Lamers et al., 2013).

Increases in polar cruise tourism pose risks and opportunities related to development, education, safety (including search and rescue), security within communities and environmental sustainability (Johnston et al., 2012a; Johnston et al., 2012b; Stewart et al., 2013; Dawson et al., 2014; Lasserre and Têtu, 2015; Stewart et al.,

2015). In the Arctic, there are also risks and opportunities related to employment, health and well-being, and the commodification of culture (Stewart et al., 2013; Stewart et al., 2015). There is *high confidence* that biodiversity supported by ice-free areas, particularly those on the AP, are vulnerable to the introduction of terrestrial alien species via tourists and scientists (Chown et al., 2012; Huiskes et al., 2014; Hughes et al., 2015; Duffy et al., 2017; Lee et al., 2017a) (Box 3.3) as well as to the direct impacts of humans (Perterra et al., 2017). The tourism sector relies on a set of regulations that apply to all types of maritime shipping, yet cruise ships intentionally travel off regular shipping corridors and serve a very different purpose than other vessel types, so there is a need for region-specific governance regimes, specialised infrastructure, and focused policy attention (Dawson et al., 2014; Pashkevich et al., 2015; Pizzolato et al., 2016; Johnston et al., 2017). Private pleasure craft remain almost completely unregulated, and will pose unique risks in the future (Johnston et al., 2017).

3.2.4.3 Transportation

The Arctic is reliant on marine transportation for the import of food, fuel and other goods. At the same time, the global appetite for maritime trade and commerce through the Arctic (including community re-supply, mining and resource development, tourism, fisheries, cargo, research, and military and icebreaking, etc.) is increasing as the region becomes more accessible because of reduced sea ice cover. There are four potential Arctic international trade routes: the Northwest Passage, the Northern Sea Route, the Arctic Bridge and the Transpolar Sea Route. All of these routes offer significant trade benefits because they provide substantial distance savings compared to traditional routes via the Suez or Panama Canals.

There is *high confidence* that shipping activity during the Arctic summer increased over the past two decades in regions for which there is information, concurrent with reductions in Arctic sea ice extent and the shift to predominantly seasonal ice cover (Pizzolato et al., 2014; Eguiluz et al., 2016; Pizzolato et al., 2016). Long term datasets over the pan-Arctic are incomplete, but the distance travelled by ships in Arctic Canada nearly tripled between 1990 and 2015 (from ~365,000 to ~920,000 km) (Dawson et al., 2018). Other non-environmental factors which influence Arctic shipping are natural resource development, regional trade, geopolitics, commodity prices, global economic and social trends, national priorities, tourism demand, ship building technologies and insurance costs (Lasserre and Pelletier, 2011; Têtu et al., 2015; Johnston et al., 2017). Current impacts associated with the observed increase in Arctic shipping include a higher rate of reported accidents per km travelled compared to southern waters (CCA, 2016), increases in vessel noise propagation (Halliday et al., 2017) and air pollution (Marelle et al., 2016). Disruptions to cultural and subsistence hunting activities from increased shipping (Huntington et al., 2015; Olsen et al., 2019) compound climate-related impacts to people (Sections 3.4.3.3.2, 3.4.3.3.3).

It is projected that shipping activity will continue to rise across the Arctic as northern routes become increasingly accessible (Stephenson et al., 2011; Stephenson et al., 2013; Barnhart et al., 2015; Melia et al.,

2016), although mitigating economic and operational factors remain uncertain and could influence future traffic volume (Zhang et al., 2016). The Northern Sea Route is expected to be more viable than other routes because of infrastructure already in place (Milaković et al., 2018); favourable summer ice conditions in recent years have reduced transit times (Aksenov et al., 2017). In comparison, the Northwest Passage and Arctic Bridge presently have limited port and marine transportation infrastructure, incomplete soundings and hydrographic charting, challenging sea ice conditions and limited search and rescue capacity; these compound the risks from shipping activity (Stephenson et al., 2013; Johnston et al., 2017; Andrews et al., 2018).

Future shipping impacts will be regionally diverse considering the unique geographies, sea ice dynamics, infrastructure and service availability and regulatory regimes that exist across different Arctic nations. Considerations include socioeconomic and political implications related to safety (marine and local accidents), security (trafficking, terrorism and local issues), and environmental and cultural sustainability (invasive species, release of biocides, chemicals and other waste, marine mammal strikes, fuel spills, air and underwater noise pollution and impacts to subsistence hunting) (Arctic Council, 2015a; Halliday et al., 2017; Hauser et al., 2018). Black carbon emissions from shipping activity within the Arctic are projected to increase (Arctic Council, 2017) and are more easily deposited at the surface in the region compared with emissions from lower latitudes (Sand et al., 2013). Commercial shipping mainly uses heavy fuel oil, with associated emissions of sulphur, nitrogen, metals, hydrocarbons, organic compounds, black carbon and fly ash to the atmosphere during combustion (Turner et al., 2017a). Mitigation approaches include banning heavy fuel oil as already implemented in Antarctica and the waters around Svalbard, and the use of new technology like scrubbers.

The predominant shipborne activities in Antarctica are fishing, logistic support to land-based stations, and marine research vessels operating for both non-governmental and governmental sectors. Uncertainty in future Antarctic sea ice conditions (Section 3.2.2.1) pose challenges to considering potential impacts on these activities (Chown, 2017).

3.3 Polar Ice Sheets and Glaciers: Changes, Consequences and Impacts

3.3.1 Ice Sheet Changes

Changes in ice sheet mass have been derived repeatedly over the satellite era using complementary methods based on time series of satellite altimetry to measure volume change, ice-flux measurements combined with modelled surface mass balance (SMB) to calculate mass inputs and outputs, and satellite gravimetry to measure regional mass change. Ice sheet changes over earlier periods have also been reconstructed from firn/ice core and geological evidence (SM3.3.1).

3.3.1.1 Antarctic Ice Sheet Mass Change

It is *virtually certain* that the Antarctic Peninsula (AP) and West Antarctic Ice Sheet (WAIS) combined have cumulatively lost mass since widespread measurements began in 1992, and that the rate of loss has increased since around the year 2006 and continued post-AR5 (Martín-Español et al., 2016; Zwally et al., 2017; Bamber et al., 2018; Gardner et al., 2018; The IMBIE Team, 2018; Rignot et al., 2019), extending and reinforcing previous findings (IPCC, 2013) (Figure 3.7, Table 3.3, SM3.3.1.1). From *medium evidence*, there is *high agreement* in the sign and *medium agreement* in the magnitude of both WAIS and AP mass change between the complementary satellite methods (Mémin et al., 2015; The IMBIE Team, 2018).

Table 3.3 | Mass balance (Gt yr^{-1}) of the West Antarctic Ice Sheet (WAIS), Antarctic Peninsula (AP), East Antarctic Ice Sheet (EAIS), the combined Antarctic Ice Sheets (AIS) and the Greenland Ice Sheet (GIS) and the total sea level contribution (mm yr^{-1}).

Ice sheet	1992–1996	1997–2001	2002–2006	2007–2011	2012–2016
WAIS and AP (Bamber et al., 2018)	-55 ± 30	-53 ± 30	-77 ± 17	-197 ± 11	-172 ± 27
WAIS and AP (The IMBIE Team, 2018)	-60 ± 32	-44 ± 31	-85 ± 31	-183 ± 32	-192 ± 31
WAIS only (The IMBIE Team, 2018)	-53 ± 29	-41 ± 28	-65 ± 27	-148 ± 27	-159 ± 26
EAIS (Bamber et al., 2018)	28 ± 76	-50 ± 76	52 ± 37	80 ± 17	-19 ± 20
EAIS (The IMBIE Team, 2018)	11 ± 58	8 ± 56	12 ± 43	23 ± 38	-28 ± 30
GIS (Bamber et al., 2018)	31 ± 83	-47 ± 81	-206 ± 28	-320 ± 10	-247 ± 15
	1992–2006			2007–2016	
WAIS and AP (Bamber et al., 2018; The IMBIE Team, 2018)	-56 ± 20			-185 ± 17	
	1992–2016				
EAIS (Bamber et al., 2018)	18 ± 52				
EAIS (The IMBIE Team, 2018)	15 ± 41				
	1992–2001	2002–2011	2006–2015	2012–2016	
AIS (Bamber et al., 2018; The IMBIE Team, 2018)	-51 ± 73	-82 ± 27	-155 ± 19	-199 ± 26	
GIS (Bamber et al., 2018)	-8 ± 82	-263 ± 21	-278 ± 11	-247 ± 15	
Total sea level contribution (mm yr^{-1})	0.16 ± 0.3	0.96 ± 0.1	1.20 ± 0.1	1.24 ± 0.1	

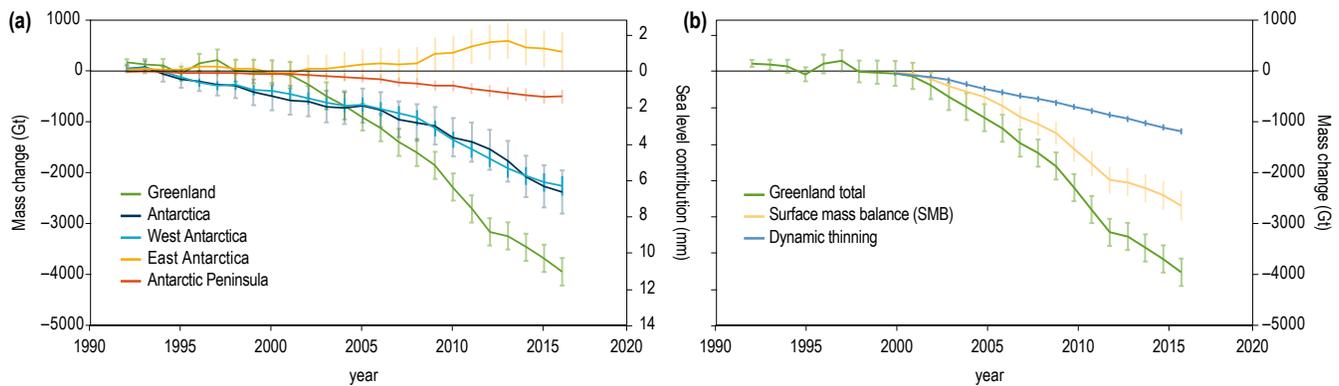


Figure 3.7 | (a) Cumulative Ice Sheet mass change, 1992–2016, (after Bamber et al., 2018; The IMBIE Team, 2018). **(b)** Greenland Ice Sheet (GIS) mass change components from surface mass balance (SMB) (orange) and dynamic thinning (blue) from 2000 to 2016, (after van den Broeke et al., 2016; King et al., 2018). Uncertainties are 1 standard deviation.

WAIS mass loss and recent increases in loss were concentrated in the Amundsen Sea Embayment (ASE) (*high confidence*) with increases particularly in the late 2000s (Mouginot et al., 2014), accounting for most of the $-112 \pm 10 \text{ Gt yr}^{-1}$ WAIS loss from 2003 to 2013 (Martín-Español et al., 2016). The ice sheet margins of nearby Getz Ice Shelf also lost mass rapidly ($-67 \pm 27 \text{ Gt yr}^{-1}$, 2008–2015) (Gardner et al., 2018). This region also experienced losses during previous warm periods (Cross-Chapter Box 8 in Chapter 3).

On the AP, the Bellingshausen Sea ice sheet margin shifted from close to mass balance in the 2000s to rapid loss from 2009 ($-56 \pm 8 \text{ Gt yr}^{-1}$ from 2010 to 2014) (*high confidence*) (Helm et al., 2014; McMillan et al., 2014b; Wouters et al., 2015; Hogg et al., 2017). This shift accompanied ongoing mass loss (*high confidence*) from the smaller northeastern AP glaciers that fed the former Prince Gustav, Larsen A and B ice shelves, though now at a lower rate than immediately following shelf collapse in 1995 and 2002 (Seehaus et al., 2015; Wuite et al., 2015; Rott et al., 2018). Of 860 marine-terminating AP glaciers, 90% retreated from their 1940s positions (Cook et al., 2014), established in the early to mid-Holocene (Ó Cofaigh et al., 2014) (*medium confidence*). Early 21st century combined AP glacier (Fieber et al., 2018) and ice sheet loss was around -30 Gt yr^{-1} (Table 3.3).

The East Antarctic Ice Sheet (EAIS, covering 85% of the Antarctic Ice Sheet (AIS)) has remained close to balance, with large interannual variability and no clear mass trend over the satellite record (*medium confidence*) (Table 3.3, Figure 3.7, SM3.3.1.2), and relatively large observation uncertainties (SM3.3.1) (Velicogna et al., 2014; Martín-Español et al., 2017; Bamber et al., 2018). SMB trends are particularly ambiguous, leading to disagreement between one altimetry and one flux-based estimate of $136 \pm 43 \text{ Gt yr}^{-1}$ (spanning 1992–2008) (Zwally et al., 2017), and $-41 \pm 8 \text{ Gt yr}^{-1}$ (1979–2017) (Rignot et al., 2019), respectively. Both differ from the multi-method averages reported here (Table 3.3).

EAIS mass gains on the Siple Coast and Dronning Maud Land (e.g., $63 \pm 6 \text{ Gt yr}^{-1}$ from 2003 to 2013 (Velicogna et al., 2014)) contrast with Wilkes Land losses e.g., from $-17 \pm 4 \text{ Gt yr}^{-1}$ from the Totten Glacier area, 2003–2013 (Velicogna et al., 2014) that drain a large area of deeply-grounded EAIS with potential for multi-metre sea level contributions (Zwally et al., 2017; Rignot et al., 2019).

Limited palaeo ice sheet evidence suggests that this area has previously lost substantial mass in previous interglacials (*medium confidence*) (Aitken et al., 2016; Wilson et al., 2018).

Overall, 2012–2016 Antarctic Ice Sheet mass losses were *extremely likely* greater than those from 2002 to 2011 and *likely* greater than from 1992 to 2001, and it is *extremely likely* that the negative 2012–2016 Antarctic Ice Sheet mass balance was dominated by losses from WAIS (Table 3.3).

3.3.1.2 Components of Antarctic Ice Sheet Mass Change

Antarctic Ice Sheet mass changes are dominated by changes in snowfall and glacier flow. The WAIS and AP loss trends in recent decades are dominated by glacier flow acceleration (also known as dynamic thinning) (*very high confidence*) (Figure SM3.8). Dynamic thinning losses were $-112 \pm 12 \text{ Gt yr}^{-1}$ for 2003–2013, largely from the Amundsen Sea Embayment (Figure SM3.8) (Martín-Español et al., 2016), which contributed $-102 \pm 10 \text{ Gt yr}^{-1}$ from 2003 to 2011 (Sutterley et al., 2014). Total Amundsen Sea Embayment ice discharge increased by 77% since the 1970s (Mouginot et al., 2014), primarily from acceleration of Pine Island Glacier that began around 1945, Smith, Pope and Kohler glaciers around 1980, and Thwaites Glacier around 2000 (Mouginot et al., 2014; Konrad et al., 2017; Smith et al., 2017c). Dynamic thinning in the Amundsen Sea Embayment and western AP accounted for 88% of the $-36 \pm 15 \text{ Gt yr}^{-1}$ increase in Antarctic Ice Sheet mass loss from 2008 to 2015 (Gardner et al., 2018). Glacier acceleration of up to 25% also affected the Getz Ice Shelf margin from 2007 to 2014 (Chuter et al., 2017).

Reduction or loss of ice shelf buttressing has dominated Antarctic Ice Sheet dynamic thinning (*high confidence*). Ice shelves buttress 90% of Antarctic Ice Sheet outflow (Depoorter et al., 2013; Rignot et al., 2014; Fürst et al., 2016; Reese et al., 2018), and ice shelf thinning increased in WAIS by 70% in the decade to 2012, averaged 8% thickness loss from 1994 to 2012 in the Amundsen Sea Embayment (Paolo et al., 2015), and explains the post-2009 onset of rapid dynamic thinning on the southern-AP Bellingshausen Sea coast (Wouters et al., 2015; Hogg et al., 2017; Martín-Español et al., 2017) (Figure SM3.8). Grounding line retreat, an indicator of thinning, has been observed with *high confidence* (Rignot et al., 2014; Christie et al.,

2016; Hogg et al., 2017; Konrad et al., 2018; Roberts et al., 2018). From 2010 to 2016, 22%, 3% and 10% of grounding lines in WAIS, EAIS and the AP respectively retreated at rates faster than 25 m yr^{-1} (the average pace since the Last Glacial Maximum; Konrad et al., 2018), with highest rates along the Amundsen and Bellingshausen Sea coasts, and around Totten Glacier, Wilkes Land, EAIS (Konrad et al., 2018), where dynamic thinning has occurred at least since 1979 (Roberts et al., 2018; Rignot et al., 2019). Ice shelf collapse has driven dynamic thinning in the northern AP over recent decades (*high confidence*) (Seehaus et al., 2015; Wuite et al., 2015; Friedl et al., 2018; Rott et al., 2018).

ASE ice shelf basal melting, grounding line retreat and dynamic thinning have varied with ocean forcing (*medium confidence*) (Dutrieux et al., 2014; Paolo et al., 2015; Christianson et al., 2016; Jenkins et al., 2018) but this variability is superimposed on sustained mass losses compatible with the onset of Marine Ice Sheet Instability (MISI) for several major glaciers (*medium confidence*) (Favier et al., 2014; Joughin et al., 2014; Mouginito et al., 2014; Rignot et al., 2014; Christianson et al., 2016). Whether unstable WAIS retreat has begun or is imminent remains a critical uncertainty (Cross-Chapter Box 8 in Chapter 3).

Mass gains due to increased snowfall have somewhat offset dynamic-thinning losses (*high confidence*). On the AP, snowfall began to increase in the 1930s, accelerated in the 1990s (Thomas et al., 2015; Goodwin et al., 2016), and now offsets sea-level rise by $6.2 \pm 1.7 \text{ mm per century}$ (Medley and Thomas, 2018). EAIS and WAIS snowfall increases offset 20th century sea-level rise by $7.7 \pm 4.0 \text{ mm}$ and $2.8 \pm 1.7 \text{ mm}$ respectively (Medley and Thomas, 2018) (*medium confidence*). AIS snowfall increased by 4 ± 1 then $14 \pm 1 \text{ Gt per decade}$ over the 19th and 20th centuries, of which EAIS contributed 10% (Thomas et al., 2017b). Longer records suggest either an AIS snowfall decrease over the last 1000 years (Thomas et al., 2017a) or a statistically negligible change over the last 800 years (*low confidence*) (Frezzotti et al., 2013).

Mass balance contributions from ice sheet basal melting were not described in AR5 (IPCC, 2013) and the sensitivity of the AIS subglacial hydrological system to climate change is poorly understood. Around half of the AIS bed melts (Siegert et al., 2017), producing $\sim 65 \text{ Gt yr}^{-1}$ of water (Pattyn, 2010) (*low confidence*), some of which refreezes (Bell, 2008) and some accumulates in subglacial lakes with a total volume of $10\text{s of } 1000\text{s of km}^3$ (Popov and Masolov, 2007; Lipenkov et al., 2016; Siegert, 2017). This system contributes fresh water and nutrients to the ocean (Section 3.3.3.3) (Fricker et al., 2007; Siegert et al., 2007; Carter and Fricker, 2012; Horgan et al., 2013; Le Brocq, 2013; Flament et al., 2014; Siegert et al., 2016), and lubricates glacier sliding (e.g., Dow et al., 2018b). Changes in the ice sheet thickness can redistribute subglacial water, affecting drainage pathways and ice flow (Fricker et al., 2016), but hydrological observations are very scarce.

3.3.1.3 Greenland Ice Sheet Mass Change

The Greenland Ice Sheet (GIS) experienced a marked shift to strongly negative mass balance between the early 1990s and mid-2000s (*very high confidence*) (Shepherd et al., 2012; Schrama et al., 2014; Velicogna et al., 2014; van den Broeke et al., 2016; Bamber et al., 2018; King et al., 2018; Sandberg Sørensen et al., 2018; WCRP, 2018).

It is *extremely likely* that the 2002–2011 and 2012–2016 ice losses were greater than in the 1992–2001 period (Bamber et al., 2018) (Table 3.3, Figure 3.7, SM3.3.1.3). Greenland Ice Sheet mass balance is characterised by large interannual variability (e.g., van den Broeke et al., 2017) but from 2005 to 2016, Greenland Ice Sheet was the largest terrestrial contributor to global sea level rise (WCRP, 2018).

A geodetic reconstruction of past ice sheet elevations indicates a Greenland Ice Sheet mass change of $-75.1 \pm 29.4 \text{ Gt yr}^{-1}$ from 1900 to 1983, $-73.8 \pm 40.5 \text{ Gt yr}^{-1}$ from 1983 to 2003, and $-186.4 \pm 18.9 \text{ Gt yr}^{-1}$ from 2003 to 2010, with the losses consistently concentrated along the northwest and southeast coasts, and more locally in the southwest and on the large west coast Jakobshavn Glacier, though intensifying and spreading to the remainder of the coastal ice sheet in the latest period (Kjeldsen et al., 2015). Palaeo evidence also suggests that the GIS has contributed substantially to sea level rise during past warm intervals (Cross-Chapter Box 8 in Chapter 3).

3.3.1.4 Components of Greenland Ice Sheet Mass Change

Ongoing GIS mass loss over recent years has resulted from a combined increase in dynamic thinning and a decrease in SMB. Of these, reduced SMB due to an increase in surface melting and runoff recently came to dominate (*high confidence*) (Andersen et al., 2015; Fettweis et al., 2017; van den Broeke et al., 2017; King et al., 2018), accounting for 42% of losses for 2000–2005, 64% for 2005–2009 and 68% for 2009–2012 (Enderlin et al., 2014) (Figure 3.7).

The GIS was close to balance in the early years of the 1990s (Hanna et al., 2013; Khan et al., 2015), the interior above 2000 m altitude gained mass from 1961 to 1990 (Colgan et al., 2015) and both coastal and ice sheet sites experienced an increasing precipitation trend from 1890 to 2012 and 1890 to 2000 respectively (Mernild et al., 2015), but since the early 1990s multiple observations and modelling studies show strong warming and an increase in runoff (*very high confidence*). High-altitude GIS sites NEEM and Summit warmed by, respectively, $2.7^\circ\text{C} \pm 0.33^\circ\text{C}$ over the past 30 years (Orsi et al., 2017) and by $2.7^\circ\text{C} \pm 0.3^\circ\text{C}$ from 1982 to 2011 (McGrath et al., 2013), while satellite thermometry showed statistically significant widespread surface warming over northern GIS from 2000 to 2012 (Hall et al., 2013). The post-1990s period experienced the warmest GIS near-surface summer air temperatures of 1840–2010 ($+1.1^\circ\text{C}$) (statistically highly significant) (Box, 2013), and ice core analysis found the 2000–2010 decade to be the warmest for around 2000 years (Vinther et al., 2009; Masson-Delmotte et al., 2012), and possibly around 7000 years (Lecavalier et al., 2017). This significant summer warming since the early 1990s increased GIS melt event duration (Mernild et al., 2017) and intensity to levels exceptional over at least 350 years (Trusel et al., 2018), and melt frequency to levels unprecedented for at least 470 years (Graeter et al., 2018). GIS melt intensity for 1994–2013 was two to fivefold the pre-industrial intensity (*medium confidence*) (Trusel et al., 2018). In response, GIS meltwater production and runoff increased (Hanna et al., 2012; Box, 2013; Fettweis et al., 2013; Tedstone et al., 2015; van den Broeke et al., 2016; Fettweis et al., 2017), resulting in 1994–2013 runoff being 33% higher the 20th century mean and 50% higher than the 18th century (Trusel et al., 2018), and 80% higher in a western-GIS

marginal river catchment in 2003–2014 relative to 1976–2002 (Ahlstrom et al., 2017).

Only around half of the 1960–2014 surface melt ran off, most of the rest being retained in firn and snow (Steger et al., 2017), particularly in recently observed firn aquifers in south and west Greenland (Humphrey et al., 2012; Forster et al., 2013; Munneke et al., 2014; Poinar et al., 2017) that cover up to 5% of GIS (Miège et al., 2016; Steger et al., 2017) and stored around one fifth of the meltwater increase since the late 1990s (Noël et al., 2017) (*medium confidence*). While potential aquifer storage is equivalent to about a quarter of annual GIS melt production (Koenig et al., 2014; van den Broeke et al., 2016) and aquifers have spread to higher altitudes (Steger et al., 2017), their potential to buffer runoff has been reduced by firn densification (Polashenski et al., 2014), diversion of water to the bed via crevasses (Poinar et al., 2017), and the formation of ice layers that prevent drainage and promote surface ponding on the firn (Charalampidis et al., 2016) (*high confidence*). Such ponding lowers the firn albedo, promoting further melting (*high confidence*) (e.g., Charalampidis et al., 2015), but the extent of bare ice is a fivefold stronger control on melt (Ryan et al., 2019). Bare ice produced ~78% of runoff from 1960 to 2014, and its extent is expected to increase non-linearly as snow cover retreats to higher, flatter areas of ice sheet (Steger et al., 2017). This extent is not well reproduced in climate models, however, with biases of –6% to 13% (Ryan et al., 2019).

The remaining ~40% of non-SMB GIS mass loss from 1991 to 2015 has resulted from increased ice discharge due to dynamic thinning (*high confidence*) (Enderlin et al., 2014; van den Broeke et al., 2016; King et al., 2018) (Figure 3.7). From 2000 to 2016, dynamic thinning of 89% of GIS outlet glaciers accounted for -682 ± 31 Gt mass change, of which 92% came from the northwest and southeast GIS (King et al., 2018). Half came from only four glaciers (Jakobshavn Isbræ, Kangerdlugssuaq, Koge Bugt, and Ikertivaq South) (Enderlin et al., 2014). Glacier thinning has decreased glacier discharge, however, reducing the dynamic contribution to GIS mass loss (e.g., from 58% from 2000 to 2005 to 32% between 2009 and 2012; Enderlin et al., 2014). Furthermore, there is now *high confidence* that for most of the GIS, increased surface melt has not led to sustained increases in glacier flux on annual timescales because subglacial drainage networks have evolved to drain away the additional water inputs (e.g., Sole et al., 2013; Tedstone et al., 2015; Stevens et al., 2016; Nienow et al., 2017; King et al., 2018).

3.3.1.5 Drivers of Ice Sheet Mass Change

3.3.1.5.1 Ocean drivers

The reduction of ice shelf buttressing that has dominated AIS mass loss (Section 3.3.1.2) has been driven primarily by increases in sub-ice shelf melting (Khazendar et al., 2013; Pollard et al., 2015; Cook et al., 2016; Rintoul et al., 2016; Walker and Gardner, 2017; Adusumilli et al., 2018; Dow et al., 2018a; Minchew et al., 2018) (*high confidence*). Shoaling of relatively warm Circumpolar Deep Water has controlled recent variability in melting in the Amundsen and Bellingshausen seas, Wilkes Land (Roberts et al., 2018) and the AP (*medium confidence*) (Jacobs et al., 2011; Pritchard et al., 2012;

Depoorter et al., 2013; Rignot et al., 2013; Dutrieux et al., 2014; Paolo et al., 2015; Wouters et al., 2015; Christianson et al., 2016; Cook et al., 2016; Jenkins et al., 2018; Roberts et al., 2018). Changes in winds have driven this shoaling by affecting continental shelf edge undercurrents (Walker et al., 2013; Dutrieux et al., 2014; Kimura et al., 2017) and overturning in coastal polynyas (St-Laurent et al., 2015; Webber et al., 2017) (*medium confidence*). Winds over the Amundsen Sea are highly variable, however, with complex interactions between SAM, El Niño/Southern Oscillation (ENSO), Atlantic Multidecadal Oscillation, and the Amundsen Sea Low (Uotila et al., 2013; Li et al., 2014; Turner et al., 2016) (SM3.1.3).

Through their effects on Antarctic coastal ocean circulation, ENSO or other tropical-ocean variability may have triggered changes to Pine Island Glacier in the 1940s (Smith et al., 2017c) and again in the 1970s and 1990s (Jenkins et al., 2018), and recent ENSO variability is correlated with recent changes in ice shelf thickness (Paolo et al., 2018) (*medium confidence*). Such coupling between wind variability, ocean upwelling, ice shelf melt, buttressing and glacier flow rate has also been observed in EAIS, at Totten Glacier, Wilkes Land (Greene et al., 2017).

Around Greenland, an anomalous inflow of subtropical water driven by wind changes, multi-decadal natural ocean variability (Andresen et al., 2012), and a long-term increase in the North Atlantic's upper ocean heat content since the 1950s (Cheng et al., 2017), all contributed to a warming of the subpolar North Atlantic (Häkkinen et al., 2013) (*medium confidence*). Water temperatures near the grounding zone of GIS outlet glaciers are critically important to their calving rate (O'Leary and Christoffersen, 2013) (*medium confidence*), and warm waters have been observed interacting with major GIS outlet glaciers (*high confidence*) (e.g., Holland et al., 2008; Straneo et al., 2017).

The processes behind warm-water incursions in coastal Greenland that force glacier retreat remain unclear, however (Straneo et al., 2013; Xu et al., 2013b; Bendtsen et al., 2015; Murray et al., 2015; Cowton et al., 2016; Miles et al., 2016), and there is *low confidence* in understanding coastal GIS glacier response to ocean forcing because submarine melt rates, calving rates (Rignot et al., 2010; Todd and Christoffersen, 2014; Benn et al., 2017), bed and fjord geometry and the roles of ice mélange and subglacial discharge (Enderlin et al., 2013; Gladish et al., 2015; Slater et al., 2015; Morlighem et al., 2016; Rathmann et al., 2017) are poorly understood, and extrapolation from a small sample of glaciers is impractical (Moon et al., 2012; Carr et al., 2013; Straneo et al., 2016; Cowton et al., 2018).

3.3.1.5.2 Atmospheric drivers

Snow accumulation and surface melt in Antarctica are influenced by the Southern Hemisphere extratropical circulation (SM3.1.3), which has intensified and shifted poleward in austral summer from 1950 to 2012 (Arblaster et al., 2014; Swart et al., 2015a) (*medium confidence*). The austral summer SAM has been in its most positive extended state for the past 600 years (Abram et al., 2014; Dätwyler et al., 2017), and from 1979 to 2013 has contributed to intensified atmospheric circulation and increasing and decreasing snowfall

in the western and eastern AP respectively (Marshall et al., 2017) (*medium confidence*). WAIS accumulation trends (Section 3.3.1.2) resulted from a deepening of the Amundsen Sea Low over recent decades (Raphael et al., 2016) (*high confidence*).

During the 1990s, WAIS experienced record surface warmth relative to the past 200 years, though similar conditions occurred for 1% of the preceding 2000 years (Steig et al., 2013), and WAIS surface melting remains limited. In contrast, AP surface melting has intensified since the mid-20th century and the last three decades were unprecedented over 1000 years (Abram et al., 2013a). The northeast AP began warming 600 years ago and past-century rates were unusual over 2000 years (Mulvaney et al., 2012; Stenni et al., 2017). Increased föhn winds due to the more positive SAM (Cape et al., 2015) caused increased surface melting on the Larsen ice shelves (Grosvenor et al., 2014; Luckman et al., 2014; Elvidge et al., 2015) and after 11,000 years intact, the 2002 melt-driven collapse of the Larsen B ice shelf followed strong warming between the mid-1950s and the late 1990s (Domack et al., 2005) (*medium confidence*).

In Greenland, associations between atmospheric pressure indices such as the North Atlantic Oscillation (NAO) and temperature, insolation and snowfall indicate with *high confidence* that, as in Antarctica, variability of large-scale atmospheric circulation is an important driver of SMB changes (Fettweis et al., 2013; Tedesco et al., 2013; Ding et al., 2014; Tedesco et al., 2016b; Ding et al., 2017; Hofer et al., 2017). A post-1990s decrease in summer NAO reflects increased anticyclonic weather (e.g., Tedesco et al., 2013; Hanna et al., 2015) that advected warm air over the GIS, explaining ~70% of summer surface warming from 2003 to 2013 (Fettweis et al., 2013; Tedesco et al., 2013; Mioduszewski et al., 2016), and reduced the cloud cover, increasing shortwave insolation (Tedesco et al., 2013) that, combined with albedo feedbacks (Box et al., 2012; Charalampidis et al., 2015; Tedesco et al., 2016a; Stibal et al., 2017; Ryan et al., 2018) (*high confidence*), explains most of the post-1990s melt increase (Hofer et al., 2017). These drivers culminated in July 2012 in exceptional warmth and surface melt up to the ice sheet summit (Nghiem et al., 2012; Tedesco et al., 2013; Hanna et al., 2014; Hanna et al., 2016; McLeod and Mote, 2016).

3.3.1.6 Natural and Anthropogenic Forcing

There is *medium agreement* but *limited evidence* of anthropogenic forcing of AIS mass balance through both SMB and glacier dynamics (*low confidence*). Partitioning between natural and human drivers of atmospheric and ocean circulation changes remains very uncertain. Partitioning is challenging because, along with the effects of greenhouse gas increases and stratospheric ozone depletion (Vaughn et al., 2015; England et al., 2016; Li et al., 2016a), atmospheric and ocean variability in the areas of greatest AIS mass change are affected by a complex chain of processes (e.g., Fyke et al., 2018; Zhang et al., 2018a) that exhibit considerable natural variability and have multiple interacting links to sea surface conditions in the Pacific (Schneider et al., 2015; England et al., 2016; Raphael et al., 2016; Clem et al., 2017; Steig et al., 2017; Paolo et al., 2018) and Atlantic (Li et al., 2014), with additional local feedbacks (e.g., Stammerjohn et al., 2012; Goosse and Zunz, 2014). Recent AP warming and consequent

ice shelf collapses have evidence of a link to anthropogenic ozone and greenhouse gas forcing via the SAM (e.g., Marshall, 2004; Shindell, 2004; Arblaster and Meehl, 2006; Marshall et al., 2006; Abram et al., 2014) and to anthropogenic Atlantic sea surface warming via the Atlantic Multidecadal Oscillation (e.g., Li et al., 2014). This warming was highly unusual over the last 1000 years but not unprecedented, and along with subsequent cooling is within the bounds of the large natural decadal-scale climate variability in this region (Mulvaney et al., 2012; Turner et al., 2016). More broadly over the AP and coastal WAIS where dynamic mass losses are concentrated, natural variability in atmospheric and ocean forcing appear to dominate observed mass balance (*medium confidence*) (Smith and Polvani, 2017; Jenkins et al., 2018).

Evidence exists for an anthropogenic role in the atmospheric circulation (NAO) changes that have driven GIS mass loss (Section 3.3.1.5.2) (*medium confidence*), although this awaits formal attribution testing (e.g., Easterling et al., 2016). Arctic amplification of anthropogenic warming (e.g., Serreze et al., 2009) affects atmospheric circulation (Francis and Vavrus, 2015; Mann et al., 2017) and has reduced sea ice extent (Section 3.2.1.1.1), feeding back to exacerbate both warming and NAO changes (Screen and Simmonds, 2010) that impact GIS mass balance. Negative-NAO wind patterns increased GIS melt observed in a 40-year runoff signal (Ahlstrom et al., 2017), and an increase in melting beginning in the mid-1800s closely followed the onset of industrial era Arctic warming and emerged beyond the range of natural variability in the last few decades (Graeter et al., 2018; Trusel et al., 2018) (Section 3.3.1.4).

3.3.1.7 Ice Sheet Projections

Section 4.2 assesses the sea level impacts from observed and projected changes in ice sheets.

3.3.2 Polar Glacier Changes

3.3.2.1 Observations, Components of Change, and Drivers

Chapter 3 assesses changes in polar glaciers in the Canadian and Russian Arctic, Svalbard, Greenland and Antarctica, independent of the Greenland and Antarctic ice sheets (Figure 3.8). Glaciers in all other regions including Alaska, Scandinavia and Iceland are assessed in Chapter 2.

Changes in the mass of Arctic glaciers for the 'present day' (2006–2015) are assessed using a combination of satellite observations and direct measurements (Figure 3.8; Appendix 2.A, Table 1). During this period, glacier mass loss was largest in the periphery of Greenland ($-47 \pm 16 \text{ Gt yr}^{-1}$), followed by Arctic Canada North ($-39 \pm 8 \text{ Gt yr}^{-1}$), Arctic Canada South ($-33 \pm 9 \text{ Gt yr}^{-1}$), the Russian Arctic ($-15 \pm 12 \text{ Gt yr}^{-1}$) and Svalbard and Jan Mayen ($-9 \pm 5 \text{ Gt yr}^{-1}$). When combined with the Arctic regions covered in Chapter 2 (Alaska, the Yukon territory of Canada, Iceland and Scandinavia), Arctic glaciers as a whole lost mass at a rate of $-213 \pm 29 \text{ Gt yr}^{-1}$, a sea level contribution of $0.59 \pm 0.08 \text{ mm yr}^{-1}$ (*high confidence*). Overall during this period, Arctic glaciers caused a similar amount of sea

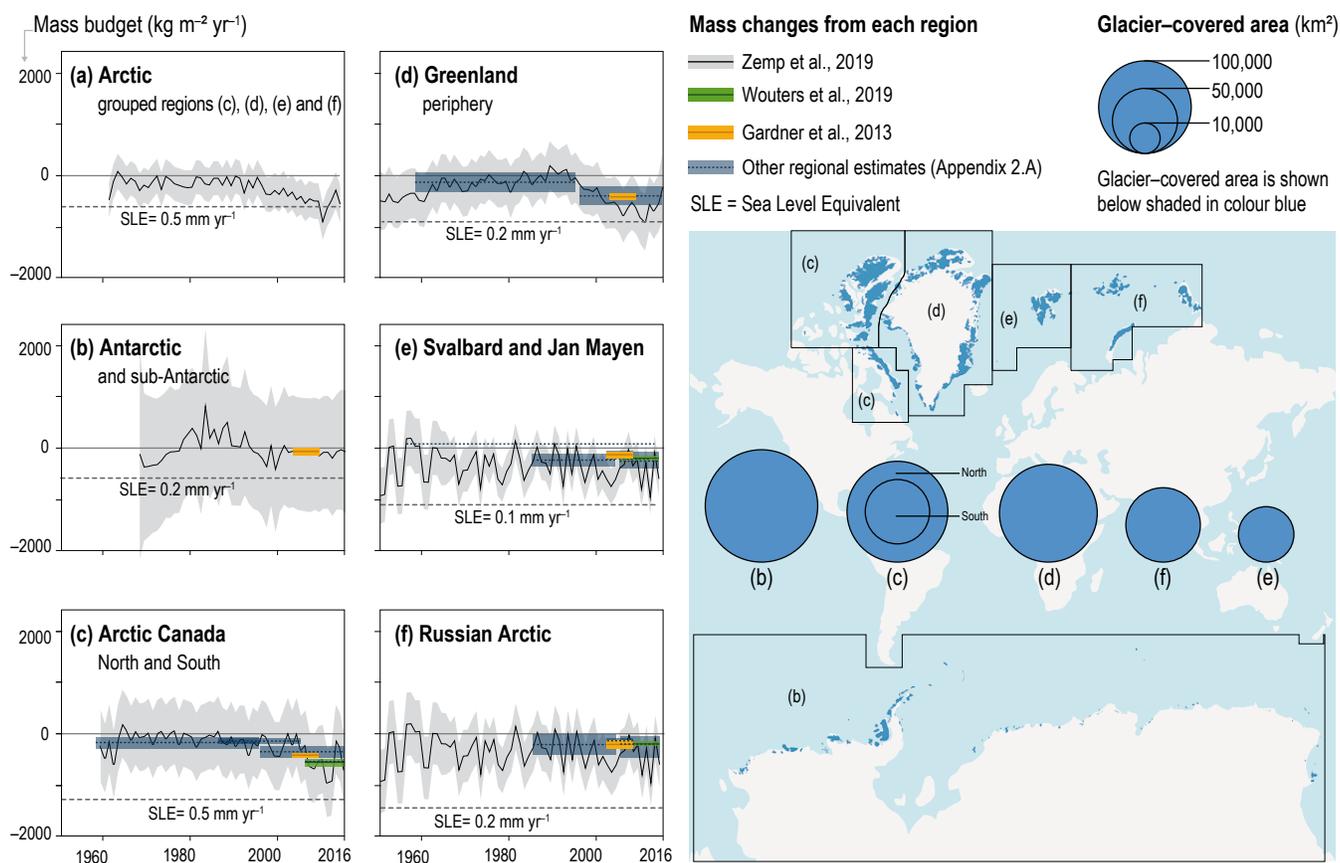


Figure 3.8 | Glacier mass budgets for the six polar regions assessed in Chapter 3. Glacier mass budgets for all other regions (including Iceland, Scandinavia and Alaska) are shown in Chapter 2, Figure 2.4. Regional time series of annual mass change are based on glaciological and geodetic balances (Zemp et al., 2019). Superimposed are multi-year averages by Wouters et al. (2019) and Gardner et al. (2013) from the Gravity Recovery and Climate Experiment (GRACE). Estimates by Gardner et al. (2013) were used in the IPCC 5th Assessment Report (AR5). Additional regional estimates in some regions are listed in Appendix 2.1, Table 1. Annual and time-averaged mass-budget estimates include the errors reported in each study. Glacier outlines and areas are based on RGI Consortium (2017).

level rise to the GIS (Section 3.3.1.3), but their rate of mass loss per unit area was larger (Bolch et al., 2013).

There is *limited evidence (high agreement)* that the current rate of glacier mass loss is larger than at any time during the past 4000 years (Fisher et al., 2012; Zdanowicz et al., 2012). Further back in time during the early to mid- Holocene, pre-historic glacial deposits, ice core records, and numerical modelling evidence shows that many Arctic glaciers were at various stages similar to or smaller than present (Gilbert et al., 2017; Zekollari et al., 2017), experienced greater melt rates (Lecavalier et al., 2017), or may have disappeared altogether (Solomina et al., 2015) (*medium confidence*). This evidence, however, does not provide a complete assessment of the rates and magnitudes of past glacier mass loss.

Atmospheric circulation changes (Box et al., 2018) have led to pan-Arctic variability in glacier mass balance (*high confidence*), including different rates of retreat between eastern and western glaciers in Greenland's periphery (Bjørk et al., 2018), and a high rate of surface melt in the Canadian Arctic (Gardner et al., 2013; Van Wychen et al., 2016; Millan et al., 2017) through persistently high summer air temperatures (Bezeau et al., 2014; McLeod and Mote, 2016). Atmospheric circulation anomalies from 2007 to 2012

associated with glacier mass loss are also linked to enhanced GIS melt (Section 3.3.1.4) and Arctic sea ice loss (Section 3.2.1.1), and exceed by a factor of two the interannual variability in daily mean pressure (sea level and 500 hPa) of the Arctic region over the 1871–2014 period (Belleflamme et al., 2015) (Section 3.3.1.6).

Increased surface melt on Arctic glaciers has led to a positive feedback from lowered surface albedo, causing further melt (Box et al., 2012), and in Svalbard, mean glacier albedo has reduced between 1979 and 2015 (Möller and Möller, 2017). Across the Arctic, increased surface melt and subsequent ice-layer formation via refreezing within snow and firn also reduces the ability of glaciers to store meltwater, increasing runoff (Zdanowicz et al., 2012; Gascon et al., 2013a; Gascon et al., 2013b; Noël et al., 2017; Noël et al., 2018).

Between the 1990s and 2017, tidewater glaciers have exhibited regional patterns in glacier dynamics; glaciers in Arctic Canada have largely decelerated, while glaciers in Svalbard and the Russian Arctic have accelerated (Van Wychen et al., 2016; Strozzini et al., 2017). Annual retreat rates of tidewater glaciers in Svalbard and the Russian Arctic for 2000–2010, have increased by a factor 2 and 2.5 respectively, between 1992 and 2000 (Carr et al., 2017). Acceleration due to surging (an internal dynamic instability) of a few key glaciers

has dominated dynamic ice discharge on time-scales of years to decades (Van Wychen et al., 2014; Dunse et al., 2015).

The recent acceleration and surge behaviour of polythermal glaciers in Svalbard and the Russian Arctic is caused by destabilisation of the marine termini due to increased surface melt, and changes in basal temperature, lubrication and weakening of subglacial sediments (Dunse et al., 2015; Sevestre et al., 2018; Willis et al., 2018) or terminus thinning and response to warmer ocean temperatures (McMillan et al., 2014a) (*low confidence*). Iceberg calving rates in Svalbard are linked to ocean temperatures which control rates of submarine melt (Luckman et al., 2015; Vallot et al., 2018) (*medium confidence*). Rapid disintegration of ice shelves in the Canadian and Russian Arctic continues and has led to acceleration and thinning in tributary-glacier basins (*high confidence*) (Willis et al., 2015; Copland and Mueller, 2017).

Little information is available on Holocene and historic changes in glaciers in Antarctica (separate from the ice sheet), and on sub-Antarctic islands (Hodgson et al., 2014). Mass changes of glaciers in these regions between 2006 and 2015 ($-90 \pm 860 \text{ Gt yr}^{-1}$) have *low confidence* as they are based on a single data compilation with large uncertainties in the Antarctic region (Zemp et al., 2019) (Figure 3.8). *Limited evidence with high agreement* from individual glaciers suggests that regional variability in glacier mass changes may be linked to changes in the large-scale Southern Hemisphere atmospheric circulation (Section 3.3.1.5.2). On islands adjacent to the AP, glaciers experienced retreat and mass loss during the mid to late 20th century, but since around 2009 there has been a reduction in mass loss rate or a return to slightly positive balance (Navarro et al., 2017; Oliva et al., 2017). Reduced mass loss has been linked to increased winter snow accumulation and decreased summer melt at these locations, associated with recent deepening of the circumpolar pressure trough (Oliva et al., 2017). Conversely, on the sub-Antarctic Kerguelen Islands, increased glacier mass loss (Verfaillie et al., 2015) may be due to reduced snow accumulation rather than increased air temperature as a result of southward migration of storm tracks (Favier et al., 2016).

3.3.2.2 Projections

Projections of all glaciers, including those in polar regions, are covered in Cross-Chapter Box 6 in Chapter 2.

3.3.3 Consequences and Impacts

3.3.3.1 Sea Level

Chapter 4 assesses the sea level impacts from observed and projected changes in ice sheets (Section 3.3.1) and polar glaciers (Section 3.3.2), including uncertainties related to marine ice sheets (Cross-Chapter Box 8 in Chapter 3).

3.3.3.2 Physical Oceanography

The major large-scale impacts of freshwater release from Greenland on ocean circulation relate to the potential modulation/inhibition of the formation of water masses that represent the headwaters of the Atlantic

Meridional Overturning Circulation. The timescales and likelihood of such effects are assessed separately in Chapter 6 (Section 6.7). Freshwater release also affects local circulation within fjords through two principle mechanisms; subglacial release from tidewater glaciers enhances buoyancy driven circulation, whereas runoff from land-terminating glaciers contributes to surface layer freshening and estuarine circulation (Straneo and Cenedese, 2015). There is *limited evidence* that freshening occurred between 2003 and 2015 in North East Greenland fjords and coastal waters (Sejr et al., 2017).

For Antarctica, freshwater input to the ocean from the ice sheet is divided approximately equally between melting of calved icebergs and of ice shelves *in situ* (Depoorter et al., 2013; Rignot et al., 2014). There is *high confidence* that the input of ice shelf meltwater has increased in the Amundsen and Bellingshausen Seas since the 1990s, but *low confidence* in trends in other sectors (Paolo et al., 2015).

Freshwater injected from the AIS affect water mass circulation and transformation, though sea ice dominates upper ocean properties away from the Antarctic ice shelves (Abernathy et al., 2016; Haumann et al., 2016). Over the ice shelf regions, where dense waters sink and flood the global ocean abyss, the role of glacial freshwater input is clearer. From 1980 to 2012, the salinity of Antarctic Bottom Water reduced by an amount equivalent to $73 \pm 26 \text{ Gt y}^{-1}$ of freshwater added, around half the estimated increase in freshwater input by Antarctic glacial discharge up to that time (Purkey and Johnson, 2013). In some places, notably the Indian-Australian sector, Antarctic Bottom Water freshening may be accelerating (Menezes et al., 2017). There is *medium confidence* in an overall freshening trend and *low confidence* that this is accelerating, given the sparsity of information and significant interannual variability in Antarctic Bottom Water properties at other export locations (Meijers et al., 2016).

For the Southern Ocean, there is *limited evidence* for stratification changes in the post-AR5 period, and *low confidence* in how stratification changes are affecting sea ice and basal ice shelf melt. An increase in stratification caused by release of freshwater from the AIS was invoked as a mechanism to suppress vertical heat flux and permit an increase in sea ice extent (Bintanja et al., 2013; Bronselaer et al., 2018; Purich et al., 2018), though some studies conclude that glacial freshwater input is insufficient to cause a significant sea ice expansion (Swart and Fyfe, 2013; Pauling et al., 2017) (Section 3.2.1.1). In contrast, where warm water intrusions drive melting within ice shelf cavities, a significant entrained heat flux to the surface can exist and increase stratification and potentially reduce sea ice extent (Jourdain et al., 2017; Merino et al., 2018). It has been argued that freshening from glacial melt can enhance basal melting of ice shelves by reducing dense water production and modulating oceanic heat flow into ice shelf cavities (Silvano et al., 2018).

3.3.3.3 Biogeochemistry

Both polar ice sheets have the potential to release dissolved and sediment-bound nutrients and organic carbon directly to the surface ocean via subglacial and surface meltwater, icebergs, melting of the base of ice shelves (Shadwick et al., 2013; Wadham et al., 2013; Hood et al., 2015; Herraiz-Borreguero et al., 2016; Raiswell et al.,

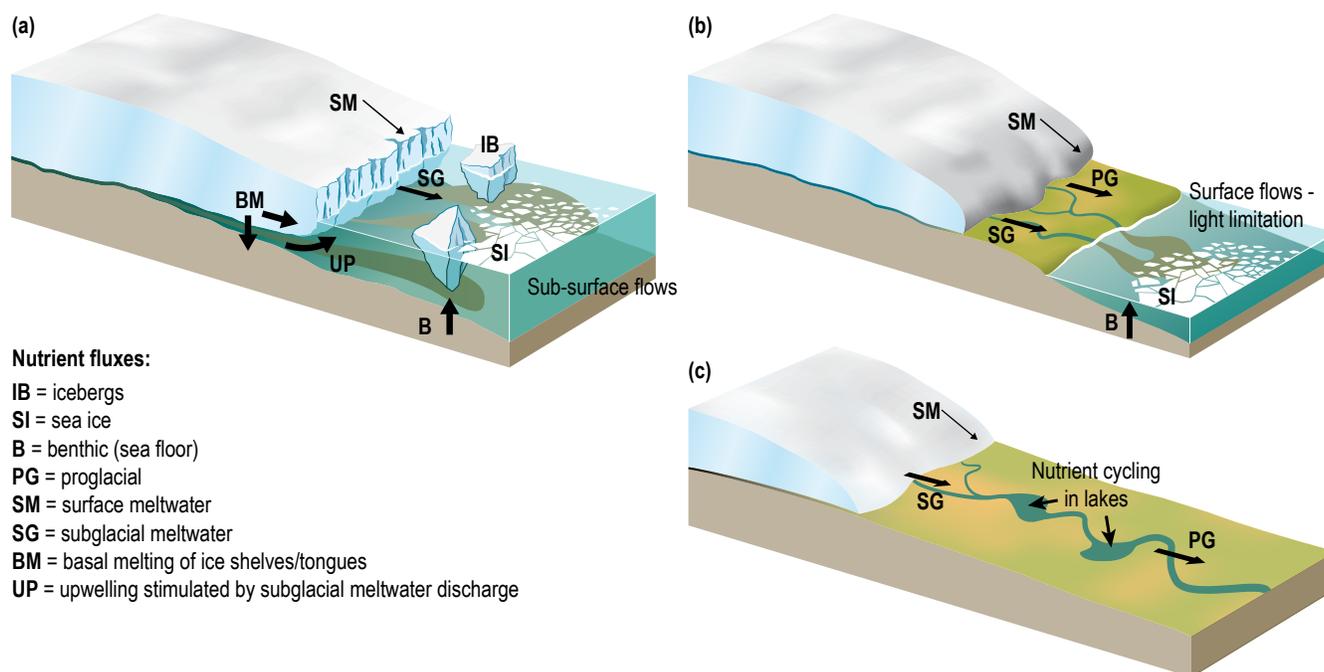


Figure 3.9 | Potential shifts in nutrient fluxes with landward retreat of marine-terminating glaciers (a) at different stages (b and c).

2016; Yager et al., 2016; Hodson et al., 2017), in addition to indirectly stimulating nutrient input via upwelling associated with subglacial meltwater plumes (Meire et al., 2016b; Cape et al., 2018; Hopwood et al., 2018; Kanna et al., 2018) (Figure 3.9). These nutrient additions stimulate primary production in the surrounding ocean waters in some regions (*medium confidence*) (Gerringa et al., 2012; Death et al., 2014; Duprat et al., 2016; Arrigo et al., 2017b). There is also some evidence to support melting ice sheets as source of contaminants (AMAP, 2015).

In Greenland, direct measurements suggest that meltwater is a significant source of bioavailable silica and iron (Bhatia et al., 2013; Hawkings et al., 2014; Meire et al., 2016a; Hawkings et al., 2017) but may be less important for the supply of bioavailable forms of dissolved nitrogen or phosphorous (Hawkings et al., 2016; Wadham et al., 2016), which often limit the integrated primary production during summer in fjords (Meire et al., 2016a; Hopwood et al., 2018). The offshore export of iron, however, has been linked to primary productivity in surface ocean waters in the Labrador Sea (Arrigo et al., 2017b) (*limited evidence, high agreement*).

Subglacial meltwater plumes from tidewater glaciers have emerged recently as an important indirect source of nutrients to fjords, by entraining nutrient-replete seawater (Meire et al., 2016b; Meire et al., 2017; Cape et al., 2018; Hopwood et al., 2018; Kanna et al., 2018) (*medium evidence, high agreement*). There is *medium evidence with high agreement* that these upwelled nutrient fluxes enhance primary production in fjords over a distance of up to 100 km along the trajectory of the outflowing plume (Juul-Pedersen et al., 2015; Cape et al., 2018; Kanna et al., 2018).

In Antarctica, there is *medium evidence with high agreement* that enhanced input of iron from ice shelves, glacial meltwater and icebergs stimulates primary production in polynyas, coastal regions

and the wider Southern Ocean (Gerringa et al., 2012; Shadwick et al., 2013; Herraiz-Borreguero et al., 2016). Satellite observations and modelling also indicate variable potential for icebergs to fertilise the Southern Ocean beyond the coastal zone (Death et al., 2014; Duprat et al., 2016; Wu and Hou, 2017).

Dissolved nutrient fluxes from ice sheets may be increasing during high melt years (Hawkings et al., 2015). The dominant sediment-bound fraction, however, may not increase with rising melt (Hawkings et al., 2015). Thus, there is *low confidence* overall in the magnitude of the response of direct nutrient fluxes from ice sheets to enhanced melting.

Future predictions of nutrient cycling proximal to ice sheets is made more challenging by the landward progression of marine-terminating glaciers and the collapse of ice shelves (Cook et al., 2016). This has the potential to drive major shifts in nutrient supply to coastal waters (Figure 3.9). The erosion of newly exposed glacial sediments in front of retreating land-terminating glaciers (Monien et al., 2017) and changes in the diffuse nutrient fluxes from newly exposed glacial sediments on the seafloor (Wehrmann et al., 2014) may amplify nutrient supply, whilst other nutrient sources may be cut off (e.g., icebergs, upwelling of marine water; Meire et al., 2017) (*low confidence*).

There is *medium evidence with high agreement* that long-term tidewater glacier retreat into shallower water or onto land, a plausible scenario for about 55% of the 243 distinct outlet glaciers in Greenland (Morlighem et al., 2017), will reduce or diminish upwelling a source of nutrients, thereby reducing summer productivity in Greenland fjord ecosystems (Meire et al., 2017; Hopwood et al., 2018).

3.3.3.4 Ecosystems

For Greenland and Svalbard, there is *limited evidence with high agreement* that the retreat of marine-terminating glaciers will alter food supply to higher trophic levels of marine food webs (Meire et al., 2017; Milner et al., 2017). The consequences of changes in glacial systems on marine ecosystems are often mediated via the fjordic environments that fringe the edge of the ice sheets, for example changing physical-chemical conditions have affected the benthic ecosystems of Arctic fjords (Bourgeois et al., 2016). The amplification of nutrient fluxes caused by enhanced upwelling at calving fronts (Meire et al., 2017), combined with high carbon/nutrient burial and recycling rates (Wehrmann et al., 2013; Smith et al., 2015), plays an important role in sustaining high productivity of the Arctic fjord ecosystems of Greenland and Svalbard (Lydersen et al., 2014). Glacier retreat, causing glaciers to shift from being marine-terminating to land-terminating, can reduce the productivity in coastal areas off Greenland with potentially large ecological implications, also negatively affecting production of commercially harvested fish (Meire et al., 2017). There is also evidence that marine-terminating glaciers are important feeding areas for marine mammals and seabirds at Greenland (Laidre et al., 2016) and Svalbard (Lydersen et al., 2014).

For Antarctica, there is *high agreement* based on *medium evidence* that ice shelf retreat or collapse is leading to new marine habitats and to biological colonisation (Gutt et al., 2011; Fillinger et al., 2013; Trathan et al., 2013; Hauquier et al., 2016; Ingels et al., 2018). The loss of ice shelves and retreat of coastal glaciers around the AP in the last 50 years has exposed at least 2.4×10^4 km² of new open water. These newly-revealed habitats have allowed new phytoplankton blooms to be produced resulting in new marine zooplankton and seabed communities (Gutt et al., 2011; Fillinger et al., 2013; Trathan et al., 2013; Hauquier et al., 2016) (Section 3.2.3.2.1), and have resulted in enhanced carbon uptake by coastal marine ecosystems (*medium confidence*), although quantitative estimates of biological carbon uptake are highly variable (Trathan et al., 2013; Barnes et al., 2018). Newly available habitat on coastlines may also provide breeding or haul out sites for land-based predators such as penguins and seals (Trathan et al., 2013) (*low confidence*). Fjords that have been studied in the subpolar western AP are hotspots of abundance and biodiversity of benthic macro-organisms (Grange and Smith, 2013) and there is evidence that glacier retreat in these environments can impact the structure and function of benthic communities (Moon et al., 2015; Sahade et al., 2015) (*low confidence*).

Cross-Chapter Box 8 | Future Sea Level Changes and Marine Ice Sheet Instability

Authors: Robert M. DeConto (USA), Alexey Ekaykin (Russian Federation), Andrew Mackintosh (Australia), Roderik van de Wal (Netherlands), Jeremy Bassis (USA)

Over the last century, glaciers were the main contributors to increasing ocean water mass (Section 4.2.1.2). However, most terrestrial frozen water is stored in Antarctic and Greenland ice sheets, and future changes in their dynamics and mass balance will cause sea level rise over the 21st century and beyond (Section 4.2.3).

About a third of the Antarctic Ice Sheet (AIS) is 'marine ice sheet', i.e., rests on bedrock below sea level (Figure 4.5), with most of the ice sheet margin terminating directly in the ocean. These features make the overlying ice sheet vulnerable to dynamical instabilities with the potential to cause rapid ice loss; so-called Marine Ice Sheet and Marine Ice Cliff instabilities, as discussed below.

In many places around the AIS margin, the seaward-flowing ice forms floating ice shelves (Figure CB8.1). Ice shelves in contact with bathymetric features on the sea floor or confined within embayments provide back stress (buttressing) that impedes the seaward flow of the upstream ice and thereby stabilises the ice sheet. The ice shelves are thus a key factor controlling AIS dynamics. Almost all Antarctic ice shelves provide substantial buttressing (Fürst et al., 2016) but some are currently thinning at an increasing rate (Khazendar et al., 2016). Today, thinning and retreat of ice shelves is associated primarily with ocean driven basal melt that, in turn, promotes iceberg calving (Section 3.3.1.2).

Accumulation and percolation of surface melt and rain water also impact ice shelves by lowering albedo, deepening surface crevasses, and causing flexural stresses that can lead to hydrofracturing and ice shelf collapse (Macayeal and Sergienko, 2013). In some cases supraglacial (i.e., flowing on the glacier surface) rivers might diminish destabilising impact of surface melt by removing meltwater before it ponds on the ice shelf surface (Bell et al., 2017). In summary, both ocean forcing and surface melt affect ice shelf mechanical stability (*high confidence*), but the precise importance of the different mechanisms remains poorly understood and observed.

The future dynamic response of the AIS to warming will largely be determined by changes in ice shelves, because their thinning or collapse will reduce their buttressing capacity, leading to an acceleration of the grounded ice and to thinning of the ice margin. In turn, this thinning can initiate grounding line retreat (Konrad et al., 2018). If the grounding line is located on bedrock sloping downwards toward the ice sheet interior (retrograde slope), initial retreat can trigger a positive feedback, due to non-linear response of the seaward ice flow to the grounding line thickness change. As a result, progressively more ice will flow into the ocean (Figure CB8.1a).

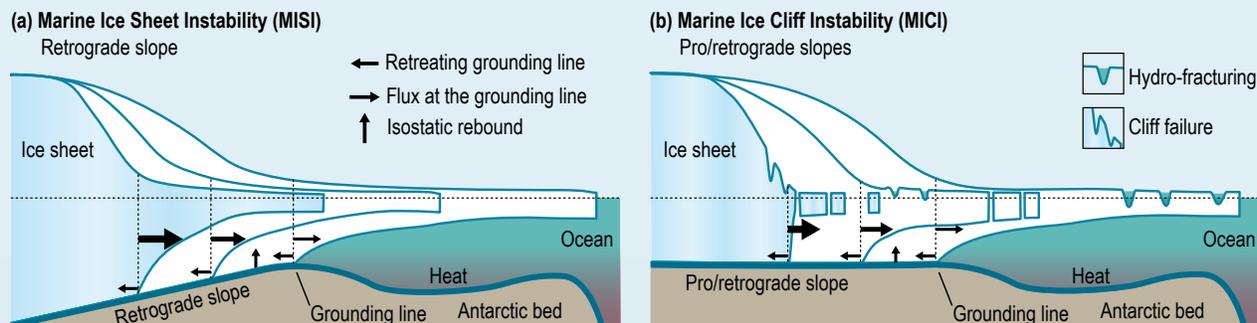


Figure CB8.1 | Schematic representation of Marine Ice Sheet Instability (MISI, a) and Marine Ice Cliff Instability (MICI, b) from Pattyn (2018). **(a)** thinning of the buttressing ice shelf leads to acceleration of the ice sheet flow and thinning of the marine-terminated ice margin. Because bedrock under the ice sheet is sloping towards ice sheet interior, thinning of the ice causes retreat of the grounding line followed by an increase of the seaward ice flux, further thinning of the ice margin, and further retreat of the grounding line. **(b)** disintegration of the ice shelf due to bottom melting and/or hydro-fracturing produces an ice cliff. If the cliff is tall enough (at least ~800 m of total ice thickness, or about 100 m of ice above the water line), the stresses at the cliff face exceed the strength of the ice, and the cliff fails structurally in repeated calving events. Note that MISI requires a retrograde bed slope, while MICI can be realised on a flat or seaward-inclined bed. Like MISI, the persistence of MICI depends on the lack of ice shelf buttressing, which can stop or slow brittle ice failure at the grounding line by providing supportive backstress.

This self-sustaining process is known as Marine Ice Sheet Instability (MISI). The onset and persistence of MISI is dependent on several factors in addition to overall bed slope, including the details of the bed geometry and conditions, ice shelf pinning points, lateral shear from the walls, self-gravitation effects on local sea level and isostatic adjustment. Hence, long-term retreat on every retrograde sloped bed is not necessarily unstoppable (Gomez et al., 2015).

The MISI process might be particularly important in West Antarctica, where most of the ice sheet is grounded on bedrock below sea level (Figure 4.5). Since AR5, there is growing observational and modelling evidence that accelerated retreat may be underway in several major Amundsen Sea outlets, including Thwaites, Pine Island, Smith, and Kohler glaciers (e.g., Rignot et al., 2014) supporting the MISI hypothesis, although observed grounding line retreat on retrograde slope is not definitive proof that MISI is underway.

It has been shown recently (Barletta et al., 2018) that the Amundsen Sea Embayment (ASE) experiences unexpectedly fast bedrock uplift (up to 41 mm yr^{-1} , due to mantle viscosity much lower than the global average) as an adjustment to reduced ice mass loading, which could help stabilise grounding line retreat.

One of the largest outlets of the East Antarctic Ice Sheet (EAIS), Totten glacier, has also been retreating and thinning in recent decades (Li et al., 2015b). Totten's current behaviour suggests that East Antarctica could become a substantial contributor to future sea level rise, as it has been in the previous warm periods (Aitken et al., 2016). It is not clear, however, if the changes observed recently are a linear response to increased ocean forcing (Section 3.3.1.2), or an indication that MISI has commenced (Roberts et al., 2018).

The disappearance of ice shelves may allow the formation of ice cliffs, which may be inherently unstable if they are tall enough (subaerial cliff height between 100 and 285 m) to generate stresses that exceed the strength of the ice (Parizek et al., 2019). This ice cliff failure can lead to ice sheet retreat via a process called marine ice cliff instability (MICI; Figure CB8.1b), that has been hypothesised to cause partial collapse of the West Antarctic Ice Sheet (WAIS) within a few centuries (Pollard et al., 2015; DeConto and Pollard, 2016).

Limited evidence is available to confirm the importance of MICI. In Antarctica, marine-terminating ice margins with the grounding lines thick enough to produce unstable ice cliffs are currently buttressed by ice shelves, with a possible exception of Crane glacier on the Antarctic Peninsula (Section 4.2.3.1.2).

Overall, there is *low agreement* on the exact MICI mechanism and *limited evidence* of its occurrence in the present or the past. Thus the potential of MICI to impact the future sea level remains very uncertain (Edwards et al., 2019).

Limited evidence from geological records and ice sheet modelling suggests that parts of AIS experienced rapid (i.e., on centennial time-scale) retreat *likely* due to ice sheet instability processes between 20,000 and 9,000 years ago (Golledge et al., 2014; Weber et al., 2014; Small et al., 2019). Both the WAIS (including Pine Island glacier) and EAIS also experienced rapid thinning and

Cross-Chapter Box 8 (continued)

grounding line retreat during the early to mid-Holocene (Jones et al., 2015b; Wise et al., 2017). In the Ross Sea, grounding lines may have retreated several hundred kilometers inland and then re-advanced to their present-day positions due to bedrock uplift after ice mass removal (Kingslake et al., 2018), thus supporting the stabilising role of glacial isostatic adjustment on ice sheets (Barletta et al., 2018). These past rapid changes have *likely* been driven by the incursion of Circumpolar Deep Water onto the Antarctic continental shelf (Section 3.3.1.5.1) (Golledge et al., 2014; Hillenbrand et al., 2017) and MISI (Jones et al., 2015b). *Limited evidence* of past MICI in Antarctica is provided by deep iceberg plough marks on the sea-floor (Wise et al., 2017).

The ability of models to simulate the processes controlling MISI has improved since AR5 (Pattyn, 2018), but significant discrepancies in projections remain (Section 4.2.3.2) due to poor understanding of mechanisms and lack of observational data on bed topography, isostatic rebound rates, etc. to constrain the models. Inclusion of MICI in one ice sheet model has improved its ability to match (albeit uncertain) geological sea level targets in the Pliocene (Pollard et al., 2015) and Last Interglacial (DeConto and Pollard, 2016), although the MICI solution may not be unique (Aitken et al., 2016) (Section 4.2.3.1.2).

The Greenland Ice Sheet (GIS) has limited direct access to the ocean through relatively narrow subglacial troughs (Morlighem et al., 2017), and most of the bedrock at the ice sheet margin is above sea level (Figure 4.5). However, since AR5 it has been argued that several Greenland outlet glaciers (Petermann, Kangerdlugssuaq, Jakobshavn Isbræ, Helheim, Zachariæ Isstrøm) and North-East Greenland Ice Stream may contribute more than expected to future sea level rise (Mouginot et al., 2015). It has also been shown that Greenland was nearly ice free for extensive episodic periods during the Pleistocene, suggesting a sensitivity to deglaciation under climates similar to or slightly warmer than present (Schaefer et al., 2016).

A MICI-style behaviour is seen today in Greenland at the termini of Jakobshavn and Helheim glaciers (Parizek et al., 2019), but calving of these narrow outlets is controlled by a combination of ductile and brittle processes, which might not be representative examples of much wider Antarctic outlet glaciers, like Thwaites.

Overall, this assessment finds that unstable retreat and thinning of some Antarctic glaciers, and to a lesser extent Greenland outlet glaciers, may be underway. However, the timescale and future rate of these processes is not well known, casting deep uncertainty on projections of the sea level contributions from the AIS (Cross-Chapter Box 5 in Chapter 1, Section 4.2.3.1).

3.4 Arctic Snow, Freshwater Ice and Permafrost: Changes, Consequences and Impacts

3.4.1 Observations

3.4.1.1 Seasonal Snow Cover

Terrestrial snow cover is a defining characteristic of the Arctic land surface for up to nine months each year, with changes influencing the surface energy budget, ground thermal regime and freshwater budget. Snow cover also interacts with vegetation, influences biogeochemical activity and affects habitats and species, with consequences for ecosystem services. Arctic land areas are almost always completely snow covered in winter, so the transition seasons of autumn and spring are key when characterising variability and change.

3.4.1.1.1 Extent and duration

Dramatic reductions in Arctic (land areas north of 60°N) spring snow cover extent have occurred since satellite charting began in 1967 (Estilow et al., 2015). Declines in May and June of -3.5% ($\pm 1.9\%$) and -13.4% respectively per decade ($\pm 5.4\%$) between 1967 and 2018 (relative to the 1981–2010 mean) were determined from

multiple datasets based on the methodology of (Mudryk et al., 2017) (Figure 3.10) (*high confidence*). The loss of spring snow extent is reflected in shorter snow cover duration estimated from surface observations (Bulygina et al., 2011; Brown et al., 2017), satellite data (Wang et al., 2013; Estilow et al., 2015; Anttila et al., 2018), and model-based analyses (Liston and Hiemstra, 2011) (*high confidence*). These trends range between -0.7 and -3.9 days per decade depending on region and time period, but all spring snow cover duration trends from all datasets are negative (Brown et al., 2017). These same multi-source datasets also identify reductions in autumn snow extent and duration (-0.6 to -1.4 days per decade; summarized in Brown et al., 2017) (*high confidence*). There is *low confidence* in positive October and November snow cover extent trends apparent in a single dataset (Hernández-Henríquez et al., 2015) because they are not replicated in other surface, satellite and model datasets (Brown and Derksen, 2013; Mudryk et al., 2017).

3.4.1.1.2 Depth and water equivalent

Weather station observations across the Russian Arctic identify negative trends in the maximum snow depth between 1966 and 2014 (Bulygina et al., 2011; Osokin and Sosnovsky, 2014). There is *medium confidence* in this trend because the pointwise nature of these measurements does not capture prevailing conditions across

the landscape. Seasonal maximum snow depth trends over the North American Arctic are mixed and largely statistically insignificant (Vincent et al., 2015; Brown et al., 2017). The timing of maximum snow depth has shifted earlier by 2.7 days per decade for the North American Arctic (Brown et al., 2017); comparable analysis is not available for Eurasia. Gridded products from remote sensing and land surface models identify negative trends in snow water equivalent between 1981 and 2016 for both the Eurasian and North American sectors of the Arctic (Brown et al., 2017). While the snow water equivalent anomaly time series show reasonable consistency between products when averaged at the continental scale, considerable inter-dataset variability in the spatial patterns of change (Liston and Hiemstra, 2011; Park et al., 2012; Brown et al., 2017) mean there is only *medium confidence* in these trends.

3.4.1.1.3 Drivers

Despite uncertainties due to sparse observations (Cowtan and Way, 2014), surface temperature has increased across Arctic land areas in recent decades (Hawkins and Sutton, 2012; Fyfe et al., 2013), driving reductions in Arctic snow extent and duration (*high confidence*). Changes in Arctic snow extent can be directly related to extratropical temperature increases (Brutel-Vuilmet et al., 2013; Thackeray et al., 2016; Mudryk et al., 2017). Based on multiple historical datasets, there is a consistent temperature sensitivity for Arctic snow extent, with approximately 800,000 km² of snow cover lost per degrees Celsius warming in spring (Brown and Derksen, 2013; Brown et al., 2017), and 700,000–800,000 km² lost in autumn (Derksen and Brown, 2012; Brown and Derksen, 2013) (*high confidence*).

There is *high confidence* that darkening of snow through the deposition of black carbon and other light absorbing particles enhances snow melt (Bullard et al., 2016; Skiles et al., 2018; Boy et al., 2019). The global direct radiative forcing for black carbon in seasonal snow and over sea ice is estimated to be 0.04 W m⁻², but the effective forcing can be up to threefold greater at regional scales due to the enhanced albedo feedback triggered by the initial darkening (Bond et al., 2013). Lawrence et al. (2011) estimate the present-day radiative effect of black carbon and dust in land-based snow to be 0.083 W m⁻², only marginally greater than the simulated 1850 effect (0.075 W m⁻²) due to offsetting effects from increased black carbon emissions and reductions in dust darkening (*medium confidence*). Kylling et al. (2018) estimate a surface radiative effect of 0.292 W m⁻² caused by dust deposition (largely transported from Asia) to Arctic snow, approximately half of the black carbon central scenario estimate of Flanner et al. (2007). The forcing from brown carbon deposited in snow (associated with both combustion and secondary organic carbon) is estimated to be 0.09–0.25 W m⁻², with the range due to assumptions of particle absorptivity (Lin et al., 2014) (*low confidence*).

Precipitation remains a sparse and highly uncertain measurement over Arctic land areas: *in situ* datasets remain uncertain (Yang, 2014) and are largely regional (Kononova, 2012; Vincent et al., 2015). Atmospheric reanalyses show increases in Arctic precipitation in recent decades (Lique et al., 2016; Vihma et al., 2016), but there remains *low confidence* in reanalysis-based closure of the Arctic freshwater budget due to a wide spread between available reanalysis derived

precipitation estimates (Lindsay et al., 2014). Despite improved process understanding, estimates of sublimation loss during blowing snow events remain a key uncertainty in the mass budget of the Arctic snowpack (Sturm and Stuefer, 2013).

3.4.1.2 Permafrost

3.4.1.2.1 Temperature

Record high temperatures at ~10–20 m depth in the permafrost (near or below the depths affected by intra-annual fluctuation in temperature) have been documented at many long-term monitoring sites in the Northern Hemisphere circumpolar permafrost region (AMAP, 2017d) (Figure 3.10) (*very high confidence*). At some locations, the temperature is 2°C–3°C higher than 30 years ago. During the decade between 2007 and 2016, the rate of increase in permafrost temperatures was 0.39°C ± 0.15°C for colder continuous zone permafrost monitoring sites, 0.20°C ± 0.10°C for warmer discontinuous zone permafrost, giving a global average of 0.29 ± 0.12°C across all polar and mountain permafrost (Biskaborn et al., 2019). Relatively smaller increases in permafrost temperature in warmer sites indicate that permafrost is thawing with heat absorbed by the ice-to-water phase change, and as a result, the active layer may be increasing in thickness. In contrast to temperature, there is only *medium confidence* that active layer thickness across the region has increased. This confidence level is because decadal trends vary across regions and sites (Shiklomanov et al., 2012) and because mechanical probing of the active layer can underestimate the degradation of permafrost in some cases because the surface subsides when ground ice melts and drains (Mekonnen et al., 2016; AMAP, 2017d; Streletskiy et al., 2017). Permafrost in the Southern Hemisphere polar region occurs in ice-free exposed areas (Bockheim et al., 2013), 0.18% of the total land area of Antarctica (Burton-Johnson et al., 2016). This area is three orders of magnitude smaller than the 13–18 × 10⁶ km² area underlain by permafrost in the Northern Hemisphere terrestrial permafrost region (Gruber, 2012). Antarctic permafrost temperatures are generally colder (Noetzi et al., 2017) and increased 0.37°C ± 0.10°C between 2007 and 2016 (Biskaborn et al., 2019).

3.4.1.2.2 Ground ice

Permafrost thaw and loss of ground ice causes the land surface to subside and collapse into the volume previously occupied by ice, resulting in disturbance to overlying ecosystems and human infrastructure (Kanevskiy et al., 2013; Reynolds et al., 2014). Excess ice in permafrost is typical, varying for example from 40% of total volume in some sands up to 80–90% of total volume in fine-grained soil/sediments (Kanevskiy et al., 2013). Ice rich permafrost areas where impacts of thaw could be greatest include the Yedoma deposits in Siberia, Alaska, and the Yukon in Canada, with ice divided between massive wedges interspersed with frozen soil/sediment containing pore ice and smaller ice features (Schirmer et al., 2011; Strauss et al., 2017). Other areas including, for example, Northwestern Canada, the Canadian Archipelago, the Yamal and Gydan peninsulas of West Siberia, and smaller portions of Eastern Siberia and Alaska contain buried glacial ice bodies of significant thickness and extent (Lantuit

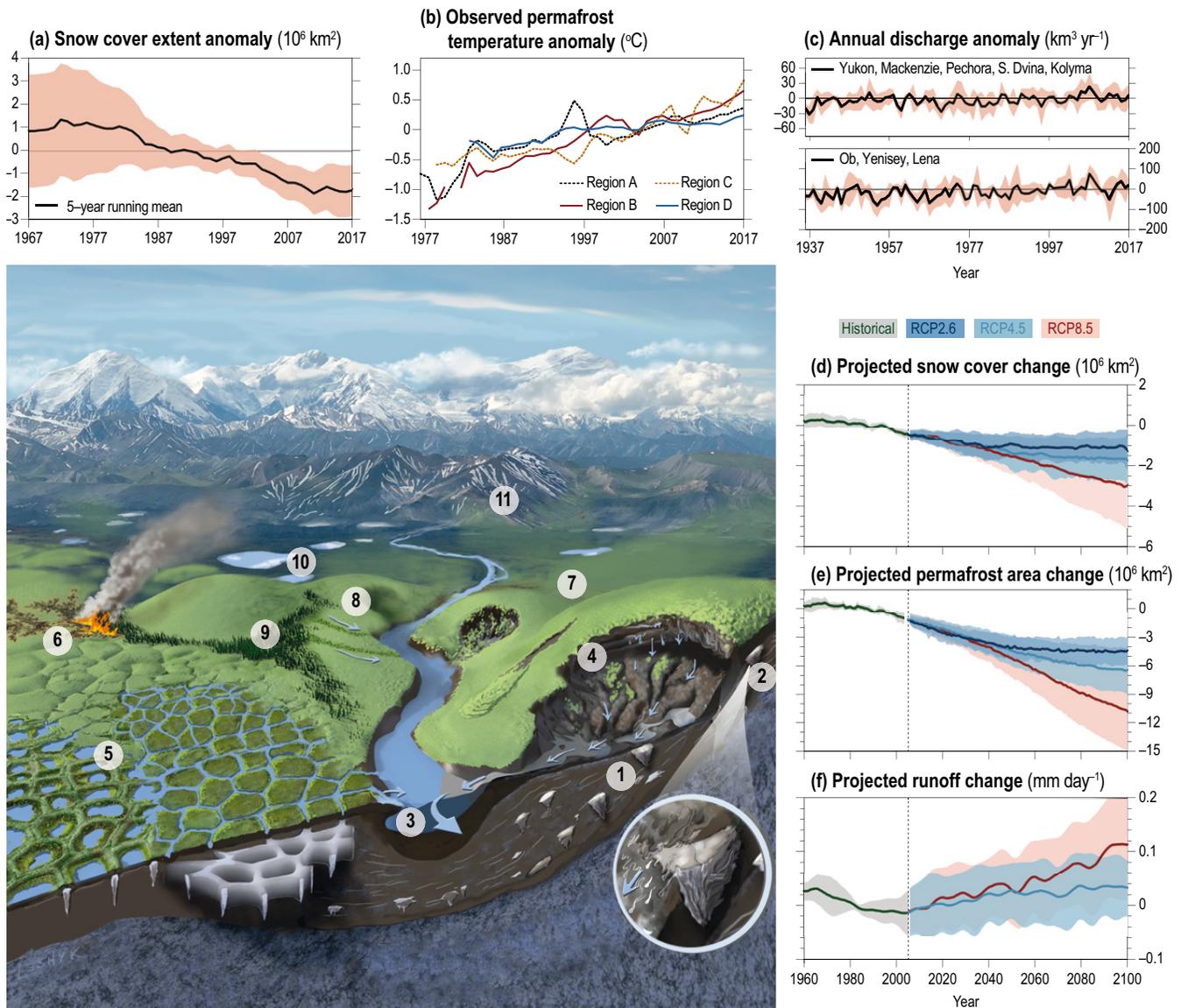


Figure 3.10 | Schematic of important land surface components influenced by the Arctic terrestrial cryosphere: permafrost (1); ground ice (2); river discharge (3); abrupt thaw (4); surface water (5); fire (6); tundra (7); shrubs (8); boreal forest (9); lake ice (10); seasonal snow (11). Time series of snow cover extent anomalies in June (relative to 1981–2010 climatology) from 5 products based on the approach of Mudryk et al. (2017) (a); permafrost temperature change normalised to a baseline period (Romanovsky et al., 2017), Region A: Continuous to discontinuous permafrost in Scandanavia, Svalbard, and Russia/Siberia, Region B: Cold continuous permafrost in northern Alaska, Northwest Territories, and NE Siberia, Region C: Cold continuous permafrost in Eastern and High Arctic Canada, Region D: Discontinuous permafrost in Interior Alaska and Northwest Canada (b), and runoff from northern flowing watersheds normalised to a baseline period (1981–2010) (Holmes et al., 2018), multi-station average (± 1 standard deviation) (c). Coupled Model Intercomparison Project Phase 5 (CMIP5) multi-model average (± 1 standard deviation) projections for different Representative Concentration Pathway (RCP) scenarios for June snow cover extent change (based on Thackeray et al., 2016) (d), area change of near-surface permafrost (e), and runoff change to the Arctic Ocean (based on McGuire et al., 2018) (f).

and Pollard, 2008; Leibman et al., 2011; Kokelj et al., 2017; Coulombe et al., 2019). The location and volume of ground ice integrated across the northern permafrost region ($5.63\text{--}36.55 \times 10^3 \text{ km}^3$, equivalent to 2–10 cm sea level rise) is known with *medium confidence* and with no recent updates at the circumpolar scale (Zhang et al., 2008).

3.4.1.2.3 Carbon

The permafrost region represents a large, climate sensitive reservoir of organic carbon with the potential for some of this pool to be rapidly decayed and transferred to the atmosphere as CO₂ and methane as

permafrost thaws in a warming climate, thus accelerating the pace of climate change (Schuur et al., 2015). The current best mean estimate of total (surface plus deep) organic soil carbon (terrestrial) in the northern circumpolar permafrost region ($17.8 \times 10^6 \text{ km}^2$ area) is 1460 to 1600 petagrams (*medium confidence*) (Pg; 1 Pg = 1 billion metric tonnes) (Schuur et al., 2018). All permafrost region soils estimated to 3 m in depth (surface) contain $1035 \pm 150 \text{ Pg C}$ (Tarnocai et al., 2009; Hugelius et al., 2014) (*high confidence*). Of the carbon in the surface, 800–1000 Pg C is perennially frozen, with the remainder contained in seasonally-thawed soils. The northern circumpolar permafrost region occupies only 15% of the total global soil area,

but the 1035 Pg C adds another 50% to the rest of the 3 m soil carbon inventory (2050 Pg C for all global biomes excluding tundra and boreal; Jobbágy and Jackson, 2000; Schuur et al., 2015).

Substantial permafrost carbon exists below 3 m depth (*medium confidence*). Deep carbon (>3 m) has been best quantified for the Yedoma region of Siberia and Alaska, characterised by wind- and water-moved permafrost sediments tens of meters thick. The Yedoma region covers a 1.4×10^6 km² area that remained ice-free during the last Ice Age (Strauss et al., 2013) and accounts for 327–466 Pg C in deep sediment accumulations below 3 m (Strauss et al., 2017).

The current inventory has also highlighted additional carbon pools that are likely to be present but are so poorly quantified (*low confidence*) that they cannot yet be added into the number reported above. There are deep terrestrial soil/sediment deposits outside of the Yedoma region that may contain about 400 Pg C (Schuur et al., 2015). An additional pool is organic carbon remaining in permafrost but that is now submerged on shallow Arctic sea shelves that were formerly exposed as terrestrial ecosystems during the Last Glacial Maximum ~20,000 years ago (Walter et al., 2007). This permafrost is degrading slowly due to seawater intrusion, and it is not clear what amounts of permafrost and organic carbon still remain in the sediment versus what has already been converted to greenhouse gases. A recent synthesis of permafrost extent for the Beaufort Sea shelf showed that most remaining subsea permafrost in that region exists near shore with much reduced area (*high confidence*) as compared to original subsea permafrost maps that outlined the entire 3×10^6 km² shelf area (<120 m below sea level depth) that was formerly exposed as land (Ruppel et al., 2016). These observations are supported by similar studies in the Siberian Arctic Seas (Portnov et al., 2013), and by modelling that suggests that subsea permafrost would be thawed many meters below the seabed under current submerged conditions (Anisimov et al., 2012; AMAP, 2017d; Angelopoulos et al., 2019).

3.4.1.2.4 Drivers

Changes in temperature and precipitation act as gradual 'press' (i.e., continuous) disturbances that directly affect permafrost by modifying the ground thermal regime, as discussed in Section 3.4.1.2.1. Climate change can also modify the occurrence and magnitude of abrupt physical disturbances such as fire, and soil subsidence and erosion resulting from ice rich permafrost thaw (thermokarst). These 'pulse' (i.e., discrete) disturbances (Smith et al., 2009) often are part of the ongoing disturbance and successional cycle in Arctic and boreal ecosystems (Grosse et al., 2011), but changing rates of occurrence alter the landscape distribution of successional ecosystem states, with permafrost characteristics defined by the ecosystem and climate state (Kanevskiy et al., 2013).

Pulse disturbances often rapidly remove the insulating soil organic layer, leading to permafrost degradation (Gibson et al., 2018). Of all pulse disturbance types, wildfire affects the most high-latitude land area annually at the continental scale. In some well-studied regions, there is *high confidence* that area burned, fire frequency and extreme fire years are higher now than the first half of the last century, or even the last 10,000 years (Kasischke and Turetsky, 2006; Flannigan

et al., 2009; Kelly et al., 2013; Hanes et al., 2019). Recent climate warming has been linked to increased wildfire activity in the boreal forest regions in Alaska and western Canada where this has been studied (Gillett, 2004; Veraverbeke et al., 2017). Based on satellite imagery, an estimated 80,000 km² of boreal area was burned globally per year from 1997 to 2011 (van der Werf et al., 2010; Giglio et al., 2013). Extreme fire years in northwest Canada during 2014 and Alaska during 2015 doubled the long-term (1997–2011) average area burned annually in this region (Canadian Forest Service, 2017), surpassing Eurasia to contribute 60% of the global boreal area burned (van der Werf et al., 2010; Randerson et al., 2012; Giglio et al., 2013). These extreme North American fire years were balanced by lower-than-average area burned in Eurasian forests, resulting in a 5% overall increase in global boreal area burned. The annual area burned in Arctic tundra is generally small compared to the forested boreal biome. In Alaska – the only region where estimates of burned area exist for both boreal forest and tundra vegetation types – tundra burning averaged approximately 270 km² yr⁻¹ during the last half century (French et al., 2015), accounting for 7% of the average annual area burned throughout the state (Pastick et al., 2017). There is *high confidence* that changes in the fire regime are degrading permafrost faster than had occurred over the historic successional cycle (Turetsky et al., 2011; Rupp et al., 2016; Pastick et al., 2017), and that the effect of this driver of permafrost change is under-represented in the permafrost temperature observation network.

Abrupt permafrost thaw occurs when changing environmental and ecological conditions interact with geomorphological processes. Melting ground ice causes the ground surface to subside. Pooling or flowing water causes localised permafrost thaw and sometimes mass erosion. Together, these localised feedbacks can thaw through meters of permafrost within a short time, much more rapidly than would be caused by increasing air temperature alone. This process is a pulse disturbance to permafrost that can occur in response to climate, such as an extreme precipitation event (Balsler et al., 2014; Kokelj et al., 2015), or coupled with other disturbances such as wildfire that affects the ground thermal regime (Jones et al., 2015a). There is *medium confidence* in the importance of abrupt thaw for driving change in permafrost at the circumpolar scale because it occurs at point locations rather than continuously across the landscape, but the risk for widespread change from this mechanism remains high because of the rapidity of change in these locations (Kokelj et al., 2017; Nitze et al., 2018). New research at the global scale has revealed that 3.6×10^6 km², about 20% of the northern permafrost region, appears to be vulnerable to abrupt thaw (Olefeldt et al., 2016).

3.4.1.3 Freshwater Systems

There is increasing awareness of the influence of a changing climate on freshwater systems across the Arctic, and associated impacts on hydrological, biogeophysical and ecological processes (Prowse et al., 2015; Walvoord and Kurylyk, 2016), and northern populations (Takakura, 2018) (Section 3.4.3.3.1). Assessing these impacts requires consideration of complex interconnected processes, many of which are incompletely observed. The increasing imprint of human development,

such as flow regulation on major northerly flowing rivers adds complexity to the determination of climate-driven changes.

3.4.1.3.1 Freshwater ice

Long-term *in situ* river ice records indicate that the duration of ice cover in Russian Arctic rivers decreased by 7–20 days between 1955 and 2012 (Shiklomanov and Lammers, 2014) (*high confidence*). This is consistent with historical reductions in Arctic river ice cover derived from models (Park et al., 2015) and regional analysis of satellite data (Cooley and Pavelsky, 2016).

Analysis of satellite imagery between 2000 and 2013 identified a significant trend of earlier spring ice break-up across all regions of the Arctic (Šmejkalová et al., 2016); independent satellite data showed approximately 80% of Arctic lakes experienced declines in ice cover duration during 2002–2015, due to both a later freeze-up and earlier break-up (Du et al., 2017) (*high confidence*). There are indications that lake ice across Alaska has thinned in recent decades (Alexeev et al., 2016), but ice thickness trends are not available at the pan-Arctic scale. Analysis of satellite data over northern Alaska show that approximately one-third of bedfast lakes (the entire water volume freezes by the end of winter) experienced a regime change to floating ice over the 1992–2011 period (Surdu et al., 2014; Arp et al., 2015). This can result in degradation of underlying permafrost (Arp et al., 2016; Bartsch et al., 2017). Lakes of the central and eastern Canadian High Arctic are transitioning from a perennial to seasonal ice regime (Surdu et al., 2016).

3.4.1.3.2 Runoff and surface water

A general trend of increasing discharge has been observed for large Siberian (Troy et al., 2012; Walvoord and Kurylyk, 2016) and Canadian (Ge et al., 2013; Déry et al., 2016) rivers that drain to the Arctic Ocean (*medium confidence*). Between 1976 and 2017, trends are $3.3 \pm 1.6\%$ for Eurasian rivers and $2.0 \pm 1.8\%$ for North American rivers (Holmes et al., 2018) (Figure 3.10). Extreme regional runoff events have also been identified (Stuefer et al., 2017). An observed increase in baseflow in the North American (Walvoord and Striegl, 2007; St. Jacques and Sauchyn, 2009) and Eurasian Arctic (Smith et al., 2007; Duan et al., 2017) over the last several decades is attributable to permafrost thaw and concomitant enhancement in groundwater discharge. The timing of spring season peak flow is generally earlier (Ge et al., 2013; Holmes et al., 2015). There is consistent evidence of decreasing summer season discharge for the Yenisei, Lena, and Ob watersheds in Siberia (Ye et al., 2003; Yang et al., 2004a; Yang et al., 2004b) and the majority of northern Canadian rivers (Déry et al., 2016). Long-term records indicate water temperature increases (Webb et al., 2008; Yang and Peterson, 2017); attribution to rising air temperatures is complicated by the influence of reservoir regulation over Siberian regions (Liu et al., 2005; Lammers et al., 2007). Increases in discharge and water temperature in the spring season represent notable freshwater and heat fluxes to the Arctic Ocean (Yang et al., 2014).

A large proportion of low-lying Arctic land areas are covered by lakes because permafrost limits surface water drainage and supports ponding even across areas with high moisture deficits (Grosse

et al., 2013). While thaw in continuous permafrost is linked to intensified thermokarst activity and subsequent ponding (resulting in lake/wetland expansion), observations of change in surface water coverage across the Arctic are regionally variable (Nitze et al., 2017; Ulrich et al., 2017; Pastick et al., 2019). In landscapes with degrading ice-wedge polygons, subsidence can reduce inundation, increase runoff, and decrease surface water (Liljedahl et al., 2016; Perreault et al., 2017). In discontinuous permafrost, thaw opens up pathways of subsurface flow, improving the connection among inland water systems which supports the drainage of lakes and overall reduction in surface water cover (Jepsen et al., 2013). Enhanced subsurface connectivity from thaw in discontinuous permafrost serves tempers short-term lake fluctuations (Rey et al., 2019).

3.4.1.3.3 Drivers

There is *high confidence* that environmental drivers of Arctic surface water change are diverse and depend on local and regional factors such as permafrost properties and geomorphology (Nitze et al., 2018). Thermokarst lake expansion has been observed in the continuous permafrost of northern Siberia (Smith et al., 2005; Polishchuk et al., 2015) and Alaska (Jones et al., 2011); surface water area reduction has been observed in discontinuous permafrost of central and southern Siberia (Smith et al., 2005; Sharonov et al., 2012), western Canada (Labrecque et al., 2009; Carroll et al., 2011; Lantz and Turner, 2015) and interior Alaska (Chen et al., 2012; Rover et al., 2012). Increased evaporation from warmer/longer summers, decreased recharge due to reductions in snow melt volume, and dynamic processes such as ice-jam flooding (Chen et al., 2012; Bouchard et al., 2013; Jepsen et al., 2015) are important considerations for understanding observed surface water area change across the Arctic.

Satellite and model-derived estimates of evapotranspiration show increases across the Arctic (Rawlins et al., 2010; Liu et al., 2014; Liu et al., 2015b; Fujiwara et al., 2016; Suzuki et al., 2018) (*medium confidence*). Increases in the seasonal active layer thickness impact temporary water storage and thus runoff regimes in drainage basins. Formation of taliks underneath lakes and rivers may result in reconnection of surface with sub-permafrost ground water aquifers with varying hydrological consequences depending on local geological and hydraulic settings (Wellman et al., 2013).

3.4.2 Projections

3.4.2.1 Seasonal Snow

Historical simulations from CMIP5 models tend to underestimate observed reductions in spring snow cover extent due to uncertainty in the parameterisation of snow processes (Essery, 2013; Thackeray et al., 2014), challenges in simulating snow-albedo feedback (Qu and Hall, 2014; Fletcher et al., 2015; Li et al., 2016b), unrealistic temperature sensitivity (Brutel-Vuilmet et al., 2013; Mudryk et al., 2017), and biases in climatological spring snow cover (Thackeray et al., 2016). The role of precipitation biases is not well understood (Thackeray et al., 2016).

Reductions in Arctic snow cover duration are projected by the CMIP5 multi-model ensemble due to later snow onset in the autumn and earlier snow melt in spring (Brown et al., 2017) driven by increased surface temperature over essentially all Arctic land areas (Hartmann et al., 2013). There is *high confidence* that projected snow cover declines are proportional to the amount of future warming in each model realisation (Thackeray et al., 2016; Mudryk et al., 2017). Projections to mid-century are primarily dependent on natural variability and model dependent uncertainties rather than the choice of forcing scenario (Hodson et al., 2013). By end of century, however, differences between scenarios emerge. Under RCP2.6 and RCP4.5, Arctic snow cover duration stabilises at 5–10% reduction (compared to a 1986–2005 reference period); under RCP8.5, snow cover duration declines reach –15 to –25% (Brown et al., 2017) (Figure 3.10) (*high confidence*).

Positive Arctic snow water equivalent changes emerge across the eastern Eurasian Arctic by mid-century for both RCP4.5 and RCP8.5 (Brown et al., 2017) (*medium confidence*). Projected snow water equivalent increases across the North American Arctic are only modest, emerge later in the century, and only under RCP8.5 (Brown et al., 2017). These projected increases are due to enhanced snowfall (Krasting et al., 2013) from a more moisture-rich Arctic atmosphere coupled with winter season temperatures that remain sufficiently low for precipitation to fall as snow. There is *low confidence* in changes to snow properties such as density and stratigraphy (relevant for understanding the impacts of changes to Arctic snow on ecosystems) which are not resolved directly by climate model simulations, but require detailed snow physics models.

3.4.2.2 Permafrost

Circumpolar- or global-scale models represent permafrost degradation in response to warming scenarios as increases in thaw depth only. The CMIP5 models project with *high confidence* that thaw depth will increase and areal extent of near-surface permafrost will decrease substantially (Koven et al., 2013; Slater and Lawrence, 2013) (Figure 3.10). However, there is only *medium confidence* in the magnitude of these changes due to at least a five-fold range of estimated present day near-surface permafrost area ($<5 - >25 \times 10^6 \text{ km}^2$) by these models. This was caused by a wide range of model sensitivity in permafrost area to air temperature change, resulting in a large range of projected near-surface permafrost loss by 2100: 2–66% for RCP2.6 ($24 \pm 16\%$; *likely* range), 15–87% under RCP4.5 and 30–99% ($69 \pm 20\%$; *likely* range) under RCP8.5. A more recent analysis of near-surface permafrost trends from a subset of models that self-identified as structurally representing the permafrost region had a significantly smaller range of estimated present day near-surface permafrost area ($13.1\text{--}19.3 \times 10^6 \text{ km}^2$; mean \pm SD, $14.1 \pm 3.5 \times 10^6 \text{ km}^2$) (McGuire et al., 2018). This subset of models also showed large reductions of near-surface permafrost area, averaging a 90% loss ($12.7 \pm 5.1 \times 10^6 \text{ km}^2$) of permafrost area by 2300 for RCP8.5 and 29% loss ($4.1 \pm 0.6 \times 10^6 \text{ km}^2$) for RCP4.5, with much of that long-term loss already occurring by 2100.

Pulse disturbances are not included in the permafrost projections described above, and there is *high confidence* that fire and abrupt thaw will accelerate change in permafrost relative to climate effects

alone, if the rates of these disturbances increase. The observed trend of increasing fire is projected to continue for the rest of the century across most of the tundra and boreal region for many climate scenarios, with the boreal region projected to have the greatest increase in total area burned (Balshi et al., 2009; Kloster et al., 2012; Wotton et al., 2017). Due to vegetation-climate interactions, there is only *medium confidence* in projections of future area burned. As fire activity increases, flammable vegetation, such as the black spruce forest that dominates boreal Alaska, is projected to decline as it is replaced by low-flammability deciduous forest (Johnstone et al., 2011; Pastick et al., 2017). In other regions such as western Canada, by contrast, black spruce could be replaced by the even more flammable jack pine, creating regional-scale feedbacks that increase the spread of fire on the landscape (Héon et al., 2014). A regional process-model study of Alaska projected annual median area burned during the 21st century to be 1.3–1.7 times higher compared with the historical average (Pastick et al., 2017). Fire also appears to be expanding as a novel disturbance into tundra and forest-tundra boundary regions previously protected by a cool, moist climate (Jones et al., 2009; Hu et al., 2010; Hu et al., 2015) (*medium confidence*). Annual tundra area burned in Alaska is projected to double under RCP6.0 from a historic rate of $270 \text{ km}^2 \text{ yr}^{-1}$ to $500\text{--}610 \text{ km}^2 \text{ yr}^{-1}$ over the 21st century (Hu et al., 2015). A statistical approach projected a fourfold increase in the 30-year probability of fire occurrence in the forest-tundra boundary by 2100 (Young et al., 2017). In contrast to fire, there has not yet been a comprehensive circumpolar projection of how abrupt thaw rates may change in the future, but one component of abrupt thaw, change in abrupt thaw lake area, has been projected to increase to increase by 53% under RCP8.5 (Walter Anthony et al., 2018) above the $1.4 \times 10^6 \text{ km}^2$ of small lakes and ponds that currently exist in the permafrost region (Muster et al., 2017). As a result, there is *low confidence* in the ability to assess the magnitude by which abrupt thaw across the entire landscape will affect regional permafrost, even though this mechanism for rapid change appears critically important for projecting future change (Kokelj et al., 2017).

3.4.2.3 Freshwater Systems

Climate model simulations project a warmer and wetter Arctic (Krasting et al., 2013), with increased specific humidity due to enhanced evaporation (Laiñé et al., 2014), and moisture flux convergence increases into the Arctic (Skific and Francis, 2013). Increased cold-season precipitation is projected across the Arctic by CMIP5 models (Lique et al., 2016) due to increased moisture flux convergence from outside the Arctic (Zhang et al., 2012) and enhanced moisture availability from reduced sea ice cover (Bintanja and Selten, 2014) (*high confidence*). Increases in precipitation extremes are also projected over northern watersheds (Kharin et al., 2013; Sillmann et al., 2013), while rain on snow events are expected to increase (Hansen et al., 2014). A net increased ratio of precipitation minus evaporation is projected, resulting in increased freshwater flux from the land surface to the Arctic Ocean, projected to be 30% above current values by 2100 under RCP4.5 (Haine et al., 2015) (Figure 3.10). This is consistent with CMIP5 model projections of increased discharge from Arctic watersheds (van Vliet et al., 2013; Gelfan et al., 2016; MacDonald et al., 2018). The water temperature of this increased discharge is projected to be approximately 1°C

warmer than current conditions, increasing the heat flux to Arctic Ocean (van Vliet et al., 2013).

Lake ice phenology is sensitive to projected changes in surface temperature (Sharma et al., 2019). Lake ice models project an earlier spring break-up of between 10–25 days by mid-century (compared with 1961–1990), and up to a 15-day delay in the freeze-up for lakes in the North American Arctic, with more extreme reductions for coastal regions (Brown and Duguay, 2011; Dibike et al., 2011; Prowse et al., 2011) (*medium confidence*). Mean maximum ice thickness is projected to decrease by 10–50 cm over the same period (Brown and Duguay, 2011). High-latitude warming is projected to drive earlier river ice break-up in spring due to both decreasing ice strength, and earlier onset of peak discharge (Cooley and Pavelsky, 2016). Complex interplay between hydrology and hydraulics in controlling spring flooding and ice jam events complicate projections of these events (Prowse et al., 2010; Prowse et al., 2011).

3.4.3 Consequences and Impacts

3.4.3.1 Global Climate Feedbacks

3.4.3.1.1 Carbon cycle

Climate warming is expected to change the storage of carbon in vegetation and soils in northern regions, and net carbon transferred to the atmosphere as CO₂ and methane acts as a feedback to accelerate global climate change. There is *high confidence* that the northern region acted as a net carbon sink as carbon accumulated in terrestrial ecosystems over the Holocene (Loisel et al., 2014; Lindgren et al., 2018). There is *medium evidence* with *low agreement* whether changing climate in the modern period has shifted these ecosystems into net carbon sources. Syntheses of ecosystem CO₂ fluxes have alternately showed tundra ecosystems as carbon sinks or neutral averaged across the circumpolar region for the 1990s and 2000s (McGuire et al., 2012), or carbon sources over the same time period (Belshe et al., 2013). Both syntheses agree that the summer growing season is a period of net carbon uptake into terrestrial ecosystems (*high confidence*), and this uptake appears to be increasing as a function of vegetation density/biomass (Ueyama et al., 2013). The discrepancy between these syntheses may be a result of CO₂ release rates during the non-summer season that are now thought to be higher than previously estimated (*high confidence*) (Webb et al., 2016) or the separation of upland and wetland ecosystem types, which was done in one synthesis but not the other. Moisture status is a primary control over ecosystem carbon sink/source strength with wetlands more often than not still acting as annual net carbon sinks even while methane is emitted (Lund et al., 2010). Recent aircraft measurements of atmospheric CO₂ concentrations over Alaska showed that tundra regions of Alaska were a consistent net CO₂ source to the atmosphere, whereas boreal forest regions were either neutral or net CO₂ sinks for the period 2012–2014 (Commane et al., 2017). That study region as a whole was estimated to be a net carbon source of

$25 \pm 14 \text{ Tg CO}_2\text{-C yr}^{-1}$ averaged over the land area of both biomes for the entire study period. For comparison to projected global emissions, this would be equivalent to a net source of 0.3 Pg CO₂-C yr⁻¹ assuming the Alaska study region ($1.6 \times 10^6 \text{ km}^2$) could be scaled to the entire northern circumpolar permafrost region soil area ($17.8 \times 10^6 \text{ km}^2$).

The permafrost soil carbon pool is climate sensitive and an order of magnitude larger than carbon stored in plant biomass (Schuur et al., 2018) (*very high confidence*). Initial estimates were converging on a range of cumulative emissions from soils to the atmosphere by 2100, but recent studies have actually widened that range somewhat (Figure 3.11) (*medium confidence*). Expert assessment and laboratory soil incubation studies suggest that substantial quantities of C (tens to hundreds Pg C) could potentially be transferred from the permafrost carbon pool into the atmosphere under RCP8.5 (Schuur et al., 2013; Schädel et al., 2014)⁴. Global dynamical models supported these findings, showing potential carbon release from the permafrost zone ranging from 37–174 Pg C by 2100 under high emission climate warming trajectories, with an average across models of $92 \pm 17 \text{ Pg C}$ (mean \pm SE) (Zhuang et al., 2006; Koven et al., 2011; Schaefer et al., 2011; MacDougall et al., 2012; Burke et al., 2013; Schaphoff et al., 2013; Schneider von Deimling et al., 2015). This range is generally consistent with several newer data-driven modelling approaches that estimated that soil carbon releases by 2100 (for RCP8.5) will be 57 Pg C (Koven et al., 2015) and 87 Pg C (Schneider von Deimling et al., 2015), as well as an updated estimate of 102 Pg C from one of the previous models (MacDougall and Knutti, 2016). However, the latest model runs performed with either structural enhancements to better represent permafrost carbon dynamics (Burke et al., 2017a), or common environmental input data (McGuire et al., 2016) show similar soil carbon losses, but also indicate the potential for stimulated plant growth (nutrients, temperature/growing season length, CO₂ fertilisation) to offset some (Kleinen and Brovkin, 2018) or all of these losses, at least during this century, by sequestering new carbon into plant biomass and increasing carbon inputs into the surface soil (McGuire et al., 2018). These future carbon emission levels would be a significant fraction of those projected from fossil fuels with implications for allowable carbon budgets that are consistent with limiting global warming, but will also depend on how vegetation responds (*high confidence*). Furthermore, there is *high confidence* that climate scenarios that involve mitigation (e.g., RCP4.5) will help to dampen the response of carbon emissions from the Arctic and boreal regions.

Northern ecosystems contribute significantly to the global methane budget, but there is *low confidence* about the degree to which additional methane from northern lakes, ponds, wetland ecosystems, and the shallow Arctic Ocean shelves is currently contributing to increasing atmospheric concentrations. Analyses of atmospheric concentrations in Alaska concluded that local ecosystems surrounding the observation site have not changed in the exchange of methane from the 1980s until the present, which suggests that either the local wetland ecosystems are responding similarly to other northern wetland ecosystems, or that increasing atmospheric methane concentrations in northern observation sites is derived from methane coming from

⁴ For context, total annual anthropogenic CO₂ emissions were $10.8 \pm 0.8 \text{ GtC yr}^{-1}$ ($39.6 \pm 2.9 \text{ GtCO}_2\text{ yr}^{-1}$) on average over the period 2008–2017. Total annual anthropogenic methane emissions were $0.35 \pm 0.01 \text{ GtCH}_4\text{ yr}^{-1}$, on average over the period 2003–2012 (Saunio et al., 2016; Le Quéré et al., 2018).

mid-latitudes (Sweeney et al., 2016). However, this contrasts with indirect integrated estimates of methane emissions from observations of expanding permafrost thaw lakes that suggest a release of an additional 1.6–5 Tg CH₄ yr⁻¹ over the last 60 years (Walter Anthony et al., 2014). At the same time, there is *high confidence* that methane fluxes at the ecosystem to regional scale have been under-observed, in part due to the low solubility of methane in water leading to ebullition (bubbling) flux to the atmosphere that is heterogeneous in time and space. Some new quantifications include: cold-season methane emissions that can be >50% of the annual budget of terrestrial ecosystems (Zona et al., 2016); geological methane seeps that may be climate sensitive if permafrost currently serves as a cap preventing atmospheric release (Walter Anthony et al., 2012; Ruppel and Kessler, 2016; Kohnert et al., 2017); estimates of shallow Arctic Ocean shelf methane emissions where the range of estimates based on methane concentrations in air and water has widened with more observations and now ranges from 3 Tg CH₄ yr⁻¹ (Thornton et al., 2016) to 17 Tg CH₄ yr⁻¹ (Shakhova et al., 2013). Observations such as these underlie the fact that source estimates for methane made from atmospheric observations are typically lower than methane source estimates made from upscaling of ground observations (e.g., Berchet et al., 2016), and this problem has not improved, even at the global scale, over several decades of research (Saunois et al., 2016; Crill and Thornton, 2017).

In many of the dynamical model projections previously discussed, methane release is not explicitly represented because fluxes are small even though higher global warming potential of methane makes these emissions relatively more important than on a mass basis alone. Global models that do include methane show that emissions may already (from 2000 to 2012) be increasing at a rate of 1.2 Tg CH₄ yr⁻¹ in the northern region as a direct response to temperature (Riley et al., 2011; Gao et al., 2013; Poulter et al., 2017). A model intercomparison study forecast northern methane emissions to increase from 18 Tg CH₄ yr⁻¹ to 42 Tg CH₄ yr⁻¹ under RCP8.5 by 2100 largely as a result of an increase in wetland extent (Zhang et al., 2017). However, projected methane emissions are sensitive to changes in surface hydrology (Lawrence et al., 2015) and a suite of models that were thought to perform well in high-latitude ecosystems showed a general soil drying trend even as the overall water cycle intensified (McGuire et al., 2018). Furthermore, most models described above do not include many of the abrupt thaw processes that can result in lake expansion, wetland formation, and massive erosion and exposure to decomposition of previously frozen carbon-rich permafrost, leading to *medium confidence* in future model projections of methane. Recent studies that addressed some of these landscape controls over future emissions projected increases in methane above the current levels on the order 10–60 Tg CH₄ yr⁻¹ under RCP8.5 by 2100 (Schuur et al., 2013; Koven et al., 2015; Lawrence et al., 2015; Schneider von Deimling et al., 2015; Walter Anthony et al., 2018). These additional methane fluxes are projected to cause 40–70% of total permafrost-affected radiative forcing in this century even though methane emissions are much less than CO₂ by mass (Schneider von Deimling et al., 2015; Walter Anthony et al., 2018). As with total carbon emissions, there is *high confidence* that mitigation of anthropogenic methane sources could help to dampen the impact of increased methane emissions from the Arctic and boreal regions (Christensen et al., 2019).

3.4.3.1.2 Energy budget

Warming induced reductions in the duration and extent of Arctic spring snow cover (Section 3.4.1.1) lower albedo because snow-free land reflects much less solar radiation than snow. The corresponding increase in net radiation absorption at the surface provides a positive feedback to global temperatures (Flanner et al., 2011; Qu and Hall, 2014; Thackeray and Fletcher, 2016) (*high confidence*). Estimates of increases in global net solar energy flux due to snow cover loss range from 0.10–0.22 W m⁻² (± 50%; *medium confidence*) depending on dataset and time period (Flanner et al., 2011; Chen et al., 2015; Singh et al., 2015; Chen et al., 2016b). Sources of uncertainty include the range in observed spring snow cover extent trends (Hori et al., 2017) and the influence of clouds on shortwave feedbacks (Sedlar, 2018; Sledd and L'Ecuyer, 2019). Terrestrial snow changes also affect the longwave energy budget via altered surface emissivity (Huang et al., 2018). Climate model simulations show that changes in snow cover dominate land surface related positive feedbacks to atmospheric heating (Euskirchen et al., 2016), but regional variations in surface albedo are also influenced by vegetation (Lorant et al., 2014). There is evidence for positive sensitivity of surface temperatures to increased northern hemisphere boreal and tundra leaf area index, which contributes a positive feedback to warming (Forzieri et al., 2017).

3.4.3.2 Ecosystems and their Services

3.4.3.2.1 Vegetation

Changes in tundra vegetation can have important ecosystem effects, in particular on hydrology, carbon and nutrient cycling and surface energy balance, which together impact permafrost (e.g., Myers-Smith and Hik, 2013; Frost and Epstein, 2014; Nauta et al., 2014). Aside from physical impacts, changing vegetation influences the diversity and abundance of herbivores (e.g., Fauchald et al., 2017b; Horstkotte et al., 2017) in the Arctic. The overall trend for tundra vegetation across the 36-year satellite period (1982–2017) shows increasing above ground biomass (greening) throughout a majority of the circumpolar Arctic (*high confidence*) (Xu et al., 2013a; Ju and Masek, 2016; Bhatt et al., 2017). Increasing greenness has been in some cases linked with shifts in plant species dominance away from graminoids (grasses and sedges) towards shrubs (*high confidence*) (Myers-Smith et al., 2015). Within the overall trend of increases (greening), some tundra areas show declines (browning) (Bhatt et al., 2017).

The spatial variation in greening and browning trends in tundra are also not consistent over time (decadal scale) and can vary across landform/ecosystem types (Lara et al., 2018), suggesting interactions between the changing environment and the biological components of the system that control these trends. There is *high confidence* that increases in summer, spring and winter temperatures lead to tundra greening, as well as increases in growing season length (e.g., Vickers et al., 2016; Myers-Smith and Hik, 2018) that are in part linked to reductions in Arctic Ocean sea ice cover (Bhatt et al., 2017; Macias-Fauria et al., 2017). Other factors that stimulate tundra greening include increases in snow water equivalent and soil moisture (Westergaard-Nielsen et al., 2017), increases in active layer thickness (via nutrient availability or changes in moisture), changes

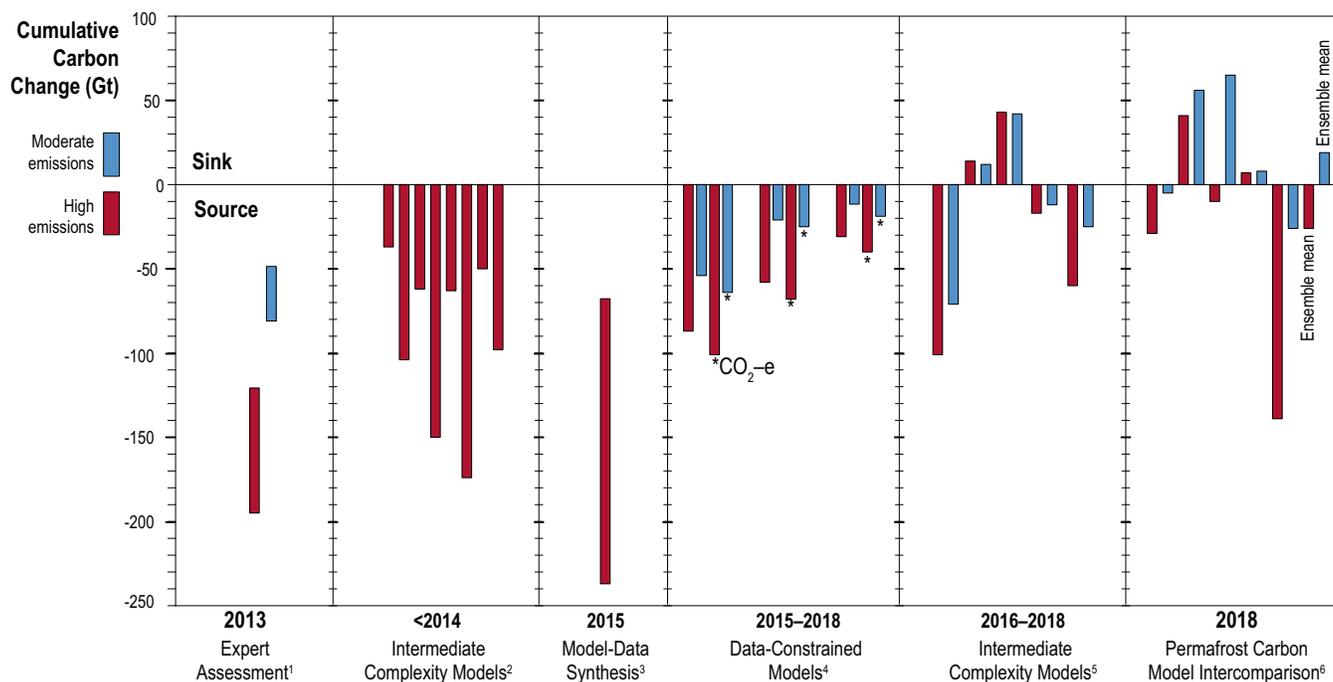


Figure 3.11 | Estimates of cumulative net soil carbon pool change for the northern circumpolar permafrost region by 2100 following medium and high emission scenarios (e.g., Representative Concentration Pathway (RCP)4.5 and RCP8.5 or equivalent). Cumulative carbon amounts are shown in Gigatons C (1 Gt=1 billion metric tonnes), with source (negative values) indicating net carbon movement from soil to the atmosphere and sink (positive values) indicating the reverse. Some data-constrained models differentiated CO₂ and CH₄; bars show total carbon by weight, paired bars with * indicate CO₂-equivalent, which takes into account the global warming potential of CH₄. Ensemble mean bars refer to the model average for the Permafrost Carbon Model Intercomparison Project [5 models]. Bars that do not start at zero are in part informed by expert assessment and are shown as ranges; all other bars represent model mean estimates. Data are from ¹ (Schuur et al., 2013); ² (Schaefer et al., 2014) [8 models]; ³ (Schuur et al., 2015); ⁴ (Koven et al., 2015; Schneider von Deimling et al., 2015; Walter Anthony et al., 2018); ⁵ (MacDougall and Knutti, 2016; Burke et al., 2017a; Kleinen and Brovkin, 2018); ⁶ (McGuire et al., 2018).

in herbivore activity, and to a lesser degree, human use of the land (e.g., Salmon et al., 2016; Horstkotte et al., 2017; Martin et al., 2017; Yu et al., 2017). Research on tundra browning is more limited but suggests causal mechanisms that include changes in winter climate – specifically reductions in snow cover due to winter warming events that expose tundra to subsequent freezing and desiccation –, insect and pathogen outbreaks, increased herbivore grazing and ground ice melting and subsidence that increases surface water (Phoenix and Bjerke, 2016; Bjerke et al., 2017) (*medium confidence*).

Projections of tundra vegetation distribution across the Arctic by 2050 in response to changing environmental conditions suggest that the areal extent of most tundra types will decrease by at least 50% (Pearson et al., 2013) (*medium confidence*). Woody shrubs and trees are projected to expand to cover 24–52% of the current tundra region by 2050, or 12–33% if tree dispersal is restricted. Adding to this, the expansion of fire into tundra that has not experienced large-scale disturbance for centuries causes large reductions in soil carbon stocks (Mack et al., 2011), shifts in vegetation composition and productivity (Bret-Harte et al., 2013), and can lead to widespread permafrost degradation (Jones et al., 2015a) at faster rates than would occur by changing environmental conditions alone. In tundra regions, graminoid (grasses and sedges) tundra is projected to be replaced by more flammable shrub tundra in future climate scenarios, and tree migration into tundra could further increase fuel loading (Pastick et al., 2017) (*medium confidence*).

Similar to tundra, boreal forest vegetation shows trends of both greening and browning over multiple years in different regions across the satellite record (Beck and Goetz, 2011; Ju and Masek, 2016) (*high confidence*). Here, patterns of changing vegetation are a result of direct responses to changes in climate (temperature, precipitation and seasonality) and other driving factors for vegetation (nutrients, disturbance) similar to what has been reported in tundra. While boreal forest may expand at the northern edge (Pearson et al., 2013), climate projections suggest that it could diminish at the southern edge and be replaced by lower biomass woodland/shrublands (Koven, 2013; Gauthier et al., 2015) (*medium confidence*). Furthermore, changes in fire disturbance are leading to shifts in landscape distribution of early and late successional ecosystem types, which is also a major factor in satellite trends. Fires that burn deeply into the organic soil layer can alter permafrost stability, hydrology and vegetation. Loss of the soil organic layer exposes mineral soil seedbeds (Johnstone et al., 2009), leading to recruitment of deciduous tree and shrub species that do not establish on organic soil (Johnstone et al., 2010). This recruitment has been shown to shift post-fire vegetation to alternate successional trajectories (Johnstone et al., 2010). Model projections suggest that Alaskan boreal forest soon may cross a point where recent increases in fire activity have made deciduous stands as abundant as spruce stands on the landscape (Mann et al., 2012) (*medium confidence*). This projected trend of increasing deciduous forest at the expense of evergreen forest is mirrored in Russian and Chinese boreal forests as well (Shakhova et al., 2013; Shuman et al., 2015; Wu et al., 2017) (*medium confidence*).

3.4.3.2.2 Wildlife

Reindeer and caribou (*Rangifer tarandus*), through their numbers and ecological role as a large-bodied herbivore, are a key driver of Arctic ecology. The seasonal migrations that characterise *Rangifer* link the coastal tundra to the continental boreal forests for some herds, while others live year-round on the tundra. Population estimates and trends exist for most herds, and indicate that pan-Arctic migratory tundra *Rangifer* have declined from about 5 million in the 1990s to about 2 million in 2017 (Gunn, 2016; Fauchald et al., 2017a) (*high confidence*). Numbers have recently increased for two Alaska herds and the Porcupine caribou herd straddling Yukon and Alaska is at a historic high.

There is *low confidence* in understanding the complex drivers of observed *Rangifer* changes. Hunting and predation (the latter exacerbated by modification of the landscape for exploration and resource extraction; Dabros et al., 2018) increase in importance as populations decline. Climate strongly influences productivity: extremes in heat, drought, winter icing and snow depth reduce *Rangifer* survival (Mallory and Boyce, 2017). Changes in the timing of sea ice formation have direct effects on risks during *Rangifer* migration via inter-island movement and connection to the mainland (Poole et al., 2010). Summer warming is changing the composition of tundra plant communities, modifying the relationship between climate, forage and *Rangifer* (Albon et al., 2017), which also impacts other Arctic species such as musk ox (*Ovibos moschatus*) (Schmidt et al., 2015). As polar trophic systems are highly connected (Schmidt et al., 2017), changes will propagate through the ecosystem with effects on other herbivores such as geese and voles, as well as predators such as wolves (Hansen et al., 2013; Klaczek et al., 2016).

In northern Fennoscandia, there are approximately 600,000 semi-domesticated reindeer. Lichen rangelands are key to sustaining reindeer carrying capacity, with variable response to climate change: enhanced summer precipitation increases lichen biomass, while an increase in winter precipitation lowers it (Kumpula et al., 2014). Fire disturbance reduces the amount of pasture available for domestic reindeer and increases predation on herding lands (Lavrillier and Gabyshev, 2017). Later ice formation on waterbodies can impact herding activities (Turunen et al., 2016). Ice formation from rain-on-snow events is associated with population changes including cases of catastrophic mass starvation (Bartsch et al., 2010; Forbes et al., 2016), but there is no evidence of trends in rain-on-snow events (Cohen et al., 2015; Dolant et al., 2017).

Management of keystone species requires an understanding of pathogens and disease in the context of climate warming, but evidence of changing patterns across northern ecosystems (spanning terrestrial, aquatic, and marine environments) is hindered by an incomplete picture of pathogen diversity and distribution (Hoberg, 2013; Jenkins et al., 2013; Cook et al., 2017). Among ungulates, it is *virtually certain* that the emergence of disease attributed to nematode pathogens has accelerated since 2000 in the Canadian Arctic islands and Fennoscandia (Kutz et al., 2013; Hoberg and Brooks, 2015; Laaksonen et al., 2017; Kafle et al., 2018). Discovery of the pathogenic bacterium *Erysipelothrix rhusiopathiae* has been linked to massive and widespread mortality

among muskoxen from the Canadian Arctic Archipelago; loss of >50% of the population since 2010 may be attributable to disease interacting with extreme temperature events, although unequivocal links to climate have not been established (Kutz et al., 2015; Forde et al., 2016a; Forde et al., 2016b). Anthrax is projected to expand northward in response to warming, and resulted in substantial mortality events for reindeer on the Yamal Peninsula of Russia in 2016 with mobilisation of bacteria possibly from a frozen reindeer carcass or melting permafrost (Walsh et al., 2018). In concert with climate forcing, pathogens are *very likely* responsible for increasing mortality in Arctic ungulates (muskox, caribou/reindeer) and alteration of transmission patterns in marine food chains, broadly threatening sustainability of subsistence and commercial hunting and fishing and safety of traditional foods for northern cultures at high latitudes (Jenkins et al., 2013; Kutz et al., 2014; Hoberg et al., 2017).

3.4.3.2.3 Freshwater

Climate-driven changes in seasonal ice and permafrost conditions influence water quality (*high confidence*). Shortened duration of freshwater ice cover (more light absorption, increased nutrient input) is expected to result in higher primary productivity (Hodgson and Smol, 2008; Vincent et al., 2011; Griffiths et al., 2017b) and may also encourage greater methane emissions from Arctic lakes (Greene et al., 2014; Tan and Zhuang, 2015). Thaw slumps, active layer detachments and peat plateau collapse affect surface water connectivity (Connon et al., 2014) and enhance sediment, particulate and solute fluxes in river and stream networks (Kokelj et al., 2013). The transfer of enhanced nutrients from land to water (driven by active layer thickening and thermokarst processes; Abbott et al., 2015; Vonk et al., 2015) has been linked to heightened autotrophic productivity in freshwater ecosystems (Wrona et al., 2016). Still, there is *low confidence* in the influence of permafrost changes on dissolved organic carbon, because of competing mechanisms that influence carbon export. Permafrost thaw could contribute to the mobilisation of previously frozen organic carbon (Abbott et al., 2014; Wickland et al., 2018; Walvoord et al., 2019) thereby enhancing both particulate and dissolved organic carbon export to aquatic systems. Increased delivery of this dissolved carbon from enhanced river discharge to the Arctic Ocean (Section 3.4.3.1.2) can exacerbate regionally extreme aragonite undersaturation of shelf waters (Semiletov et al., 2016) driven by ocean uptake of anthropogenic CO₂ (Section 3.2.1.2.4). Conversely, reduced dissolved organic carbon export could accompany permafrost thaw as (1) water infiltrates deeper and has longer residence times for decomposition (Striegl et al., 2005) and (2) the proportion of groundwater (typically lower in dissolved organic carbon and higher in DIC than runoff) to total streamflow increases (Walvoord and Striegl, 2007). Increased thermokarst also has the potential to impact freshwater cycling of inorganic carbon (Zolkos et al., 2018).

Enhanced subsurface water fluxes resulting from permafrost degradation has consequences for inorganic natural and anthropogenic constituents. Emerging evidence suggests large natural stores of mercury (Schuster et al., 2018; St Pierre et al., 2018) and other trace elements in permafrost (Colombo et al., 2018) may be released upon thaw, thereby having effects (largely unknown at this point) on aquatic ecosystems. In parallel, increased development activity in the Arctic is

likely to lead to enhanced local sources of anthropogenic chemicals of emerging Arctic concern, including siloxanes, parabens, flame retardants, and per- and polyfluoroalkyl substances (AMAP, 2017c). For legacy pollutants, there is *high confidence* that black carbon and persistent organic pollutants (e.g., hexachlorocyclohexanes, polycyclic aromatic hydrocarbons, and polychlorinated biphenyls) can be transferred downstream and affect water quality (Hodson, 2014). Lakes can become sinks of these contaminants, while floodplains can be contaminated (Sharma et al., 2015).

There is *high confidence* that habitat loss or change due to climate change impact Arctic fishes. Thinning ice on lakes and streams changes the overwintering habitat for aquatic fauna by impacting winter water volumes and dissolved oxygen levels (Leppi et al., 2016). Surface water loss, reduced surface water connectivity among aquatic habitats, and changes to the timing and magnitude of seasonal flows (Section 3.4.1.2) result in a direct loss of spawning, feeding, or rearing habitats (Poesch et al., 2016). Changes to permafrost landscapes have reduced freshwater habitat available for fish and other aquatic biota, including aquatic invertebrates upon which the fish depend for food (Chin et al., 2016). Gullying deepens channels (Rowland et al., 2011; Liljedahl et al., 2016) that otherwise may connect lake habitats occupied by fishes. This can lead to the loss of surface water connectivity, limit fish access to key habitats, and lower fish diversity (Haynes et al., 2014; Laske et al., 2016). Small connecting stream channels, which are vulnerable to drying, provide necessary migratory pathways for fishes, allowing them to access spawning and summer rearing grounds (Heim et al., 2016; McFarland et al., 2017).

Changes to the timing, duration and magnitude of high surface flow events in early and late summer threaten Arctic fish dispersal and

migration activities (Heim et al., 2016) (*high confidence*). Timing of important life history events such as spawning can become mismatched with changing stream flows (Lique et al., 2016). There is regional evidence that migration timing has shifted earlier and winter egg incubation temperature has increased for pink salmon (*Oncorhynchus gorbuscha*), directly related to warming (Taylor, 2007). While long-term, pan-Arctic data on run timing of fishes are limited, phenological shifts could create mismatches with food availability or habitat suitability in both marine and freshwater environments for anadromous species, and in freshwater environments for freshwater resident species. Changes to the Arctic growing season (Xu et al., 2013a) increase the risk of drying of surface water habitats and pose a potential mismatch in seasonal availability of food in rearing habitats.

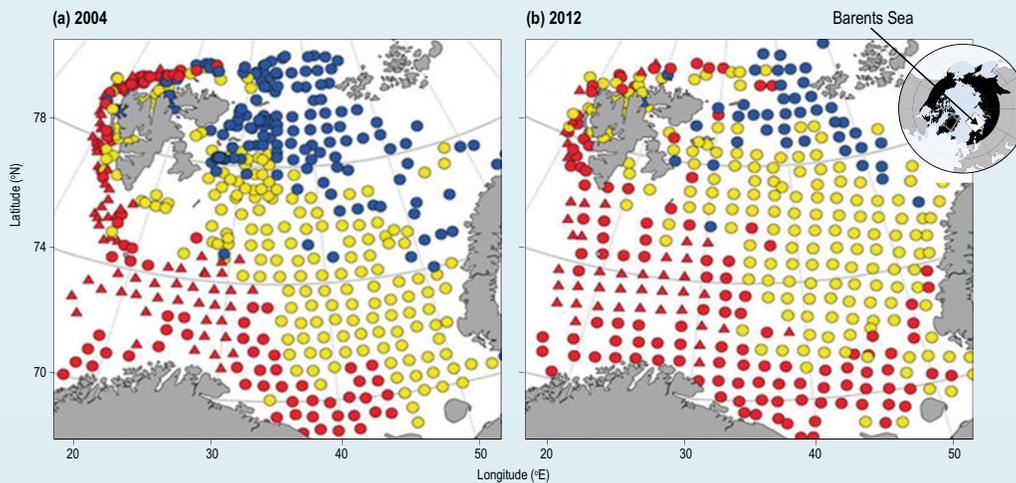
Freshwater systems across the Arctic are relatively shallow, and thus are expected to warm (*high confidence*). This may make some surface waters inhospitably warm for cold water species such as Arctic Grayling (*Thymallus arcticus*) and whitefishes (*Coregonus spp.*), or may increase the risk of *Saprolegnia fungus* that appears to have recently spread rapidly, infecting whitefishes at much higher rates in Arctic Alaska than noted in the past (Sformo et al., 2017). High infection rates may be driven by stress or nutrient enrichment from thawing permafrost, which increases pathogen virulence with fish (Wedekind et al., 2010). Warmer water and longer growing seasons will also affect food abundance because invertebrate life histories and production are temperature and degree-day dependent (Régnière et al., 2012). Increased nutrient export from permafrost loss (Frey et al., 2007), facilitated by warmer temperatures, will *likely* increase food resources for consumers, but the impact on lower trophic levels within food webs is not clearly understood.

Box 3.4 | Impacts and Risks for Polar Biodiversity from Range Shifts and Species Invasions Related to Climate Change

In polar regions climate-induced changes in terrestrial, ocean and sea ice environments, together with human introduction of non-native species, have expanded the range of some temperate species and contracted the range of some polar fish and ice-associated species (Section 3.2.3.2; Duffy et al., 2017) (*high confidence* for detection, *medium confidence* for attribution). In some cases, spatial shifts in distribution have also been influenced by fluctuations in population abundance linked to climate-induced impacts on reproductive success (Section 3.2.3). These changes have the potential to alter biodiversity in polar marine and terrestrial ecosystems (Frenot et al., 2005; Frederiksen, 2017; McCarthy et al., 2019) (*medium confidence*).

Ongoing climate change induced reductions in suitable habitat for Arctic sea ice affiliated endemic marine mammals is an escalating threat (Section 3.2.3.1) (*high confidence*). This is further complicated by the northward expansion of the summer ranges of a variety of temperate whale species, documented recently in both the Pacific and Atlantic sides of the Arctic (Brower et al., 2017; Storrie et al., 2018) and increasing pressure from anthropogenic activities. Also, over the recent decade a northward shift in benthic species, with subsequent changes in community composition has been detected in both the northern Bering Sea (Grebmeier, 2012), off Western Greenland (Renaud et al., 2015) and the Barents Sea (Kortsch et al., 2012) (*medium confidence*). At the same time as these northward expansions or shifts, a number of populations of species as different as polar bear and Arctic char show range contraction or population declines (Winfield et al., 2010; Bromaghin et al., 2015; Laidre et al., 2018).

In the Arctic a number of fish species have changed their spatial distribution substantially over the recent decades (*high confidence*). The most pronounced recent range expansion into the Arctic may be that of the summer feeding distribution of the temperate Atlantic mackerel (*Scomber scombrus*) in the Nordic Seas. From 1997 to 2016 the total area occupied by this large stock expanded from 0.4 to 2.5 million km² and the centre-of-gravity of distribution shifted westward by 1650 km and northward by 400 km (Olafsdottir



Box 3.4, Figure 1 | Spatial distribution of fish communities identified at bottom trawl stations in the Barents Sea (north of northern Norway and Russia, position indicated by red box in small globe) in (a) 2004 and (b) 2012. Atlantic (red), Arctic (blue) and Central communities (yellow). Circles: shallow sub-communities, triangles: deep sub-communities. Modified from Fosshiem et al. (2015).

et al., 2019), far into Icelandic and Greenland waters and even up to Svalbard (Berge et al., 2015; Jansen et al., 2016; Nøttestad et al., 2016). This range expansion was linked both to a pronounced increase in stock size and warming of the ocean (Berge et al., 2015; Olafsdottir et al., 2019) (*high confidence*). Under RCP4.5 and RCP8.5 further range expansions of mackerel are projected in Greenland waters (Jansen et al., 2016) (*medium confidence*). However, further northwards expansion of planktivorous species may generally be restricted by them not being adapted to lack of primary production during winter (Sundby et al., 2016). Range shifts have also been observed in the Bering Sea since 1993, with warm bottom temperatures being associated with range contractions of Arctic species, and range expansions of sub-arctic species, with responses dependent on species specific vulnerability (Alabia et al., 2018; Stevenson and Lauth, 2018).

In the Barents Sea, major expansions in distribution over the recent years to decades have been well documented for both individual species and whole biological communities (*high confidence*). New information strengthens findings reported in WGII AR5 of ecologically and commercially important fish stocks having extended their habitats markedly to the north and east, concomitant to increased sea temperature and retreating sea ice. This includes capelin (Ingvaldsen and Gjørseter, 2013), Atlantic cod (Kjesbu et al., 2014) and haddock (Landa et al., 2014). Of even greater importance is novel evidence of distinct distributional changes at the community level (Fosshiem et al., 2015; Kortsch et al., 2015; Frainer et al., 2017) (Box 3.4 Figure 1). Until recently, the northern Barents Sea was dominated by small-sized, slow-growing fish species with specialised diets, mostly living in close association with the sea floor. Simultaneous with rising sea temperatures and retreating sea ice, these Arctic fishes are being replaced by boreal, fast-growing, large-bodied generalist fish moving in from the south. These large, migratory predators take advantage of increased production while the Arctic fish species suffer from higher competition and predation and are retracting northwards and eastwards. Consequently, climate change is inducing structural change over large spatial scales, leading to a borealisation ('Atlantification') of the European Arctic biological communities (Fosshiem et al., 2015; Kortsch et al., 2015; Frainer et al., 2017) (*medium confidence*).

There is evidence based on population genetics that the ecosystem off Northeast Greenland could also become populated by a larger proportion of boreal species with ocean warming. Andrews et al. (2019) show that Atlantic cod, beaked redfish (*Sebastes mentella*), and deep-sea shrimp (*Pandalus borealis*) recently found on the Northeast Greenland shelf originate from the quite distant Barents Sea, and suggested that pelagic offspring were dispersed via advection across the Fram Strait.

Physical barriers to range expansions into the high Arctic interior shelf systems and the outflow systems of Eurasia and the Canadian Archipelago will continue to govern future expansions of fish populations (*medium confidence*). The limited available information on marine fish from other Arctic shelf regions reveals a latitudinal cline in the abundance of commercially harvestable fish species. For instance, there is evidence of latitudinal partitioning between the four dominant mid-water species (Polar cod, saffron cod (*Eleginus gracilis*), capelin, and Pacific herring (*Clupea pallasii*)) in the Chuckchi and Northern Bering Sea, with Polar cod being most abundant to the north (De Robertis et al., 2017). These latitudinal gradients suggest that future range expansions of fish populations will continue to be governed by a combination of physical factors affecting overwintering success and the availability, quality and quantity of prey (*medium confidence*).

In Antarctic marine systems, there is evidence of recent climate-related range shifts in the southwest Atlantic and West Antarctic Peninsula for penguin species (*Pygoscelis papua* and *P. antarctica*) and for Antarctic krill (*Euphausia superba*), but mesozooplankton communities do not appear to have changed or shifted in response to ocean warming (Section 3.2.3.2). Recent evidence suggests that the ACC and its associated fronts and thermal gradients may be more permeable to biological dispersal than previously thought, with storm-forced surface waves and ocean eddies enhancing oceanographic connectivity for drift particles in surface layers of the Southern Ocean (Fraser et al., 2017; Fraser et al., 2018) (*low confidence*), but it is unclear whether this will be an increasingly important pathway under climate change. Greater ship activity in the Southern Ocean may also present a risk for increasing introduction of non-native marine species, with the potential for these species to become invasive with changing environmental conditions (McCarthy et al., 2019). Current evidence of invasions by shell-crushing crabs on the Antarctic continental slope and shelf remains equivocal (Griffiths et al., 2013; Aronson et al., 2015; Smith et al., 2017d).

On Arctic land, northward range expansions have been recorded in species from all major taxon groups based both on scientific studies and local observations (*high confidence*) (CAFF, 2013a; AMAP, 2017a; AMAP, 2017b; AMAP, 2018). The most recent examples of terrestrial vertebrates expanding northwards include a whole range of mammals in Yakutia, Russia (Safronov, 2016), moose (*Alces alces*) into the Arctic region of both northern continents (Tape et al., 2016) and North American beaver (*Castor canadensis*) in Alaska (Tape et al., 2018). In parallel with these expansions, pathogens and pests are also spreading north (CAFF, 2013a; Taylor et al., 2015; Forde et al., 2016b; Burke et al., 2017b; Kafle et al., 2018). A widespread change is tundra greening, which in some cases is linked to shifting plant dominance within Arctic plant communities, in particular an increase in woody shrub biomass as conditions become more favorable for them (Myers-Smith et al., 2015; Bhatt et al., 2017).

Expansion of subarctic terrestrial species and biological communities into the Arctic and displacing native species is considered a major threat, since unique Arctic species may be less competitive than encroaching subarctic species favoured by changing climatic conditions (CAFF, 2013a). Similar displacements may take place within zones of the Arctic when low- and mid-Arctic species expand northward. Here, the most vulnerable species and communities may be in the species-poor, but unique, northernmost sub-zone of the Arctic because species cannot migrate northward as southern species encroach (CAVM Team, 2003; Walker et al., 2016; AMAP, 2018). This 'Arctic squeeze' is a combined effect of the fact that the area of the globe increasingly shrinks when moving poleward and that there is nowhere further north on land to go for terrestrial biota at the northern coast. The expected overall result of these shifts and limits will be a loss of biodiversity (CAFF, 2013a; CAFF, 2013b; AMAP, 2018) (*medium confidence*). At the southern limit of the Arctic, thermal hotspots may support high biological productivity, but not necessarily high biodiversity (Walker et al., 2015) and may even act as advanced bridgeheads for expansion of subarctic species into the true Arctic (*medium confidence*). At the other end of the Arctic zonal range, a temperature increase of only 1°C–2°C in the northernmost subzone may allow the establishment of woody dwarf shrubs, sedges and other species into bare soil areas that may radically change its appearance and ecological functions (Walker et al., 2015; Myers-Smith et al., 2019) (*medium confidence*).

Range expansions also include the threat from alien species brought in by humans to become invasive and outcompete native species. Relatively few invasive alien species are presently well established in the Arctic, but many are thriving in the subarctic and may expand as a result of climate change (CAFF, 2013a; CAFF, 2013b). Examples of this include: American mink (*Neovison vison*) and Nootka lupin (*Lupinus nootkatensis*) in Arctic western Eurasia, Greenland and Iceland that are already causing severe problems to native fauna and flora (CAFF and PAME, 2017).

Alien species are a major driver of terrestrial biodiversity change also in the Antarctic region (Frenot et al., 2005; Chown et al., 2012; McClelland et al., 2017). The Protocol on Environmental Protection to the Antarctic Treaty restricts the introduction of non-native species to Antarctica as do the management authorities of sub-Antarctic islands (De Villiers et al., 2006). Despite this, alien species and their propagules continue to be introduced to the Antarctic continent and sub-Antarctic islands (Hughes et al., 2015). To date, 14 non-native terrestrial species have colonised the Antarctic Treaty area (excluding sub-Antarctic islands) (Hughes et al., 2015), while the number in the sub-Antarctic is much higher (on the order of 200 species) (Frenot et al., 2005) (*low confidence*). Species distribution models for terrestrial invasive species indicate that climate does not currently constitute a barrier for the establishment of invasive species on all subantarctic islands, and that the AP region will be the most vulnerable location on the Antarctic continent to invasive species establishment under RCP8.5 (Duffy et al., 2017). Thus, for continental Antarctica, existing climatic barriers to alien species establishment will weaken as warming continues across the region (*medium confidence*). An increase in the ice-free area linked to glacier retreat in Antarctica is expected to increase the area available for new terrestrial ecosystems (Lee et al., 2017a). Along with growing number of visitors, this is expected to increase in the establishment probability of terrestrial alien species (Chown et al., 2012; Hughes et al., 2015) (*medium confidence*).

3.4.3.3 Impacts on Social-Ecological Systems

The Arctic is home to over four million people, with large regional variation in population distribution and demographics (Heleniak, 2014). 'Connection with nature' is a defining feature of Arctic identity for indigenous communities (Schweitzer et al., 2014) because the lands, waters and ice that surround communities evoke a sense of home, freedom and belonging, and are crucial for culture, life and survival (Cunsolo Willox et al., 2012; Durkalec et al., 2015). Climate-driven environmental changes are affecting local ecosystems and influencing travel, hunting, fishing and gathering practises. This has implications for people's livelihoods, cultural practices, economies and self-determination.

3.4.3.3.1 Food and water security

Impacts of climate change on food and water security in the Arctic can be severe in regions where infrastructure (including ice roads), travel and subsistence practices are reliant on elements of the cryosphere such as snow cover, permafrost and freshwater or sea ice (Cochran et al., 2013; Inuit Circumpolar Council-Alaska (ICC-AK), 2015).

There is *high confidence* in indicators that food insecurity risks are on the rise for Indigenous Arctic peoples. Food is strongly tied to culture, identity, values and ways of life (Donaldson et al., 2010; Cunsolo Willox et al., 2015; Inuit Circumpolar Council-Alaska (ICC-AK), 2015); thus, impacts to food security go beyond access to food and physical health. Food systems in northern communities are intertwined with northern ecosystems because of subsistence hunting, fishing and gathering activities. Environmental changes to animal habitat, population sizes and movement mean that culturally important food species may no longer be found within accessible ranges or familiar areas (Parlee and Furgal, 2012; Rautio et al., 2014; Inuit Circumpolar Council-Alaska (ICC-AK), 2015; Lavrillier et al., 2016) (Section 3.4.3.2.2). This impacts negatively the accessibility of culturally important local food sources (Lavrillier, 2013; Rosol et al., 2016) that make important contributions to a nutritious diet (Donaldson et al., 2010; Hansen et al., 2013; Dudley et al., 2015). Longer open water seasons and poorer ice conditions on lakes impact fishing options (Laidler, 2012) and waterfowl hunting (Goldhar et al., 2014). Permafrost warming and increases in active layer thickness (Section 3.4.1.3) reduce the reliability of permafrost for natural refrigeration. In some cases these changes have reduced access to, and consumption of, locally resourced food and can result in increased incidence of illness (Laidler, 2012; Cochran et al., 2013; Cozzetto et al., 2013; Rautio et al., 2014; Beaumier et al., 2015). These consequences of climate change are intertwined with processes of globalisation, whereby complex social, economic and cultural factors are contributing to a dietary transformation from locally resourced foods to imported market foods across the Arctic (Harder and Wenzel, 2012; Parlee and Furgal, 2012; Nymand and Fondahl, 2014; Beaumier et al., 2015). Limiting exposures to zoonotic, foodborne and waterborne pathogens (Section 3.4.3.2.2) depends on accurate and comprehensive data on species diversity, biology and distribution and pathways for invasion (Hoberg and Brooks, 2015; Kafle et al., 2018).

There is *high confidence* that changes to travel conditions impact food security through access to hunting grounds. Shorter snow cover

duration (Section 3.4.1.1), and changes to snow conditions (such as density) make travel more difficult and dangerous (Laidler, 2012; Ford et al., 2019). Changes in dominant wind direction and speed reduce the reliability of traditional navigational indicators such as snow drifts, increasing safety concerns (Ford and Pearce, 2012; Laidler, 2012; Ford et al., 2013; Clark et al., 2016b). Permafrost warming, increased active layer thickness and landscape instability (Section 3.4.1.3), fire disturbance and changes to water levels (Section 3.4.1.2) impact overland navigability in summer (Goldhar et al., 2014; Brinkman et al., 2016; Dodd et al., 2018).

There is *high confidence* that both risks and opportunities arise for coastal communities with changing sea ice and open water conditions. Of particular concern for coastal communities is landfast sea ice (Section 3.3.1.1.5), which creates an extension of the land in winter that facilitates travel (Inuit Circumpolar Council Canada, 2014). The floe edge position, timing and dynamics of freeze-up and break-up, sea ice stability through the winter, and length of the summer open water season are important indicators of changing ice conditions and safe travel (Gearheard et al., 2013; Eicken et al., 2014; Baztan et al., 2017). Warming water temperature, altered salinity profiles, snow properties, changing currents and winds all have consequences for the use of sea ice as a travel or hunting platform (Hansen et al., 2013; Eicken et al., 2014; Clark et al., 2016a). More leads (areas of open water), especially in the spring, can mean more hunting opportunities such as whaling off the coast of Alaska (Hansen et al., 2013; Eicken et al., 2014). In Nunavut, a floe edge closer to shore improves access to marine mammals such as seals or narwhal (Ford et al., 2013). However, these conditions also hamper access to coastal or inland hunting grounds (Hansen et al., 2013; Durkalec et al., 2015), have increased potential for break-off events at the floe edge (Ford et al., 2013), or can result in decreased presence (or total absence) of ice-associated marine mammals with an absence of summer sea ice (Eicken et al., 2014).

Many northern communities rely on ponds, streams and lakes for drinking water (Cochran et al., 2013; Goldhar et al., 2013; Nymand and Fondahl, 2014; Daley et al., 2015; Dudley et al., 2015; Masina et al., 2019), so there is *high confidence* that projected changes in hydrology will impact water supply (Section 3.4.2.2). Surface water is vulnerable to thermokarst disturbance and drainage, as well as bacterial contamination, the risks of which are increased by warming ground and water temperatures (Cozzetto et al., 2013; Goldhar et al., 2013; Dudley et al., 2015; Masina et al., 2019). Icebergs or old multi-year ice are important sources of drinking water for some coastal communities, so reduced accessibility to stable sea ice conditions affects local water security. Small remote communities have limited capacity to respond quickly to water supply threats, which amplifies vulnerabilities to water security (Daley et al., 2015).

3.4.3.3.2 Communities

Culture and knowledge

Spending time on the land is culturally important for indigenous communities (Eicken et al., 2014; Durkalec et al., 2015). There is *high confidence* that daily life is influenced by changes to ice freeze-up and break-up (rivers/lakes/sea ice), snow onset/melt, vegetation

phenology, and related wildlife/fish/bird behaviour (Inuit Circumpolar Council-Alaska (ICC-AK), 2015). Inter-generational knowledge transmission of associated values and skills is also influenced by climate change because younger generations do not have the same level of experience or confidence with traditional indicators (Ford, 2012; Parlee and Furgal, 2012; Eicken et al., 2014; Pearce et al., 2015). Climate-driven changes undermine confidence in indigenous knowledge holders in regards to traditional indicators used for safe travel and navigation (Parlee and Furgal, 2012; Golovnev, 2017; Ford et al., 2019).

Economics

The Arctic mixed economy is characterised by a combination of subsistence activities, and employment and cash income. There is *low confidence* about the extent and nature of impact of climate change on local subsistence activities and economic opportunities across the Arctic (e.g., hunting, fishing, resource extraction, tourism and transportation; see Section 3.2.4) because of high variability between communities (Harder and Wenzel, 2012; Cochran et al., 2013; Clark et al., 2016b; Fall, 2016; Ford et al., 2016; Lavrillier et al., 2016). Longer ice-free travel windows in Arctic seas could lower the costs of access and development of northern resources (delivering supplies and shipping resources to markets) and thus, may contribute to increased opportunities for marine shipping, commercial fisheries, tourism and resource development (Sections 3.2.4.2, 3.2.4.3) (Ford et al., 2012; Huskey et al., 2014; Overland et al., 2017). This has important implications for economic development, particularly in relation to local employment opportunities but also raises concerns of detrimental impacts on animals, habitat and subsistence activities (Cochran et al., 2013; Inuit Circumpolar Council-Alaska (ICC-AK), 2015).

3.4.3.3 Health and wellbeing

For many polar residents, especially Indigenous peoples, the physical environment underpins social determinants of well-being, including physical and mental health. Changes to the environment impact most dimensions of health and well-being (Parlee and Furgal, 2012; Ostapchuk et al., 2015). Climate change consequences in polar regions (Sections 3.3.1.1, 3.4.1.2) have impacted key transportation routes (Gearheard et al., 2006; Laidler, 2006; Ford et al., 2013; Clark et al., 2016a) and pose increased risk of injury and death during travel (Durkalec et al., 2014; Durkalec et al., 2015; Clark et al., 2016b; Driscoll et al., 2016).

Foodborne disease is an emerging concern in the Arctic because warmer waters, loss of sea ice (Section 3.3.1.1) and resultant changes in contaminant pathways can lead to bioaccumulation and biomagnification of contaminants in key food species. While many hypothesised foodborne diseases are not well studied (Parkinson and Berner, 2009), foodborne gastroenteritis is associated with shellfish harvested from warming waters (McLaughlin et al., 2005; Young et al., 2015). Mercury presently stored in permafrost (Schuster et al., 2018) has potential to accumulate in aquatic ecosystems.

Climate change increases the risk of waterborne disease in the Arctic via warming water temperatures and changes to surface hydrology (Section 3.4.1.2) (Parkinson and Berner, 2009; Brubaker et al., 2011;

Dudley et al., 2015). After periods of rapid snowmelt, bacteria can increase in untreated drinking water, with associated increases in acute gastrointestinal illness (Harper et al., 2011). Consumption of untreated drinking water may increase duration and frequency of exposure to local environmental contaminants (Section 3.4.3.2.3) or potential waterborne diseases (Goldhar et al., 2014; Daley et al., 2015). The potential for infectious gastrointestinal disease is not well understood, and there are concerns in relation to the safety of storage containers of raw water in addition to the quality of the source water itself (Goldhar et al., 2014; Wright et al., 2018; Masina et al., 2019).

Climate change has negatively affected place attachment via hunting, fishing, trapping and traveling disruptions, which have important mental health impacts (Cunsolo Willox et al., 2012; Durkalec et al., 2015; Cunsolo and Ellis, 2018). The pathways through which climate change impacts mental wellness in the Arctic varies by gender (Bunce and Ford, 2015; Ostapchuk et al., 2015; Bunce et al., 2016) and age (Petrasek-MacDonald et al., 2013; Ostapchuk et al., 2015). Emotional impacts of climate-related changes in the environment were significantly higher for women compared to men, linked to concern for family members (Ostapchuk et al., 2015). However, men are also vulnerable due to gendered roles in subsistence and cultural activities (Bunce and Ford, 2015). In coastal areas, sea ice means freedom for travel, hunting and fishing, so changes in sea ice affect the experience of and connection with place. In turn, this influences individual and collective mental/emotional health, as well as spiritual and social vitality according to relationships between sea ice use, culture, knowledge and autonomy (Cunsolo Willox et al., 2013a; Cunsolo Willox et al., 2013b; Gearheard et al., 2013; Durkalec et al., 2015; Inuit Circumpolar Council-Alaska (ICC-AK), 2015).

3.4.3.4 Infrastructure

Permafrost is undergoing rapid change (Section 3.4.1.2), creating challenges for planners, decision makers and engineers (AMAP, 2017d). The observed changes in the ground thermal regime (Romanovsky et al., 2010; Romanovsky et al., 2017; Biskaborn et al., 2019) threaten the structural stability and functional capacities of infrastructure, in particular that which is located on ice rich frozen ground. Extensive summaries of construction damages along with adaptation and mitigation strategies are available (Larsen et al., 2014; Dore et al., 2016; AMAP, 2017d; Pendakur, 2017; Shiklomanov et al., 2017a; Shiklomanov et al., 2017b; Vincent et al., 2017).

Projections of climate and permafrost suggest that a wide range current infrastructure will be impacted by changing conditions (*medium confidence*). A circumpolar study found that approximately 70% of infrastructure (residential, transportation and industrial facilities), including over 1200 settlements (~40 with population more than 5000) are located in areas where permafrost is projected to thaw by 2050 under RCP4.5 (Hjort et al., 2018). Regions associated with the highest hazard are in the thaw-unstable zone characterised by relatively high ground-ice content and thick deposits of frost susceptible sediments (Shiklomanov et al., 2017b). By 2050, these high hazard environments contain one-third of existing pan-Arctic infrastructure. Onshore hydrocarbon extraction and transportation in the Russian Arctic are at risk: 45% of the oil and natural gas

production fields in the Russian Arctic are located in the highest hazard zone.

In a regional study of the state of Alaska, cumulative expenses projected for climate-related damage to public infrastructure totalled USD 5.5 billion between 2015 and 2099 under RCP8.5 (Melvin et al., 2017). The top two causes of damage related costs were projected to be road flooding from increased precipitation, and building damage associated with near-surface permafrost thaw. These costs decreased by 24% to USD 4.2 billion for the same time frame under RCP4.5, indicating that reducing greenhouse gas emissions globally could lessen damages (Figure 3.13). In a related study that included these costs and others, as well as positive gains from climate change in terms of a reduction in heating costs attributable to warmer winter, annual net costs were still USD 340–700 million, or 0.6–1.3% of Alaska's GDP, suggesting that climate change costs will outweigh positive benefits, at least for this region (Berman and Schmidt, 2019).

Winter roads (snow covered ground and frozen lakes) are distinct from the infrastructure considered earlier, but have a strong influence on the reliability and costs of transportation in some remote northern communities and industrial development sites (Parlee and Furgal, 2012; Huskey et al., 2014; Overland et al., 2017). For these communities, changing lake and river levels and the period of safe ice cover all affect the duration of use of overland travel routes and inland waterways, with associated implications for increased travel risks, time, and costs (Laidler, 2012; Ford et al., 2013; Goldhar et al., 2014). There have been recent instances of severely curtailed ice road shipping seasons due to unusually warm conditions in the early winter (Sturm et al., 2017). While the impact of human effort on the maintenance of winter roads is difficult to quantify, a reduction in the operational time window due to winter warming is projected (Mullan et al., 2017).

3.5 Human Responses to Climate Change in Polar Regions

3.5.1 The Polar Context for Responding

Human responses to climate change in the Arctic and Antarctica are shaped by their unique physical, ecological, social, cultural and political conditions. Extreme climatic conditions, remoteness from densely populated regions, limited human mobility, short seasons of biological productivity, high costs in monitoring and research, sovereignty claims to lands and waters by southern-based governments, a rich diversity of indigenous cultures and institutional arrangements that in some cases recognise indigenous rights and support regional and international cooperation in governance are among the many factors that impede and or facilitate adaptation.

The social and cultural differences are an especially noteworthy factor in assessing polar responses. Approximately four million people currently reside in the Arctic with about three quarters residing in urban areas, and approximately 10% being Indigenous (AHDR, 2014). Regions of the Arctic differ widely in population, ranging from 94% of Iceland's population living in urban environments to 68% of Nunavut's population living in rural areas. And while there has been a general

movement to greater urbanisation in the Arctic (AHDR, 2014), that trend is not true for all regions (Heleniak, 2014). About 4400 people reside in Antarctica in the summer and about 1100 in the winter, predominantly based at research stations of which approximately 40 are occupied year-round (The World Factbook, 2016).

For most Arctic Indigenous peoples, human responses to climate change are viewed as a matter of cultural survival (Greaves, 2016) (Cross-Chapter Box 3 in Chapter 1). However, Indigenous people are not homogenous in their perspectives. While in some cases Indigenous people are negatively impacted by sectoral activities such as mining and oil and gas development (Nymand and Fondahl, 2014), in other cases they benefit financially (Shadian, 2014), setting up dilemmas and potential internal conflicts (Huskey, 2018; Southcott and Natcher, 2018) (*high confidence*). Geopolitical complexities also confound responses.

Together these conditions make for complexity and uncertainty in human decision making, be it at the household and community levels to the international level. Adding to uncertainty in human choice related to climate change is the interaction of climate with other forces for change, such as globalisation and land and sea-use change. These interactions necessitate that responses to climate change consider cumulative effects as well as context-specific pathways for building resilience (Nymand and Fondahl, 2014; ARR, 2016).

3.5.2 Responses of Human Sectors

The sections below assess human responses to climate change in polar regions by examining various sectors of human-environment activity (i.e., social-ecological subsystems), reviewing their respective systems of governance related to climate change, and considering possible resilience pathways. Table 3.4 summarises the consequences, interacting drivers, responses and assets for responding to climate change by social-ecological subsystems (i.e., sectors) of Arctic and Antarctic regions. An area of response not elaborated in this assessment is geoenvironmental sea ice remediation to support local-to-regional ecosystem restoration and which may also affect climate via albedo changes. There is an emerging body of literature on this topic (e.g., Berdahl et al., 2014; Desch et al., 2017; Field et al., 2018), which at present is too limited to allow assessing dimensions of feasibility, benefits and risks, and governance.

3.5.2.1 Commercial Fisheries

Responses addressing changes in the abundance and distribution of fish resources (Section 3.2.4.1) differ by region. In some polar regions, strategies of adaptive governance, biodiversity conservation, scenario planning and the precautionary approach are in use (NPFMC, 2018). Further development of coordinated monitoring programs (Cahalan et al., 2014; Ganz et al., 2018), data sharing, social learning and decision support tools that alert managers to climate change impacts on species and ecosystems would allow for appropriate and timely responses including changes in overall fishing capacity, individual stock quotas, shifts between different target species, opening/closure of different geographic areas and balance between different fishing

fleets (Busch et al., 2016; NPFMC, 2019; see Section 3.5.4). Scenario planning, adaptive management and similar efforts will contribute to the resilience and conservation of these social-ecological systems (*medium confidence*).

Five Arctic States, known as 'Arctic 5' (Canada, Denmark, Norway, Russia and the United States) have sovereign rights for exploring and exploiting resources within their 200 nautical mile Exclusive Economic Zones (EEZs) in the High Arctic and manage their resources within their own regulatory measures. A review of future harvest in the European Arctic (Haug et al., 2017) points towards high probability of increased northern movement of several commercial fish species (Section 3.3.3.1, Box 3.4), but only to the shelf slope for the demersal species. This shift suggests increased northern fishing activity, but within the EEZs and present management regimes (Haug et al., 2017) (*medium confidence*).

In 2009, a new Marine Resources Act entered into force for Norway's EEZ. This act applies to all wild living marine resources, and states that its purpose is to ensure sustainable and economically profitable management of resources. Conservation of biodiversity is described as an integral part of its sustainable fisheries management and it is mandatory to apply "an ecosystem approach, taking into account habitats and biodiversity" (Gullestad et al., 2017). In addition to national management, the Joint Norwegian-Russian Fisheries Commission provides cooperative management of the most important fish stocks in the Barents and Norwegian Seas. The stipulation of the total quota for the various joint fish stocks is a key element, as is more long-term precautionary harvesting strategies, better allowing for responses to climate change (*medium confidence*). A scenario-based approach to identify management strategies that are effective under changing climate conditions is being explored for the Barents Sea (Planque et al., 2019).

In the US Arctic, an adaptive management approach has been introduced that utilises future ecological scenarios to develop strategies for mitigating the future risks and impacts of climate change (NPFMC, 2018). The fisheries of the southeastern Bering Sea are managed through a complex suite of regulations that includes catch shares (Ono et al., 2017), habitat protections, restrictions on forage fish, bycatch constraints (DiCosimo et al., 2015) and community development quotas. This intricate regulatory framework has inherent risks and benefits to fishers and industry by limiting flexibility (Anderson et al., 2017b). To address these challenges, the North Pacific Fishery Management Council recently adopted a Fishery Ecosystem Plan that includes a multi-model climate change action module (Punt et al., 2016; Holsman et al., 2017; Zador et al., 2017; Holsman et al., 2019). Despite this complex ecosystem-based approach to fisheries management, it may not be possible to prevent projected declines of some high value species at high rates of global warming (Ianello et al., 2016).

In the US portion of the Chukchi and Beaufort Seas EEZ, fishing is prohibited until sufficient information is obtained to sustainably manage the resource (Wilson and Ormseth, 2009). In the Canadian sector of the Beaufort Sea, commercial fisheries are currently only small-scale and locally operated. However, with decreasing ice cover

and potential interest in expanding fisheries, the Inuvialuit subsistence fishers of the western Canadian Arctic developed a new proactive ecosystem-based Fisheries Management Framework (Ayles et al., 2016). Also in Western Canada, the commercial fishery for Arctic char (*Salvelinus alpinus*) in Cambridge Bay is co-managed by local Inuit organisations and Fisheries and Oceans Canada (DFO, 2014).

The high seas region of the CAO is per definition outside of any nation's EEZ. Recent actions of the international community show that a precautionary approach to considerations of CAO fisheries has been adopted (*high confidence*) and that expansion of commercial fisheries into the CAO will be constrained until sufficient information is obtained to manage the fisheries according to an ecosystem approach to fisheries management (*high confidence*). The Arctic 5 officially adopted the precautionary approach to fishing in 2015 by signing the Oslo Declaration concerning the prevention of unregulated fishing in the CAO. The declaration established a moratorium to limit potential expansion of CAO commercial fishing until sufficient information, also on climate change impacts, is available to manage it sustainably. The Arctic 5 and several other nations subsequently agreed to a treaty (the Central Arctic Ocean Fisheries Agreement) that imposed a 16-year moratorium on commercial fishing in the CAO.

CCAMLR is responsible for the conservation of marine resources south of the Antarctic Polar Front (CCAMLR, 1982), and has ecosystem-based fisheries management embedded within its convention (Constable, 2011). This includes the CCAMLR Ecosystem Monitoring Program, which aims to monitor important land-based predators of krill to detect the effects of the krill fishery on the ecosystem. Currently, there is no formal mechanism for choosing which data are needed in a management procedure for krill or how to include such data. However, this information will be important in enabling CCAMLR fisheries management to respond to the effects of climate change on krill and krill predators in the future.

Commercial fisheries management responses to climate change impacts in the Southern Ocean may need to address the displacement of fishing effort due to poleward shifts in species distribution (Pecl et al., 2017) (Box 3.4) (*low confidence*). Fisheries in the Southern Ocean are relatively mobile and are potentially able to respond to range shifts in target species, which is in contrast to small-scale coastal fisheries in other regions. Management responses will also need to adapt to the effects of future changes in sea ice extent and duration on the spatial distribution of fishing operations (ATCM, 2017; Jabour, 2017) (Section 3.2.4).

3.5.2.2 Arctic Subsistence Systems

Subsistence users have responded to climate change by adapting their wildfood production systems and engaging in the climate policy processes at multiple levels of governance. The limitations of many formal institutions, however, suggest that in order to achieve greater resilience of subsistence systems with climate change, transformations in governance are needed to provide greater power sharing, including more resources for engaging in climate change studies and regional-to-national policy making (see Sections 3.2.4.1.1, 3.4.3.2.2, 3.4.3.3.1, 3.4.3.3.2, 3.4.3.3.3, 3.5.3).

Adaptation by subsistence users to climate change falls into several categories. In some cases harvesters are shifting the timing of harvesting and the selection of harvest areas due to changes in seasonality and access to traditional use areas (AMAP, 2017a; AMAP, 2017b; AMAP, 2018). Changes in the navigability of rivers (i.e., shallower) and more open (i.e., dangerous) seas have resulted in harvesters changing harvesting gear, such as shifting from propeller to jet-propelled boats or all-terrain vehicles, and to larger ocean-going vessels for traditional whaling (Brinkman et al., 2016). In many cases, using different gear results in an increase in fuel costs (e.g., jet boats are about 30% less efficient). Unsafe ice conditions have resulted in greater risks of travel on rivers and the ocean in the frozen months. In Savoonga, Alaska, whalers reported limitations in harvesting larger bowhead because of thin ice conditions that do not allow for safe haul outs, and as a result, community residents now anticipate a greater dependence on western Alaska's reindeer as a source of meat in the future (Rosales and Chapman, 2015). Harvesters have also responded with switching of harvested species and in some cases doing without (AMAP, 2018). In many cases, adaptation has allowed for continued provisioning of wildfoods in spite of climate change impacts (BurnSilver et al., 2016; AMAP, 2017a; Fauchald et al., 2017b) (*medium confidence*).

The impacts of climate change have also required adaptation to the non-harvesting aspects of wildfood production, such as an abandonment of traditional food storage and drying practices (e.g., ice cellars) and an increased use of household and community freezers (AMAP, 2017a). In several cases there has been an increased emphasis on community self-reliance, such as use of household and community gardens for food production (Loring et al., 2016). In the future, agriculture may be more possible with improved conditions at the southern limit of the Arctic, and could supplement hunting and fishing (AMAP, 2018).

Climate change may in the future bring both new harvestable fish, birds, mammals and berry producing plants to the north, and reduced populations and or access to currently harvested species (AMAP, 2017a; AMAP, 2017b; AMAP, 2018). Adaptive co-management and stronger links of local-to-regional level management with national to international level agreements necessitate consideration for sustainable harvest of new resources, as well as securing sustainable harvest or even full protection of dwindling or otherwise vulnerable populations. In these cases, adaptive co-management could be an efficient tool to achieve consensus on population goals, including international cooperation and agreements regarding migratory species shared between more countries (Kocho-Schellenberg and Berkes, 2014) (Section 3.5.4.3).

While there has been involvement of subsistence users in monitoring and research on climate change (Section 3.5.4.1.1), resource management regimes that regulate harvesting are largely dictated by science-based paradigms that give limited legitimacy to the knowledge and suggested preferences of subsistence users (Section 3.5.4.2, Cross-Chapter Box 4 in Chapter 1).

The social costs and social learning associated with responding to climate change are often related. Involvement in adaptive

co-management comes with high transaction costs (e.g., greater demands on overburdened indigenous leaders, added stress of communities living with limited resources) (Forbes et al., 2015). In some cases, co-management has given communities a greater voice in decision making, but when ineffective, these arrangements can perpetuate dominant paradigms of resource management (AMAP, 2018). The perceived risks of climate change can at the same time reinforce cultural identity and motivate greater political involvement, which in turn, gives indigenous leaders experience as agents of change in policy making. Penn et al. (2016) pointed to these conflicting forces, arguing the need for a greater focus on community capacity and cumulative effects.

Greater involvement of indigenous subsistence users in Canada occurs at the national and regional levels through the structures and provisions of indigenous settlement agreements (e.g., 1993 Nunavut Land Claims Agreement, 1984 Inuvialuit Final Agreement), fish and wildlife co-management agreements (e.g., Porcupine Caribou Management Agreement of 1986), and through various boundary organisations (e.g., CircumArctic Rangifer Monitoring and Assessment Network). Home rule in Greenland, established in 1979, gives the Naalakkersuisut (government of Greenland) authority on most domestic matters of governance.

Indigenous leaders are responding to the risks of climate change by engaging in political processes at multiple levels and through different venues. However, indigenous involvement in IPCC assessments remains limited (Ford et al., 2016). At the United Nations Framework Convention on Climate Change (UNFCCC), the discursive space for incorporating perspectives of Indigenous peoples on climate change adaptation has expanded since 2010, which is reflected in texts and engagement with most activity areas (Ford et al., 2015) and by the establishment of the Local Communities and Indigenous Peoples Platform Facilitative Working Group in December 2018. Aleut International Association, Arctic Athabaskan Council, Gwich'in Council International, Inuit Circumpolar Council, Russian Association of Indigenous Peoples of the North, and the Saami Council, which sit as 'Permanent Participants' of the Arctic Council, are involved in many of its working groups and partake also at the political level (Section 3.5.3.2.1).

3.5.2.3 Arctic Reindeer Herding

Herders' responses to climate change have varied by region and respective herding practices, and in some cases are constrained by limited access to pastures (Klokov, 2012; Forbes et al., 2016; Uboni et al., 2016; Mallory and Boyce, 2017). These conditions are exacerbated in some cases by high numbers of predators (Lavrillier and Gabyshev, 2018). In Fennoscandia, husbandry practices of reindeer by some (mostly Sami) include supplemental feeding, which provide a buffer for unfavourable conditions. In Alaska, reindeer herding is primarily free range, where herders must manage herd movements in the event of icing events and the potential loss of reindeer because the movements of caribou herds (wild reindeer), both of which are partially driven by climate. For Nenets of the Yamal, Russia, resilience in herding has been facilitated through herders' own agency and, to some extent, the willingness of the gas

industry to observe non-binding guidelines that provide for herders' continued use of traditional migrations routes (Forbes et al., 2015). In response to climate change (i.e., icing events and early spring runoffs blocking migration), the only way of avoiding high deer mortality is to change migration routes or take deer to other pastures. In practice, however, the full set of challenges has meant more Yamal herders opting out of the traditional collective migration partially or entirely to manage their herds privately. The reason to have private herds is one of adaptive advantage; smaller, privately owned herds are nimbler in the face of rapid changes in land cover and the expansion of infrastructure (Forbes, 2013). The same logic has more recently been applied by some herders in the wake of recent rain-on-snow events (Section 3.4.3.2.2) (Forbes et al., 2016). In all these regions, restrictions affecting the movement of reindeer to pastures are expected to negatively interact with the effects of climate and affect the future sustainability of herding systems (*high confidence*).

3.5.2.4 Tourism

The growth of the polar tourism market is, in part, a response to climate change, as travellers seek 'last-chance' opportunities, which, in turn, is creating new challenges in governance (Section 3.2.4.2). Polar-class expedition cruise vessels are now, for the first time, being purposefully built for recreational Arctic sea travel. The anticipated near- and long-term growth of Arctic tourism, especially with small vessels (yachts) (Johnston et al., 2017), points to a deficiency in current regulations and policies to address human safety, environmental risks and cultural impacts. Industry growth also points to the need for operators, governments, destination communities and others to identify and evaluate adaptation strategies, such as disaster relief management plans, updated navigation technologies for vessels, codes of conduct for visitors and improved maps (Pizzolato et al., 2016) and to respond to perceptions of tourism by residents of local destinations (Kaján, 2014; Stokke and Haukeland, 2017). Efforts were initiated with stakeholders in Arctic Canada to identify strategies that would lower risks (Pizzolato et al., 2016); a next step to lower risks and build resilience is to further develop those strategies (AMAP, 2017a; AMAP, 2017b; AMAP, 2018). Opportunities for tourism vessels in the Arctic to contribute to international research activities ('ships of opportunity') may improve sovereignty claims in some regions, contribute to science and enhance education of the public (Stewart et al., 2013; Arctic Council, 2015a; Stewart et al., 2015; de la Barre et al., 2016).

Tourism activities in the Antarctic are conducted in accordance with the Protocol on Environmental Protection to the Antarctic Treaty, which establishes general environmental principles, environmental assessment requirements, a scheme of establishing protected areas and restrictions on waste disposal. Site-specific management tools are in place. While there are varying views amongst Antarctic Treaty Parties on the best management regulations for Antarctic tourism, these Parties continue to work to manage tourism activity, including growth in numbers of visitors. In addition to the Protocol, mandatory measures have been agreed to manage aspects of tourism activity. Industry self-regulation supplements these requirements, coordinated by the International Association of Antarctica Tour Operators, which has worked with Antarctic Treaty Consultative Parties to manage changes in operations and their impact on ice-free areas (ATCM, 2016).

3.5.2.5 Arctic Non-Renewable Extractive Industries

Climate change has resulted a limited response by non-renewable resource extraction industries and agencies in the Arctic to changes in sea ice, thawing permafrost, spring runoffs, and resultant timing of exploration, construction and use of ice roads, and infrastructure design (AHDR, 2014). In some regions, climate change has offered new development opportunities, although off-shore prospects remaining cost prohibitive given current world markets (Petrick et al., 2017). (In the area covered by the Antarctic Treaty, exploitation of mineral resources is prohibited by the Protocol on Environmental Protection to the Antarctic Treaty.)

Climate change in some Arctic regions is facilitating easier access to natural resources (Section 3.5.2.3), which may generate financial capital for Arctic residents and their governments, including Indigenous peoples but also greater exposure to risks such as oil spills and increases in noise. Receding sea ice and glaciers has opened new possibilities for development, such as areas of receding glaciers of eastern Greenland (Smits et al., 2017). As mineral development commenced in Greenland, its home rule government developed environmental impact assessment protocols to provide for improved public participation (Forbes et al., 2015). Indigenous peoples are considered as non-state actors and in many, but not all cases, promote environmental protection in support of the sustainability of their traditional livelihoods. This protection is at times in opposition to the industrial development business sector, which is well-funded and lobbies strongly. Bilateral agreements for resource development in the Arctic are typically state dominated and controlled, and are negotiated with powerful non-state actors, such as state-dominated companies (Young, 2016). Among the non-state actors, new networks and economic forums have been established (Wehrmann, 2016). One example is the Arctic Economic Council, created by the Arctic Council during 2013–2015 as an independent organisation that facilitates Arctic business-to-business activities and supports economic development.

Several regional governments are assessing the long-term viability of ice roads, historically used for accessing mineral development sites, as well as some Arctic human settlements. In Northwest Territories, Canada, several ice roads are being replaced with all-season roads, with other replacements proposed. Assessing future conditions is key for planning and initiating new projects (Hori et al., 2018; Kiani et al., 2018) but is often constrained by uncertainties of available climate models (Mullan et al., 2017).

On the North Slope of Alaska, oil and gas development is now undergoing new expansion, while industry concurrently faces increasing challenges of climate change, such as shorter and warmer winters, the main season for oil exploration and production (Lilly, 2017). The method for building of ice roads on the North Slope has been somewhat modified to account for warmer temperatures during construction. There are also knowledge gaps in understanding implications of seismic studies with climate change on the landscape (Dabros et al., 2018). The issue of cumulative effects also raises questions of current practice of environmental impact assessment to evaluate potential cumulative effects (Kirkfeldt et al., 2016).

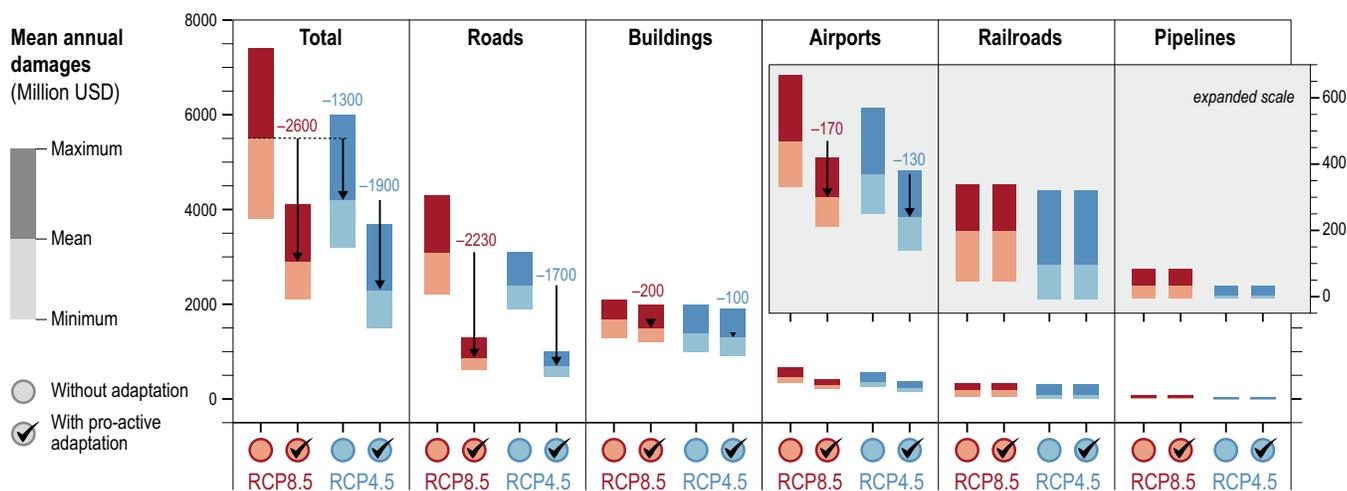


Figure 3.12 | Changes in public infrastructure damage costs in cumulative USD by 2100 in Alaska under different emission scenarios (Representative Concentration Pathways (RCP)). The inset showing airports, railroads, and pipelines has a different in scale than roads, buildings, and the total. Bars over open circles represent climate-related costs of impact with no engineering adaptation measures, whereas bars over check-marked circles represent the costs following savings from engineering adaptation (figure modified from Melvin et al., 2017).

Lilly (2017) reported that optimising Alaska North Slope transportation networks during winter field operations is critical in managing increasing resource development and could potentially provide a better framework for environmentally responsible development. Better understanding of environmental change is also important in ensuring continued oil field operations with protection of natural resources. Improved forecasting of short-term conditions (i.e., snow, soil temperatures, spring runoffs) could allow management agencies to respond to conditions more proactively and give industry more time to plan winter mobilisation, such as construction of ice roads (*low confidence*).

3.5.2.6 Infrastructure

Reducing and avoiding the impacts of climate change on infrastructure will require special attention to engineering, land use planning, maintenance operations, local culture and private and public budgeting (AMAP, 2017a; AMAP, 2017b; AMAP, 2018). In some cases, relocation of human settlements will be required, necessitating more formal methods of assessing relocation needs and identifying sources of funding to support relocations (Cross-Chapter Box 9) (*high confidence*).

A discussion of the relocation of Alaska's coastal villages is found in Cross-Chapter Box 9. Alaskan coastal communities are not the only settlements potentially requiring relocation. Subsidence due to thawing permafrost and river and delta erosion makes other rural communities of Alaska and Russia vulnerable, potentially requiring relocation in the future (Bronen, 2015; Romero Manrique et al., 2018). These situations raise issues of environmental justice and human rights (Bronen, 2017), and illustrate the limits of incremental adaptation when transformation change is needed (Kates et al., 2012). In other cases, cultural resources in the form of historic infrastructure are being threatened and require mitigation (Radosavljevic et al., 2015). Responsibility for funding has been a key issue in the relocation process (Iverson, 2013) as well as the overall role of government and local communities in relocation planning

(Marino, 2012; Romero Manrique et al., 2018). The Alaska Denali Commission, an independent federal agency designed to provide critical utilities, infrastructure and economic support throughout Alaska, is now serving as the lead coordinating organisation for Alaska village relocations and managing federal funding allocations. Several efforts have also been undertaken to provide assessment frameworks and protocols for settlement relocation as an adaptive resource (Bronen, 2015; Ristroph, 2017).

While there has been discussion of future 'climigration' in rural Alaska (Bronen and Chapin, 2013; Matthews and Potts, 2018), a study of Alaska rural villages threatened by climate change showed no outmigration response (Hamilton et al., 2016). Several factors explain the lack of outmigration, including an unwillingness to move, attachment to place, people's inability to relocate, the effectiveness of alternative ways of achieving acceptable outcomes and methods of buffering through subsidies (Huntington et al., 2018) (*medium confidence*).

The current pan-Arctic trend of urbanisation (AHDR, 2014), suggests that climate change responses related to infrastructure in towns and cities of the North will require significant adaptation in designs and increases in spending (Streletskiy et al., 2012). These costs do not include costs related to flooding and other stressors associated with warming or additional costs of commercial and industrial operations. Engineers in countries with permafrost are actively working to adapt the design of structures to degrading permafrost conditions (Dore et al., 2016) and the effects of a warming climate, for example the Cold Climate Housing Research Center of Alaska.

An analysis of the costs of total damages from climate change to public infrastructure in Alaska show the financial benefits of proactive adaptation (Melvin et al., 2017) (Figure 3.12). In addition to global carbon emission mitigation, hardening and redesigning of infrastructure can reduce costs of future climate-related impacts. For example, retrofitting and redesigning of infrastructure in order to handle increased precipitation and warmer temperatures can reduce

climate-related costs by 50%, from USD 5.5 to 2.9 billion under RCP8.5 by 2100. The cost savings of retrofitting and redesigning infrastructure is even higher than the savings from carbon mitigation, where impact costs are estimated at USD 4.2 billion under RCP4.5 by 2100. Engineering adaptation provide proportionally similar cost savings no matter which emission scenario was used.

3.5.2.7 Marine Transportation

Increases in Arctic marine transportation create impacts and risks for ecosystems and people, such as an increased likelihood of accidents, the introduction of invasive species, oil spills, waste discharges, detrimental impacts on animals, habitat and subsistence activities (Sections 3.2.4.3, 3.4.3.3.2). There has been a rise in geopolitical debate regarding national and international level regulations and policies, and maritime infrastructure to support Arctic shipping development (Heininen and Finger, 2017; AMAP, 2018; Drewniak et al., 2018; Nilsson and Christensen, 2019). Without further action leading to adequate implementation of well-developed management plans and region-specific regulations, anticipated future increases in Arctic shipping will pose a greater risk to people and ecosystems (*high confidence*).

The International Maritime Organization (IMO) has responsibility for the safety and security of shipping and the prevention of marine and atmospheric pollution by ships, including in the Arctic and Antarctic. There are a number of mechanisms standardising regulation and governance, such as the International Convention for the Prevention of Pollution from Ships; the International Convention for the Safety of Life at Sea; the International Convention on Standards of Training, and the Certification and Watchkeeping for Seafarers, and the newly implemented International Code for Ships Operating in Polar Waters, or Polar Code (IMO, 2017).

The Polar Code of 2017 sets new standards for vessels travelling in polar areas to mitigate environmental damage and improve safety (IMO, 2017). The Polar Code, however, currently excludes fishing vessels and vessels on government service, thereby excluding many shipping activities, particularly in the Antarctic region (IMO, 2017). Many ships travelling these waters will therefore continue to pose risks to the environment and to themselves, as they are not regulated under the Polar Code (*high confidence*). The Polar Code does not enhance enforcement capabilities or include environmental protection provisions to address a number of particular polar region-specific risks such as black carbon, ballast water and heavy fuel oil transport and use in the Arctic (Anderson, 2012; Sakhuja, 2014; IMO, 2017). However, both Russian and Canadian legislation provide the possibility for stricter shipping provisions in ice-covered waters. The IMO has prohibited the use of heavy fuel oil in the Antarctic.

States can individually or cooperatively pursue the establishment of Special Areas and Particularly Sensitive Sea Areas at the IMO with a view to protect ecologically unique or vulnerable and economically or culturally important areas in national and international waters from risks and impacts of shipping, including through routing, discharge and equipment measures. Continued, and in some areas, greater, international cooperation on shipping governance can

facilitate addressing emerging climate change issues (Arctic Council, 2015a; ARR, 2016; PEW Charitable Trust, 2016; Chénier et al., 2017; IMO, 2017) (*high confidence*). Cooperation of the member states of the Arctic Council resulted in the 2011 Agreement on Cooperation on Aeronautical and Maritime Search and Rescue in the Arctic and in the 2013 Agreement on Cooperation on Marine Oil Pollution Preparedness and Response in the Arctic. These agreements can, if adequately implemented, reduce risks from increased Arctic shipping (*medium confidence*), however, developing more effective measures is needed as preparedness and response gaps still exist, for example, for the central Arctic Ocean.

Industry has responded to the increase in shipping activity by investing in development of shipping designs for travel in mixed-ice environments (Stephenson et al., 2011; Stephenson et al., 2013). These increases in investments are occurring in spite of the limited total savings when comparing shorter travel to increased CO₂ emissions (Lindstad et al., 2016). In anticipation of spills, research in several regions has explored oil spill response viability and new methods of oil spill response for the Arctic environment (Bullock et al., 2017; Dilliplaine, 2017; Holst-Andersen et al., 2017; Lewis and Prince, 2018) (*medium confidence*). A comparative risk assessment for spills has been developed for the Arctic waters (Robinson et al., 2017) and Statoil has developed and uses risk assessment decision-support tools for environmental management, together with environmental monitoring (Utvik and Jahre-Nilsen, 2016). These tools facilitate the assessment of Arctic oil-spill response capability, ice detection in low visibility, improved management of sea ice and icebergs, and numerical modelling of icing and snow as risk mitigation.

3.5.2.8 Arctic Human Health and Well Being

At present health adaptation to climate change is generally under-represented in policies, planning, and programming (AHDR, 2014). For instance, all initiatives of the Fifth National Communications of Annex I parties to the UNFCCC affect health vulnerability, however, only 15% of initiatives had an explicit human health component described (Lesnikowski et al., 2011). The Arctic is no exception to this global trend. Despite the substantial health risks associated with climate change in the Arctic, health adaptation responses remain sparse and piecemeal (Lesnikowski et al., 2011; Panic and Ford, 2013; Ford et al., 2014b; Loboda, 2014), with the health sector substantially under-represented in adaptation initiatives compared to other sectors (Pearce et al., 2011; Ford et al., 2014b; National Research Council, 2015). Furthermore, the geographic distribution of publicly available documentation on adaptation initiatives is skewed in the Arctic, with more than three-quarters coming from Canada and USA (Ford et al., 2014a; Loboda, 2014).

Many Arctic health adaptation efforts by governments have been groundwork actions, focused increasing awareness of the health impacts of climate change and conducting vulnerability assessments (Lesnikowski et al., 2011; Panic and Ford, 2013; Austin et al., 2015). For instance, in Canada this effort has included training, information resources, frameworks, general outreach and education and dissemination of information to decision makers (Austin et al., 2015). Finland's national adaptation strategy outlines various

anticipatory and reactive measures for numerous sectors, including health (Gagnon-Lebrun and Agrawala, 2007). In Alaska, the Arctic Investigations Program responds to infectious disease via advancing molecular diagnostics, integrating data from electronic health records and environmental observing networks, as well as improving access to in-home water and sanitation services. Furthermore, circumpolar efforts are also underway, including a circumpolar working group with experts from public health to assess climate-sensitive infectious diseases, and to identify initiatives that reduce the risks of disease (Parkinson et al., 2014). Importantly, health adaptation is occurring at the local scale in the Arctic (Ford et al., 2014a; Ford et al., 2014b). Adaptation at the local-scale is broad, ranging from community freezers to increase food security, to community-based monitoring programs to detect and respond to climate health events, to Elders mentoring youth in cultural activities to promote mental health when people are 'stuck' in the communities due to unsafe travel conditions (Pearce et al., 2010; Brubaker et al., 2011; Harper et al., 2012;

Brubaker et al., 2013; Douglas et al., 2014; Austin et al., 2015; Bunce et al., 2016; Cunsolo et al., 2017) (*high confidence*). Several regional and national-level initiatives on food security (ICC, 2012), as well as research reporting high levels of household food insecurity (Kofinas et al., 2016; Watts et al., 2017) have prompted greater concerns for climate change (Loring et al., 2013; Beaumier et al., 2015; Islam and Berkes, 2016). A new initiative to operationalise One Health concepts and approaches under the AC's Sustainable Development Working Group has gained momentum since 2015 (Ruscio et al., 2015). One Health approaches seek to link human, animal, and environmental health, using interdisciplinary and participatory methods that can draw on indigenous knowledge and local knowledge (Dudley et al., 2015). Thus far, the initiative has supported new regional-to-international networks, and proposals for its expansion. In the future, the ability to manage, respond, and adapt to climate-related health challenges will be a defining issue for the health sector in the Arctic (Ford et al., 2010; Durkalec et al., 2015) (*medium confidence*).

Table 3.4 | Response of key human sectors /systems to climate change in polar regions. Table 3.4 summarises the consequences, interacting drivers, responses, and assets of climate change responses by select human sectors (i.e., social-ecological systems) of Arctic and Antarctic regions. Also noted are anticipated future conditions and level of certainty and other drivers of change that may interact with climate and affect outcomes. Implications to world demands on natural resources, innovation and development of technologies, population trends and economic growth are likely to affect all systems, as is the Paris Agreement (AMAP, 2017b). In several cases, drivers of change interacting with climate change are regionally specific and not easily captured. In many cases there is limited information on human responses to climate change in the Russian Arctic.

Sector / System	Consequence of climate change	Documented responses	Key assets and strategies of adaptive and transformative capacity	Anticipated future conditions / level of certainty	Other forces for change that may interact with climate and affect outcomes
Commercial Fisheries	Consequences are multi-dimensional, including impacts to abundance and distribution of different target species differently, by region. Changes in coastal ecosystems affecting fisheries productivity	Implementation of adaptive management practices to assess stocks, change allocations as needed, and address issues of equity	Implementation of adaptive management that is closely linked to monitoring, research, and public participation in decisions	Displacement of fishing effort will impact fishing operations in the eastern Bering Sea and Barents Sea as well as the Convention for the Conservation of Antarctic Marine Living Resources area	Changes in human preference, demand and markets, changes in gear, changes in policies affecting property rights. Changes due to offshore development and transportation
Subsistence (marine and terrestrial)	Changes in species distribution and abundance (not all negative); impediments to access of harvesting areas; safety; changes in seasonality; reduced harvesting success and process of food production (processing, food storage; quality); threats to culture and food security	Change in gear, timing of hunting, species switching; mobilisation to be involved in political action	Systems of adaptive co-management that allow for species switching, changes in harvesting methods and timing, secure harvesting rights	Less access to some areas, more in others. Changes in distribution and abundance of resources. More restrictions with regulations related to species at risk. Adaptation at the individual, household, and community levels may be seriously restricted by conditions where there is poverty (<i>high confidence</i>)	Changes in cost of fuel, land use affecting access, food preferences, harvesting rights; international agreements to protect vulnerable species
Reindeer Herding	Rain-on-snow events causing high mortality of herds; shrubification of tundra pasture lowering forage quality	Changes in movement patterns of herders; policies to ensure free-range movements; supplemental feeding	Flexibility in movement to respond to changes in pastures, secure land use rights and adaptive management. Continued economic viability and cultural tradition.	Increased frequency of extreme events and changing forage quality adding to vulnerabilities of reindeer and herders (<i>medium confidence</i>)	Change in market value of meat; overgrazing; land use policies affecting access to pasture and migration routes, property rights
Tourism (Arctic and Antarctic)	Warmer conditions, more open water, public perception of 'last chance' opportunities	Increased visitation, (quantity and quality) increase in off-season tourism to polar regions	Policies to ensure safety, cultural integrity, ecological health, adequate quarantine procedures	Increased risk of introduction of alien species and direct effects of tourists on wildlife	Travel costs. Shifting tourism market, more enterprises

Sector / System	Consequence of climate change	Documented responses	Key assets and strategies of adaptive and transformative capacity	Anticipated future conditions/level of certainty	Other forces for change that may interact with climate and affect outcomes
Non-Renewable Resource Extraction (Arctic only)	Reduced sea ice and glaciers offering some new opportunities for development; changes in hydrology (spring runoff), thawing permafrost, and temperature affect production levels, ice roads, flooding events, and infrastructure	Some shifts in practices, greater interest in offshore and on-land development opportunities in some regions	Modification of practices and use of climate change scenario analysis	Increased cost of operations in areas of permafrost thawing; more accessible areas in open waters and receding glaciers	Changes in policies affecting extent of sea and land use area, new extraction technologies (e.g., fracking), changes in markets (e.g., price of barrel of oil)
Infrastructure -urban and rural human settlements, year-round	Thawing permafrost affecting stability of ground; coastal erosion	Damaged and loss of infrastructure, increase in operating costs	Resources for assessments, mitigation, and where needed, relocation	Increasing cost to maintain infrastructure and greater demand for technological solutions to mitigate issues. Shortening windows of operation for use of ice roads; construction of all-season roads	Weak regional and national economies, other disasters that divert resources, disinterest by southern-based law makers
Marine Transportation	Open seas allowing for more vessels; greater constraints in use of ice roads	Increased shipping, tourism, more private vessels. Increased risk of hazardous waste and oil spills and accidents requiring search and rescue	Strong international cooperation leading to agreed-upon and enforced policies that maintain standards for safety; well-developed response plans with readiness by agents in some regions	Continued increases in shipping traffic with increased risks of accidents	Political conflict in other areas that impeded acceptance of policies for safety requirements, timing, and movements. Changing insurance premiums
Human Health	Threats to food security, potential threats to physical and psychological well being	Greater focus on food security research; programs that address fundamental health issues	Human and financial resources to support public programs in hinterland regions; cultural awareness of health issues as related to climate change	Greater likelihood of illnesses, food insecurity, cost of health care	A reduction (of increase) in public resources to support health services to rural community populations, research that links ecological change to human health
Coastal Settlements (see Cross-Chapter Box 9)	Change in extent of sea ice with more storm surges, thawing of permafrost, and coastal erosion	Maintenance of erosion mitigation; relocation planning, some but incomplete allocation for funding	Local leadership and community initiatives to initiate and drive processes, responsive agencies, established processes for assessments and planning, geographic options	Increasing number of communities needing relocation, rising costs for mitigating erosion issues	Limitations of government budgets, other disasters that may take priority for spending, deficiencies in policies for addressing mitigation and relocation

3.5.3 Governance

3.5.3.1 Local to National Governance

Responses to climate change at and across local, regional and national levels occur directly and indirectly through a broad range of governance activities, such as land and sea use planning and regulations, economic development strategies, tax incentives for use of alternative energy technologies, permitting processes, resource management and national security. Increasingly, climate change is considered in environmental assessments and proposals for resource planning of polar regions.

A comprehensive literature review of 157 discrete cases of Arctic adaptation initiatives by Ford et al. (2014b) found that adaptation is primarily local and motivated by reducing risks and their related vulnerabilities (*high confidence*). Several elements for successful climate change adaptation planning at the local level have previously been identified: formal analytical models need to be relevant to the concerns and needs of stakeholders, experts should be made sensitive to community perspectives, information should be packaged and communicated in ways that are accessible to non-experts

and processes of engagement that foster creative problem solving be used. Furthermore, success of local government involvement in adaptation planning has been closely linked to transnational municipal networks that foster social learning and in which local governments assume a role as key players (Sheppard et al., 2011; Fünfgeld, 2015) (*medium confidence*). While transnational networks can be a catalyst for action and promoting innovation, there remain outstanding challenges in measuring the effectiveness of these networks (Fünfgeld, 2015).

Adaptation through formal institutions by Indigenous people is enabled through self-government, land claims and co-management institutions (Baird et al., 2016; Huet et al., 2017). However, organisational capacity is often a limiting factor in involvement (AHDR, 2014; Ford et al., 2014b; Forbes et al., 2015) (*high confidence*). Interactions across scales are also dependent on the extent to which various stakeholders are perceived as legitimate in their perceptions and recommendations, an issue related to the use of local knowledge and indigenous knowledge in governance (Cross-Chapter Box 4 in Chapter 1) (AHDR, 2014; Ford et al., 2014b; Forbes et al., 2015) (*high confidence*).

At a more regional level, Alaska's 'Climate Action for Alaska' was reconstituted in 2017 and is now actively linking local concerns with state-level policies and funding, as well as setting targets for future reductions in the state's carbon emission. The role of cross-scale boundary organisations in climate change adaptation planning, and how central government initiatives can ultimately translate into 'hybrid' forms of adaptation at the local level that allow for actions that are sensitive to local communities has proven important in Norway (Dannevig and Aall, 2015).

At the national level, Norway, Sweden and Finland have engaged in the European Climate Adaptation Platform (Climate-ADAPT), a partnership that aims to support Europe in adapting to climate change by helping users to access and share data and information on expected climate change in Europe, current and future vulnerability of regions and sectors, national and transnational adaptation strategies and actions, adaptation case studies and potential adaptation options, and tools that support adaptation planning. Level of participation by country and the extent to which national level efforts are linked with regional and local adaptation varies. The Canadian government's actions on climate change have been among the most extensive of the Arctic nations, including funding of ArcticNet, a Network of Centres of Excellence, and consideration of climate change by The Northern Contaminants and Nutrition North Canada programs.

3.5.3.2 International Climate Governance and Law: Implications for International Cooperation

The way states and institutions manage international cooperation on environmental governance is changing in response to climate change in the polar regions. Rather than treating regional impacts of climate change and their governance in isolation (i.e., purely with a regional lens), the need to cooperate in a global multi-regulatory fashion across several levels of governance is increasingly realised (Stokke, 2009; Cassotta et al., 2016) (*medium confidence*).

In both polar regions, cooperative approaches to regional governance have been developed to allow for the participation of non-state actors. In some cases, regimes allow for a substantial level of participation by specific groups of the civil society (Jabour, 2017; Keil and Knecht, 2017). For example, in the Antarctic Treaty System, the Antarctic Treaty Parties included the Scientific Committee on Antarctic Research into their Protocol on Environmental Protection to the Antarctic Treaty. In the Arctic, the status of Permanent Participants has enabled the effective participation of Indigenous Peoples in the work of the Council (Pincus and Ali, 2016). Climate change has contributed to modifying the balance between the interests of state and non-state actors, leading to changing forms of cooperation (Young, 2016). While such changes and modifications occur in both the Arctic and Antarctic, the role of states has remained present in all the regimes and sectors of human responses (Young, 2016; Jabour, 2017).

Addressing the risks of climate change impacts in polar regions also requires linking levels of governance and sector governance across local to global scales, considering impacts and human adaptation (Stokke, 2009; Berkman and Vylegzhanin, 2010; Tuori, 2011; Young,

2011; Koivurova, 2013; Prior, 2013; Shibata, 2015; Young, 2016) (*high confidence*). Despite established cooperation in international polar region governance, several authors have come to the conclusion that the current international legal framework is inadequate when applying a precautionary approach at the regional level (*medium confidence*). For example, several studies have shown that the Convention on the Protection of the Marine Environment of the North East Atlantic, which applies only to the North East Atlantic, and that provides a framework for implementation of the United Nations Convention on the Law of the Sea (UNCLOS) and the Convention on Biological Diversity (CBD), are insufficient to deal with risks when applying a precautionary approach (Jakobsen, 2014; Hossain, 2015).

In the Arctic, responses to climate change do not only lead to international governance cooperation but also to competition in access to natural resources, especially hydrocarbons. With ice retreating and thinning, and improved access to natural resources, coastal states are increasingly recurring to the option to invoke Article 76 of the UNCLOS (Art. 76 UNCLOS; Verschuuren, 2013) and seek to demonstrate with scientific data, submitted to the Commission on the Limits of Continental Shelf, and within a set timeline, that their continental shelf is extended. In that case they can enjoy sovereign rights beyond the EEZ. It is *very unlikely* that this new trend from states to refer to Article 76 will lead to future (military) conflicts (Berkman and Vylegzhanin, 2013; Kullerud et al., 2013; Stokke, 2013; Verschuuren, 2013), although the issue cannot be totally dismissed (Kraska, 2011; Åtland, 2013; Huebert, 2013; Cassotta et al., 2015; Barret, 2016; Cassotta et al., 2016).

In the Antarctic, cooperation in general does occur via UNCLOS, the Convention for the Safety of Life at Sea and the Convention for the Prevention of Pollution from Ships and the Polar Code. Global environmental and climate regimes that are implemented and managed through regional regimes (such as the Kyoto Protocol or the Paris Agreement) are also relevant for the Antarctic Treaty and its Protocol on Environmental Protection, which requires, amongst other issues, a minimisation of adverse environmental impacts. Cooperation in the Antarctic also occurs through the the Convention for the Conservation of Antarctic Marine Living Resources. Climate change and its consequences for the marine environment are a central issue for this Convention because it challenges ways to regulate and manage fisheries and designate and manage Marine Protected Areas. Nevertheless, CCAMLR has not agreed to any climate change program and at its most recent meeting, there was again no agreement to do so (Brooks et al. (2018), CCAMLR Report on the 37th Meeting of the Commission, CCAMLR (2018)).

3.5.3.2.1 Formal arrangements: polar conventions and institutions

The Arctic Council

International cooperation on issues related to climate change in the Arctic mainly occurs at the Arctic Council (herein 'the Council'), and consequently in important areas of its mandate: the (marine) environment and scientific research (Morgera and Kulovesi, 2016; Tesar et al., 2016a; Wehrmann, 2016; Young, 2016). The Council is composed of eight Arctic States and six Permanent Participants representing organisations of Arctic Indigenous peoples. Observers status is open

to: non-Arctic states, intergovernmental and inter-parliamentary organisations, global and regional non-governmental organisations (NGOs). The Council is an example of cooperation through soft law, a unique institutional body that does not possess a legal personality and is neither an international law nor a completely state-centric institution. However, it is acting state-centric and increasingly operating in a context of the Arctic affected by a changing climate, globalisation and transnationalism (Baker and Yeager, 2015; Cassotta et al., 2015; Pincus and Speth, 2015) (*medium confidence*). In 2013, China, South Korea, Italy, Japan, India and Singapore joined France, Germany, the Netherlands, Poland, Spain and the UK as Observer states to the Arctic Council; Switzerland was granted Observer status in 2017. Non-Arctic States are stimulating the Council towards adopting a new approach for Arctic governance that would leave greater space for their participation.

Despite lacking the role to enact hard law, three binding agreements were negotiated under the auspices of the Council (in its task forces), the latest of which is the Agreement on Enhancing International Arctic Scientific Cooperation, which is an indication that the Council is preparing a regulatory role to respond to climate change in the Arctic using hard-law instruments (Morgera and Kulovesi, 2016; Shapovalova, 2016). Through organising the Task Force on Black Carbon and Methane (Morgera and Kulovesi, 2016), the Council has catalysed action on short-lived climate forcers as the task force was followed by the adoption in 2015 of the Arctic Council Framework for Action on Enhanced Black Carbon and Methane Emission Reductions. In this non-legally binding agreement, Arctic States lay out a common vision for national and collective action to accelerate decline in black carbon and methane emissions (Shapovalova, 2016). The Council thereby moved from merely assessing problems to attempting to solve them (Baker and Yeager, 2015; Young, 2016; Koivurova and Caddell, 2018). While mitigation of global emissions from fossil fuels requires global cooperation, progress with anthropogenic emissions of short-term climate forcers (such as black carbon and methane) may be achieved through smaller groups of countries (Aakre et al., 2018). However, even though the Council has also embraced the Ecosystem Approach, it does not have a mandate to manage climate-related risks and impacts, or apply a precautionary approach, on fisheries issues.

Several studies have shown that the Council has the potential to enhance internal coherence in the current, fragmented landscape of multi-regulatory governance by providing integrated leadership. However, it is *about as likely as not* that the Council could play a strong role in combatting global climate problems and operating successfully within the climate transnational context unless it goes through restructuring and reconfiguration (Stokke, 2013; Baker and Yeager, 2015; Pincus and Speth, 2015; Cassotta et al., 2016; Tesar et al., 2016a; Wehrmann, 2016; Young, 2016; Koivurova and Caddell, 2018).

The future of the governance of the changing Arctic Ocean, including the role of the Council will also depend on the implications of the development for a new agreement on the Conservation and Sustainable use of Marine Biodiversity of Areas beyond National Jurisdictions under the UNCLOS (Baker and Yeager, 2015; De Lucia, 2017; Nengye et al., 2017; Koivurova and Caddell, 2018) (*medium confidence*).

The Antarctic Treaty System

The Antarctic Treaty System (ATS) is the collective term for the Antarctic Treaty and related agreements. The ATS regulates international relations with respect to Antarctica. 54 countries have acceded to the Treaty and 29 of them participate in decision making as Consultative Parties. 27 countries are Party to the CCAMLR, and 40 have ratified the Protocol on Environmental Protection to the Antarctic Treaty. The importance of understanding, mitigating and adapting to the impacts of changes to the Southern Ocean and Antarctic cryosphere has been realised by all of the major bodies responsible for governance in the Antarctic region (south of 60°S). The Antarctic Treaty Consultative Parties agreed that a Climate Change Response Work Programme would address these matters (ATCM, 2016). This led to the establishment of the Subsidiary Group of the Committee for Environmental Protection on Climate Change Response (ATCM, 2017). By contrast, consensus is currently limiting work programme-level responses to climate change by CCAMLR (2017a), while opportunities exist to incorporate climate concerns into mechanisms for implementation and monitoring aimed to conserve ecosystems and the environment (Brooks et al., 2018).

3.5.3.2.2 Informal arrangements

The Antarctic Treaty Consultative Parties, through the Committee for Environmental Protection (CEP) and its Subsidiary Group of the Committee for Environmental Protection on Climate Change Response, continue to work closely with the Scientific Committee on Antarctic Research, the Council of Managers of National Antarctic Programs, the International Association of Antarctica Tour Operators and other NGOs to understand, mitigate and adapt to impacts associated with changes to the Southern Ocean and Antarctic cryosphere. Understanding, mitigating and adapting to climate change are among the key priorities identified for research in the region (Kennicutt et al., 2014a; Kennicutt et al., 2014b) and nationally funded bilateral and multilateral projects are underway.

3.5.3.2.3 Role of informal actors

Several studies show that informal actors of the Arctic can influence decision making process of the Council and shift the Council towards more cooperation with different actors to enhance the co-production of knowledge (Duyck, 2011; Makki, 2012; Keil and Knecht, 2017). Recently, non-state observers at the Council, such as the World Wide Fund for Nature and the Circumpolar Conservation Union have played a role in raising awareness on climate change responses and contributing to the work of the Council's Working Groups and Expert Groups (Keil and Knecht, 2017).

Within the Antarctic Treaty System, several non-state actors play a major role in providing advice and influencing the governance of Antarctica and the Southern Ocean. Among the most prominent actors are formal observers such as the Scientific Committee on Antarctic Research, and invited experts such as the International Association of Antarctica Tour Operators and the Antarctic and Southern Ocean Coalition. At meetings of CCAMLR, the Scientific Committee's 2009 report on Antarctic Climate Change and the Environment (Turner et al., 2009) precipitated an Antarctic Treaty Meeting of Experts on

Table 3.5 | Summary of the assessment of practices, tools and strategies that can contribute to climate resilient pathways. Practices are shown with the potential extent of their contribution to resilience building, considering also seven general strategies (Biggs et al., 2012; Quinlan et al., 2016; Cross-Chapter Box 2 in Chapter 1). Also shown is the current level of their application in polar regions and key conditions facilitating implementation.

Type of resilience-building activity	Practices, tool, or strategy	Potential extent of contribution to resilience building	Current level of application in polar regions
		and Areas of potential contributions to resilience: DIV = Maintain diversity & redundancy CON = Manage connectivity PAR = Broaden participation LEA = Encourage learning & experimentation SYS = Foster complex system understanding GOV = Enhance polycentric governance SLO = Manage slow variables and feedbacks Confidence regarding potential contribution to resilience building: ●●● = high ●● = medium ● = low	and Key conditions facilitating implementation: F = Financial support I = Institutional support T&S = Technical and science support L&I = Local & indigenous capacity and knowledge C = Interdisciplinary and/or cross-cultural cooperation
Knowledge Co-Production and Integration	Community-based monitoring	DIV, PAR, SYS ●●	F, I, T&S, L&I, C
	Understanding regime shifts	LEA, SYS, SLO ●●●	I, T&S, C
	Indicators of resilience and adaptive capacity	PAR, LEA, SYS, SLO ●●	F, L&I, T&S
Linking Knowledge with Decision Making	Participatory scenario analysis and planning	PAR, LEA, SYS ●●	T&S, L&I, C
	Structured decision making	PAR, LEA, SYS ●	I, T&S, C
Resilience-based Ecosystem Stewardship	Adaptive ecosystem governance	DIV, PAR, LEA, SYS, GOV, SLO ●●●	I, T&S, L&I, C
	Spatial planning for biodiversity	DIV, CON, GOV, SLO ●●	I, T&S, L&I, C
	Linking ecosystem services with human livelihoods	DIV, PAR, SYS, GOV, SLO ●●●	I, T&S, L&I, C

Climate Change in 2010 (Antarctic Treaty Meeting of Experts, 2010). The outcomes of the meeting led the Antarctic Treaty’s Committee for Environmental Protection to develop a Climate Change Response Work Programme (ATCM, 2017).

3.5.4 Towards Resilient Pathways

This section presents the status of practices, tools and strategies currently employed in the Arctic and or Antarctica that can potentially contribute to climate resilient pathways. Seven general strategies for building resilience have been recognised: i) maintain diversity and redundancy, ii) manage connectivity, iii) manage slow variables and feedbacks, iv) foster an understanding of social-ecological systems as complex adaptive systems, v) encourage learning and experimentation, vi) broaden participation, and vii) promote polycentric governance systems (Biggs et al., 2012; Quinlan et al., 2016) (Cross-Chapter Box 2 in Chapter 1).

The practices listed below are not inclusive of the many resilience-building efforts underway in the polar regions. Those described are well represented in the literature and have shown

sufficient utility to merit further use (ARR, 2016; AMAP, 2017a; AMAP, 2017b; AMAP, 2018) (*high confidence*). Some require more refinement while others are well developed. The following sections assess the extent to which these practices operationalise resilience-building through knowledge co-production, the linking of knowledge with decision making, and implementation of resilience-based ecosystem management, considering also their application level and key facilitating conditions; a summary is presented in Table 3.5.

3.5.4.1 Knowledge Co-production and Integration

The co-production of knowledge and transdisciplinary research are currently contributing to the understanding of polar climate change through the use of a diversity of cultural, geographic, and disciplinary perspectives that provide a holistic framing of problems and possible solutions (Miller and Wyborn, 2018; Robards et al., 2018) (*high confidence*).

Several factors are important in successful knowledge co-production, including use of social-ecological frameworks, engagement of a broad set actors with diverse epistemological orientations, a ‘team science’ approach to studies, strong leadership, attention to process



(vs. only products) and mutual respect for cultural differences (Meadow et al., 2015; National Research Council, 2015; Petrov et al., 2016) (*high confidence*). Knowledge co-production involving Indigenous peoples comes with its own set of challenges (Armitage et al., 2011; Robards et al., 2018). While advancements have been made, the practice of knowledge co-production would benefit from further experimentation and innovation in methodologies and better training of researchers (van der Hel, 2016; Vlasova and Volkov, 2016; Berkes, 2017) (*medium confidence*). Three aspects of knowledge co-production are highlighted below.

3.5.4.1.1 Community-based monitoring

Community-based monitoring (CBM) in the Arctic has emerged as a practice of great interest because of its potential to link western ways of knowing with local knowledge and indigenous knowledge (Retter et al., 2004; Johnson et al., 2015a; Johnson et al., 2015b; Kouril et al., 2016; AMAP, 2017a; Williams et al., 2018). In several CBM programs, innovative approaches using the internet, mobile phones, hand-held information devices, and camera-equipped GPS units are capturing, documenting and communicating local observations of change (Brubaker et al., 2011; Brubaker et al., 2013). The integration of community observations with instrument-based observations and its use in research has proven challenging, with technical and cultural issues (Griffith et al., 2018). Execution of CBM programs in the Arctic has also proven to be labour intensive and difficult to sustain, requiring long-term financial support, agreements specifying data ownership, sufficient human capital, and in some cases, the involvement of boundary organisations that provide technical support (Pulsifer et al., 2012; Eicken et al., 2014) and link CBM with governance (CAFF, 2015b; Robards et al., 2018). As is the case in all knowledge production, power relationships (i.e., who decides what is a legitimate observation, who has access to resources for involvement and who benefits) have been challenging where the legitimacy of local knowledge and indigenous knowledge is questioned (e.g., Pristupa et al., 2018). There is *high agreement* and *limited evidence* that CBM facilitates knowledge co-production and resilience building. More analyses of Arctic communities and their institutional capabilities related to CBM are needed to evaluate the potential of these observation systems, and experimentation and innovation may help determine how CBM can more effectively inform decision making beyond the community (Johnson et al., 2015a; Johnson et al., 2015b) (*medium confidence*).

3.5.4.1.2 Understanding regime shifts

Regime shifts are especially important in polar regions where there are limited data and where rapid directional change suggests the possibility of crossing thresholds that may dramatically alter the flow of ecosystem services (ARR, 2016). Better understanding of the thresholds and dynamics of regime shifts (i.e., SES state changes) is especially important for resilience building (ARR, 2016; Biggs et al., 2018; Rocha et al., 2018) (*high confidence*). While polar regime shifts have been documented (Biggs et al., 2018), most are poorly understood and rarely predictable (Rocha et al., 2018) (*high confidence*). Moreover, the focus on Arctic regime shifts to date has been on almost entirely on biophysical state changes that impact social systems.

A limited number of studies have examined social regime shifts and fewer the feedbacks of social regimes shifts on ecosystems (Gerlach et al., 2017). Future needs for advancing knowledge of regime shifts include: 1) continued and refined updating of details on past regimes shifts, 2) structured comparative analysis of these phenomena to ascertain common patterns and variation, 3) greater investment in research resources on potential large-scale regime shifts, and 4) great attention on how social and economic change may affect ecosystems (ARR, 2016; Biggs et al., 2018).

3.5.4.1.3 Indicators of resilience and adaptive capacity

Well-crafted and effectively communicated indicators of polar geophysical, ecological and human systems have the potential to make complex issues more easily understood by society, including local residents and policy makers seeking to assess the implication of climate change (Petrov et al., 2016; Carson and Sommerkorn, 2017) (*medium confidence*). Having indicators of change is no guarantee they will be used; access to information, awareness of changing conditions, and the motivation to act are also important (e.g., van der Linden et al., 2015).

Indicators of the state of polar geophysical systems, biodiversity, ecosystems and human well-being are monitored as part of polar programs. For example, indicators are reported by the Arctic Council working groups Arctic Monitoring and Assessment Programme and Conservation of Arctic Flora and Fauna (e.g., Odland et al., 2016; CAFF, 2017; Box et al., 2019), the International Arctic Social Science Association (e.g., AHDR, 2014), the CCAMLR Ecosystem Monitoring Programme (e.g., Reid et al., 2005) and the Southern Ocean Observing System (e.g., Meredith et al., 2013).

There is limited development of indicators of social-ecological resilience (Jarvis et al., 2013; Carson and Sommerkorn, 2017). As well, indicators of human adaptive capacity are typically based on qualitative case studies with limited quantitative data, and thus have limited comparability and generalisability (Ford and King, 2013; Petrov et al., 2016; Berman et al., 2017) (*high confidence*). The identification and on-going use of indicators of social-ecological resilience are theoretically best achieved through highly participatory processes that engage stakeholders of a locale, with those processes potentially resulting in self-reflection and actions that improve adaptive capacity (Quinlan et al., 2016; Carson and Sommerkorn, 2017), however, this is untested empirically (*low confidence*).

3.5.4.2 Linking Knowledge with Decision Making

While there is a growing expectation in polar (and other) regions for a more deliberate strategy to link science with social learning and policy making about climate change (and other matters) through iterative interactions of researchers, managers and other stakeholders, meeting that expectation is confounded by several deeply rooted issues (Armitage et al., 2011; ARR, 2016; Tesar et al., 2016b; Baztan et al., 2017; Forbis Jr and Hayhoe, 2018) (*medium confidence*).

In spite of the development of practices like those described above and the establishment of many co-managed arrangements in polar

regions, scientists and policy makers often work in separate spheres of influence, tend to maintain different values, interests, concerns, responsibilities and perspectives, and gain limited exposure to the other's knowledge system (see Liu et al., 2008; Armitage et al., 2011). Information exchange flows unequally, as officials struggle with information overload and proliferating institutional voices, and where local residents are mistrusting of scientists (Powledge, 2012). Inherent tensions between science-based assessment and interest-based policy, and many existing institutions often prevent direct connectivity. Further, the longstanding science mandate to remain 'policy neutral' typically leads to norms of constrained interaction (Neff, 2009) (*high confidence*).

Creating pathways towards greater climate resilience will therefore depend, in part, on a redefined 'actionable science' that creates bridges supporting better decisions through more rigorous, accessible, and engaging products, while shaping a narrative that instils public confidence (Beier et al., 2015; Fleming and Pyenson, 2017) (*high confidence*). Stakeholders of polar regions are increasingly using a suite of creative tools and practices for moving from theory to practice in resilience building by informing decision making and fostering long-term planning (Baztan et al., 2017). As noted above, these practices include participatory scenario planning, forecasting for stakeholders, and use structured decision making, solution visualisation tools and decision theatres (e.g., Schartmüller et al., 2015; Kofinas et al., 2016; Garrett et al., 2017; Holst-Andersen et al., 2017; Camus and Smit, 2019). The extent to which these practices can contribute to resilience building in the future will depend, in part, on the willingness of key actors such as scientists, to provide active decision-support services, more often than mere decision-support products (Beier et al., 2015). While progress has been made in linking science with policy, more enhanced data collaboration at every scale, more strategic social engagement, communication that both informs decisions and improves climate literacy and explicit creation of consensus documents that provide interpretive guidance about research implications and alternative choices will be important (*high confidence*).

3.5.4.2.1 Participatory scenario analysis and planning

Participatory scenario analysis is a quickly evolving and widely used practice in polar regions, and has proven particularly useful for supporting climate adaptation at multiple scales when it uses a social-ecological perspective (ARR, 2016; AMAP, 2017a; Crépin et al., 2017; Planque et al., 2019) (*medium confidence*). While there are technical dimensions in scenario analysis and planning (e.g., the building of useful simulation models that capture and communicate nuanced social-ecological system dynamics such as long-fuse big bang processes, pathological dynamics, critical thresholds, and unforeseen processes (Crépin et al., 2017), there are also creative aspects, such as the use of art to help in the visualisation of possible future (e.g., Planque et al., 2019).

Participatory scenario analysis has been applied to various problem areas related to climate change responses in the polar regions. Applications demonstrate the utility of the practice for identifying possible local futures that consider climate change or socioeconomic

pathways (e.g., in Alaska, Ernst and van Riemsdijk, 2013; and in Eurasian reindeer-herding systems, van Oort et al., 2015; Nilsson et al., 2017) and interacting drivers of change (e.g., in Antarctica; Liggett et al., 2017). Scenario analysis proved helpful for stakeholders with different expertise and perspectives to jointly develop scenarios to inform ecosystem-based management strategies and adaptation options (e.g., in the Barents region; Nilsson et al., 2017; Planque et al., 2019) and to identify research needs (e.g., in Alaska; Vargas-Moreno et al., 2016), including informing and applying climate downscaling efforts (e.g., in Alaska; Ernst and van Riemsdijk, 2013).

A review of scenario analysis in the Arctic, however, found that while the practice is widespread and many are using best practice methods, less than half scenarios programs incorporated climate projections and that those utilising a backcasting approach had higher local participation than those only using forecasting (Flynn et al., 2018). It noted that integrating different knowledge systems and attention to cultural factors influence program utility and acceptance. Planque et al. (2019) also found that most participating stakeholders had limited experience using scenario analysis, suggesting the importance of process methods for engaging stakeholders when exploring possible, likely, and desirable futures. The long-term utility of this practice in helping stakeholders engage with each other to envision possible futures and be forward thinking in decision making will depend on the science of climate projections, further development of decision support systems to inform decision makers, attention to cultural factors and worldview, as well as refinement of processes that facilitate participants' dialogue (*medium confidence*).

3.5.4.2.2 Structured decision making

Structured decision making (SDM) is an emerging practice used with stakeholders to identify alternative actions, evaluate trade-offs, and inform decisions in complex situations (Gregory et al., 2012). Few SDM processes have been undertaken in polar regions, with most as exploratory demonstration projects led by researchers. These have included indigenous residents and researchers identifying trade-offs and actions related to subsistence harvesting in a changing environment (Christie et al., 2018) stakeholder interviews to show how a 'triage method' can link community monitoring with community needs and wildlife management priorities (Wheeler et al., 2018), and the application of multi-criteria decision analysis to address difficult decisions related to mining opportunities in Greenland (Trump et al., 2018). The Decision Theater North at the University of Alaska is also being explored as an innovative method of decision support (Kofinas et al., 2016). SDM may have potential in creating climate resilience pathways in polar regions (*low confidence*), but there is currently limited experience with its application.

3.5.4.3 Resilience-based Ecosystem Stewardship

Renewable resource management and biodiversity conservation that seek to maintain resources in historic levels and reduce uncertainty before taking action remains the dominant paradigm in polar regions (Chapin III et al., 2009; Forbes et al., 2015). The effectiveness of this approach, however, is increasingly challenged as the ranges and populations of species and state of ecosystems are being affected

by climate change (Chapin III et al., 2010; Chapin III et al., 2015). Three practices that build and maintain social-ecological resilience in the face of climate change include Adaptive Ecosystem Governance, Spatial Planning for Biodiversity, and Linking Management of Ecosystem Services with Human Livelihoods.

3.5.4.3.1 Adaptive ecosystem governance

'Adaptive Ecosystem Governance' differs from conventional resource management or integrated ecosystem management (Chapin III et al., 2009; Chapin III et al., 2010; Chapin III et al., 2015), with a strong focus on trajectories of change (i.e., emergence), implying that maintaining ecosystems in a state of equilibrium is not possible (Biggs et al., 2012; ARR, 2016). This approach strengthens response options by maintaining or increasing resource diversity (to support human adaptation) and biological diversity (to support ecosystem adaptation) (Biggs et al., 2012; Chapin III et al., 2015; Quinlan et al., 2016) (*high confidence*). Adaptive ecosystem governance emphasises iterative social learning processes of observing, understanding and acting with collaborative partnerships, such as adaptive co-management arrangements currently used in regions of the Arctic (Armitage et al., 2009; Dale and Armitage, 2011; Chapin III et al., 2015; Arp et al., 2019). This approach is also currently realised through adaptive management of Arctic fisheries in Alaska that combines annual measures and within-season provisions informed by assessments of future ecosystem trends (Section 3.5.2.1), and the use of simulation models with Canadian caribou co-management boards to assess the cumulative effects of proposed land use change with climate change (Gunn et al., 2011; Russell, 2014a; Russell, 2014b). Linking these regional efforts to pan-polar programs can enhance resilience building cross multiple scales (e.g., Gunn et al., 2013) (*medium confidence*).

3.5.4.3.2 Spatial planning for biodiversity

Shifts in the distribution, abundance and human use of species and populations due to climate-induced cryosphere and ocean change, concurrent with land use changes, increase the risks to ecosystem health and biodiversity (Kaiser et al., 2015). Building resilience in these challenging conditions follows from spatial planning for biodiversity that links multiple scales and considers how impacts to ecosystems may materialise in social-ecological systems elsewhere (Bengtsson et al., 2003; Cumming, 2011; Allen et al., 2016). Developing pathways for spatial resilience in polar regions involves systematic planning and designating networks of protected areas to protect connected tracts of representative habitats, and biologically and ecologically significant features (Ban et al., 2014). Protected area networks that combine both spatially rigid and spatially flexible regimes with climate refugia can support ecological resilience to climate change by maintaining connectivity of populations, foodwebs, and the flow of genes across scales (McLeod et al., 2009). This approach reduces direct pressures on biodiversity, and thus gives biological communities, populations and ecosystems the space to adapt (Nyström and Folke, 2001; Hope et al., 2013; Thomas and Gillingham, 2015) (*medium confidence*). Networks of protected areas are now being planned (Solovyev et al., 2017) and implemented (Juvonen and Kuhmonen, 2013) in the marine and terrestrial Arctic, respectively;

expanding the terrestrial protected area network in Antarctica is discussed (Coetzee et al., 2017). The planning of protected area networks in polar regions is currently an active topic of international collaboration in both polar regions (Arctic Council, 2015b; CCAMLR, 2016a; Wenzel et al., 2016). Designating marine protected area networks contributes to achieving Sustainable Development Goal 14 and the Aichi Targets of the CBD but is often contested due to competing interests for marine resources.

3.5.4.3.3 Linking ecosystem services with human livelihoods

Incorporating measures of ecosystem services into assessments is key in integrating environmental, economic, and social policies that build resilience to climate change in polar regions (CAFF, 2015a; Malinauskaite et al., 2019; Sarkki and Acosta García, 2019) (*high confidence*). Currently, there is limited recognition of the wide range of benefits people receive from polar ecosystems and a lack of management tools that demonstrate their benefits in decision-making processes (CAFF, 2015a). The concept of ecosystem services is increasingly used in the Arctic, yet there continues to be significant knowledge gaps in mapping, valuation, and the study of the social implications of changes in ecosystem services. There are few Arctic examples of the application of ecosystem services in management (Malinauskaite et al., 2019). A strategy of ecosystem stewardship, therefore, is to maintain a continued flow of ecosystem services, recognising how their benefits provide incentives for preserving biodiversity, while also ensuring options for sustainable development and ecosystem-based adaptation (Chapin III et al., 2015; Guerry et al., 2015; Díaz et al., 2019). Arctic stewardship opportunities at landscape, seascape, and community scales to a great extent lie in supporting culturally engrained (often traditional indigenous) values of respect for land and animals, and reliance on the local environment through the sharing of knowledge and power between local users of renewable resources and agencies responsible for managing resources (Mengerink et al., 2017) (*high confidence*). In the Antarctic, ecosystem stewardship is dependent on international formally-defined and informally-enacted cooperation, and the recognition of its service to the global community (Section 3.5.3.2).

3.6 Synopsis

This chapter has assessed the consequences of climate change in the polar regions in three sections, focusing on sea ice and the ocean (Section 3.2), glaciers and ice sheets (Section 3.3), and permafrost and snow on land (Section 3.4). A systems approach was taken to assess individual and interacting changes within and between these elements to consider consequences, impacts and risks for marine and terrestrial ecosystems and for people. Mapping on to those observed and projected impacts, Section 3.5 assessed human responses to climate change in the polar regions. This brief synopsis considers the chapter findings across sections, and draws out three key assessment points that inform global responses to polar ocean and cryosphere change.

1. *Climate-induced changes to the polar cryosphere and oceans have global consequences and impacts.*

Loss of Arctic sea ice continues to add to global radiative forcing and has the potential to influence mid-latitude weather on timescales of weeks to months (Section 3.2.1 Box 3.2), the Southern Ocean takes up a disproportionately high amount of atmospheric heat and carbon (Section 3.2.1), melting polar glaciers and the AIS and GIS contribute to observed and projected sea level rise long into the future (Sections 3.3.1, 3.3.2), and projected widespread disappearance of permafrost has the potential to accelerate global warming through the release of carbon dioxide and methane (Sections 3.4.2, 3.4.3).

2. *Across many aspects, the polar regions of the future will appear significantly different from those of today.*

By the end of this century, Arctic sea ice and snow on land are projected to be diminished compared with today, as are the masses of the AIS and GIS and the polar glaciers (Sections 3.2.2, 3.3.2; 3.4.2). Acidification of both polar oceans will have progressed; this, and changing marine habitats associated with ocean warming, are projected to impact marine ecosystems (Sections 3.2.2, 3.2.3). Permafrost thaw and decrease in snow on land are projected to drive habitat and biome shifts, affecting ranges and abundance of ecologically important species, and driving changes in wildfire, vegetation and human infrastructure (Sections 3.4.2, 3.4.3). Collectively, these very different future polar environments pose strong challenges to sustainable use of natural resources, infrastructure, cultures and lives and livelihoods. Although manifested locally, these very different future polar environments have the potential to continue/accelerate the global impacts noted above.

3. *Choices are available that will influence the nature and magnitude of changes, potentially limiting their regional and global impacts and increasing the effectiveness of adaptation actions.*

Compared with high greenhouse gas emissions scenarios, projections using low emissions scenarios result in polar regions that will be significantly less altered. For example, for stabilised global warming of 1.5°C, a sea ice-free Arctic in September is projected to occur significantly less frequently than at 2°C (1% c.f. 10–35%) (Section 3.2.2). The potential for reduced but stabilised Arctic autumn and spring snow extent by mid-century for RCP2.6 contrasts with continued loss under RCP8.5, and the area with near-surface permafrost is projected to decrease less by 2100 under RCP2.6 than under RCP8.5 (Section 3.4.2). Polar glaciers are projected to lose much less mass between 2015 and 2100 under RCP2.6 compared with RCP8.5 (Cross-Chapter Box 6 in Chapter 2). Acidification of the polar oceans will progress more slowly and affect much smaller areas under RCP2.6 compared with RCP8.5 (Section 3.2.2). These differences have strong implications for natural resource management, economic sectors and Arctic cultures (Section 3.5.2). The choices that enable these differences influence the rate and magnitude of polar change, their consequences and impacts at regional and global scales, the effectiveness of adaptation and opportunities for climate resilient pathways (Section 3.5.4).

3.7 Key Knowledge Gaps and Uncertainties

Beyond this report, progress requires that future assessments demonstrate increased confidence in various key aspects; this can be achieved by narrowing numerous gaps in knowledge. Some of the critical ones, which are priorities for future initiatives, are outlined here.

Overturning circulation in the Southern Ocean is a key factor that controls heat and carbon exchanges with the atmosphere, and hence global climate, however there are no direct measures of this and only sparse indirect indicators of how it may be changing. This is a critical weakness in sustained observations of the global ocean.

Snow depth on sea ice is essentially unmeasured, limiting mass balance estimates and ice thickness retrievals. Improved mechanistic understanding of the observed changes and trends in Antarctic sea ice is required, notably the decadal increase and very recent rapid retreat. This has consequences for climate, ecosystems and fisheries; however, lack of understanding and poor model performance translates to very limited predictive skill.

Trends in snow water equivalent over Arctic land are inadequately known, reducing confidence in assessments of snow's role in the water cycle and in insulating the underlying permafrost. Understanding of precipitation in the polar regions is critically limited by sparse observations, and there is a lack of understanding of the processes that drive regional variability in wetting/drying and greening/browning of the Arctic land surface. There is inadequate knowledge concerning carbon dioxide and methane emissions from land and sub-sea permafrost.

There are clear regional gaps in knowledge of polar ecosystems and biodiversity, and insufficient population estimates/trends for many key species. Biodiversity projections are limited by key uncertainties regarding the potential for organisms to adapt to habitat change and the resilience of foodweb structures. Relatedly, knowledge gaps exist concerning how fisheries target levels will change alongside environmental change and how to incorporate this into decision making. Similarly, there are knowledge gaps on the extent to which changes in the availability of resources to subsistence harvesters affects food security of households.

There is a need to better understand the evolution of polar glaciers and ice sheets, and their influences on global sea level. Longer and improved quantifications of their changes are required, especially where mass losses are greatest, and (relatedly) better attribution of natural versus anthropogenic drivers. Better understanding of the sensitivity of Antarctica to marine ice sheet instability is required, and whether recent changes in West Antarctica represent the onset of irreversible change.

There are critical gaps in knowledge concerning interactions between the atmosphere and specific elements of the polar ocean and cryosphere. Detailed assessment of atmospheric processes was outside the remit of this chapter, however such gaps limit understanding of ongoing and future trajectories of the polar regions and their climate systems. Relatedly, there is a paucity of studies analysing differences

in the trajectories of polar cryosphere and ocean systems between low and very low greenhouse gas emission scenarios.

There are critical needs to better understand the efficacy and limits of strategies for reducing risk and strengthening resilience for polar ecosystems and people, including the contribution of practices and tools to contribute to climate resilient pathways. Knowledge on how to translate existing theoretical understandings of social-ecological

resilience into decision making and governance is limited. There is limited understanding concerning the resources that are needed for successful adaptation responses and about the effectiveness of institutions in supporting adaptation. While the occurrence of regime shifts in polar systems is both documented and anticipated, there is little or no understanding of their preconditions or of indicators that would help pre-empt them.

Frequently Asked Questions

FAQ 3.1 | How do changes in the Polar Regions affect other parts of the world?

Climate change in the Arctic and Antarctic affect people outside of the polar regions in two key ways. First, physical and ecosystem changes in the polar regions have socioeconomic impacts that extend across the globe. Second, physical changes in the Arctic and Antarctic influence processes that are important for global climate and sea level.

Among the risks to societies and economies, aspects of food provision, transport and access to non-renewable resources are of great importance. Fisheries in the polar oceans support regional and global food security and are important for the economies of many countries around the world, but climate change alters Arctic and Antarctic marine habitats, and affects the ability of polar species and ecosystems to withstand or adapt to physical changes. This has consequences for where, when, and how many fish can be captured. Impacts will vary between regions, depending on the degree of climate change and the effectiveness of human responses. While management in some polar fisheries is among the most developed, scientists are exploring modifications to existing precautionary, ecosystem-based management approaches to increase the scope for adaptation to climate change impacts on marine ecosystems and fisheries.

New shipping routes through the Arctic offer cost savings because they are shorter than traditional passages via the Suez or Panama Canals. Ship traffic has already increased and is projected to become more feasible in the coming decades as further reductions in sea ice cover make Arctic routes more accessible. Increased Arctic shipping has significant socioeconomic and political implications for global trade, northern nations and economies strongly linked to traditional shipping corridors, while also increasing environmental risk in the Arctic. Reduced Arctic sea ice cover allows greater access to offshore petroleum resources and ports supporting resource extraction on land.

The polar regions influence the global climate through a number of processes. As spring snow and summer sea ice cover decrease, more heat is absorbed at the surface. There is growing evidence that ongoing changes in the Arctic, primarily sea ice loss, can potentially influence mid-latitude weather. As temperatures increase in the Arctic, permafrost soils in northern regions store less carbon. The release of carbon dioxide and methane from the land to the atmosphere further contributes to global warming.

Melting ice sheets and glaciers in the polar regions cause sea levels to rise, affecting coastal regions and their large populations and economies. At present, the Greenland Ice Sheet (GIS) and polar glaciers are contributing more to sea level rise than the Antarctic Ice Sheet (AIS). However, ice loss from the AIS has continued to accelerate, driven primarily by increased melting of the underside of floating ice shelves, which has caused glaciers to flow faster. Even though it remains difficult to project the amount of ice loss from Antarctica after the second half of the 21st century, it is expected to contribute significantly to future sea level rise.

The Southern Ocean that surrounds Antarctica is the main region globally where waters at depth rise to the surface. Here, they become transformed into cold, dense waters that sink back to the deep ocean, storing significant amounts of human-produced heat and dissolved carbon for decades to centuries or longer, and helping to slow the rate of global warming in the atmosphere. Future changes in the strength of this ocean circulation can so far only be projected with limited certainty.

Acknowledgements

The authors acknowledge the following individuals for their assistance in compiling references containing indigenous knowledge for the Polar Regions Chapter: Claudio Aporta (Canada), David Atkinson (Canada), Todd Brinkmann (USA), Courtney Carothers (USA), Ashlee Cunsolo (Canada), Susan Crate (USA), Bathsheba Demuth (USA),

Alexandra Lavrillier (France), Andrey Petrov (USA/Russia), Jon Rosales (USA), Florian Stammler (Finland), Hiroki Takakura (Japan), Wilbert van Rooij (Netherlands), Brent Wolfe (Canada), Torre Jorgenson (USA). Laura Gerrish (UK) is thanked for help with figure preparation.

References

- Aakre, S., S. Kallbekken, R. Van Dingenen and D.G. Victor, 2018: Incentives for small clubs of Arctic countries to limit black carbon and methane emissions. *Nature Climate Change*, **8** (1), 85–90, doi:10.1038/s41558-017-0030-8.
- Aars, J. et al., 2017: The number and distribution of polar bears in the western Barents Sea. *Polar Research*, **36** (1), 1374125, doi:10.1080/17518369.2017.1374125.
- Abadi, F., C. Barbraud and O. Gimenez, 2017: Integrated population modeling reveals the impact of climate on the survival of juvenile emperor penguins. *Global Change Biology*, **23** (3), 1353–1359, doi:10.1111/gcb.13538.
- Abbott, B.W. et al., 2015: Patterns and persistence of hydrologic carbon and nutrient export from collapsing upland permafrost. *Biogeosciences*, **12** (12), 3725–3740, doi:10.5194/bg-12-3725-2015.
- Abbott, B.W. et al., 2014: Elevated dissolved organic carbon biodegradability from thawing and collapsing permafrost. *Journal of Geophysical Research: Biogeosciences*, **119** (10), 2049–2063, doi:10.1002/2014jg002678.
- Abernathy, R. and D. Ferreira, 2015: Southern Ocean isopycnal mixing and ventilation changes driven by winds. *Geophysical Research Letters*, **42** (23), 10,357–10,365, doi:10.1002/2015gl066238.
- Abernathy, R.P. et al., 2016: Water-mass transformation by sea ice in the upper branch of the Southern Ocean overturning. *Nature Geoscience*, **9**, 596, doi:10.1038/ngeo2749.
- Abrahms, B. et al., 2018: Climate mediates the success of migration strategies in a marine predator. *Ecol Lett*, **21** (1), 63–71, doi:10.1111/ele.12871.
- Abram, N.J. et al., 2014: Evolution of the Southern Annular Mode during the past millennium. *Nature Climate Change*, **4** (7), 564–569, doi:10.1038/nclimate2235.
- Abram, N.J. et al., 2013a: Acceleration of snow melt in an Antarctic Peninsula ice core during the twentieth century. *Nature Geoscience*, **6** (5), 404–411, doi:10.1038/ngeo1787.
- Abram, N.J., E.W. Wolff and M.A.J. Curran, 2013b: A review of sea ice proxy information from polar ice cores. *Quaternary Science Reviews*, **79**, 168–183, doi:10.1016/j.quascirev.2013.01.011.
- Adusumilli, S. et al., 2018: Variable Basal Melt Rates of Antarctic Peninsula Ice Shelves, 1994–2016. *Geophysical Research Letters*, **45** (9), 4086–4095, doi:10.1002/2017GL076652.
- AHDR, 2014: *Arctic Human Development Report: Regional Processes and Global Linkages*. Nordic Council of Ministers, Larsen, J.N. and G. Fondahl, Copenhagen [Available at: <http://norden.diva-portal.org/smash/get/diva2:788965/FULLTEXT03.pdf>; Access Date: 10 October 2017].
- Ahlstrom, A.P. et al., 2017: Abrupt shift in the observed runoff from the southwestern Greenland ice sheet. *Sci Adv*, **3** (12), e1701169, doi:10.1126/sciadv.1701169.
- Ainley, D.G. et al., 2015: Trophic cascades in the western Ross Sea, Antarctica: revisited. *Marine Ecology Progress Series*, **534**, 1–16, doi:10.3354/meps11394.
- Aitken, A.R.A. et al., 2016: Repeated large-scale retreat and advance of Totten Glacier indicated by inland bed erosion. *Nature*, **533**, 385, doi:10.1038/nature17447.
- Aksenov, Y. et al., 2017: On the future navigability of Arctic sea routes: High-resolution projections of the Arctic Ocean and sea ice. *Marine Policy*, **75**, 300–317, doi:10.1016/j.marpol.2015.12.027.
- Alabia, I.D. et al., 2018: Distribution shifts of marine taxa in the Pacific Arctic under contemporary climate changes. *Diversity and Distributions*, **24** (11), 1583–1597, doi:10.1111/ddi.12788.
- Albon, S., D. et al., 2017: Contrasting effects of summer and winter warming on body mass explain population dynamics in a food-limited Arctic herbivore. *Global Change Biology*, **23** (4), 1374–1389, doi:10.1111/gcb.13435.
- Alexeev, V., A., C.D. Arp, B.M. Jones and L. Cai, 2016: Arctic sea ice decline contributes to thinning lake ice trend in northern Alaska. *Environmental Research Letters*, **11** (7), 074022, doi:10.1088/1748-9326/11/7/074022.
- Allen, C.R. et al., 2016: Quantifying spatial resilience. *Journal of Applied Ecology*, **53** (3), 625–635, doi:10.1111/1365-2664.12634.
- AMAP, 2015: *AMAP Assessment 2015: Temporal Trends in Persistent Organic Pollutants in the Arctic*. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway, vi+71 pp [Available at: www.amap.no/documents/doc/amap-assessment-2015-temporal-trends-in-persistent-organic-pollutants-in-the-arctic/1521; Access Date: 25 October 2018].
- AMAP, 2017a: *Adaptation Actions for a Changing Arctic (AACA) – Bering/Chukchi/Beaufort Region Overview report*. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway, 24 pp.
- AMAP, 2017b: *Adaptation Actions for a Changing Arctic: Perspectives from the Barents Area*. Arctic Monitoring and Assessment Programme (AMAP), xiv + 267 pp.
- AMAP, 2017c: *AMAP Assessment 2016: Chemicals of Emerging Arctic Concern*. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway, xvi+353 pp [Available at: www.amap.no/documents/doc/AMAP-Assessment-2016-Chemicals-of-Emerging-Arctic-Concern/1624; Access Date: 10 October 2018].
- AMAP, 2017d: *Snow, Water, Ice and Permafrost in the Arctic (SWIPA)*. Arctic Council Secretariat, Oslo, Norway, xiv + 269 pp [Available at: www.amap.no/documents/download/2987/inline; Access Date: 10 October 2018].
- AMAP, 2018: *Adaptation Actions for a Changing Arctic: Perspectives from the Baffin Bay/Davis Strait Region*. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway, xvi + 354 pp [Available at: www.amap.no/documents/doc/Adaptation-Actions-for-a-Changing-Arctic-Perspectives-from-the-Baffin-Bay-Davis-Strait-Region/1630; Access Date: 10 October 2018].
- Ance, A. et al., 2017: Looking for new emperor penguin colonies? Filling the gaps. *Global Ecology and Conservation*, **9**, 171–179, doi:10.1016/j.gecco.2017.01.003.
- Andersen, M., A.E. Derocher, Ø. Wiig and J. Aars, 2012: Polar bear (*Ursus maritimus*) maternity den distribution in Svalbard, Norway. *Polar Biology*, **35** (4), 499–508, doi:10.1007/s00300-011-1094-y.
- Andersen, M.L. et al., 2015: Basin-scale partitioning of Greenland ice sheet mass balance components (2007–2011). *Earth and Planetary Science Letters*, **409**, 89–95, doi:10.1016/j.epsl.2014.10.015.

- Anderson, E.H., 2012: Polar shipping, the forthcoming polar code implications for the polar environments. *Journal of Maritime Law and Commerce*, **43** (1), 59–64.
- Anderson, L.G. et al., 2017a: Export of calcium carbonate corrosive waters from the East Siberian Sea. *Biogeosciences*, **14** (7), 1811–1823, doi:10.5194/bg-14-1811-2017.
- Anderson, S.C. et al., 2017b: Benefits and risks of diversification for individual fishers. *Proceedings of the National Academy of Sciences*, **114** (40), 10797–10802, doi:10.1073/pnas.1702506114.
- Andresen, C.S. et al., 2012: Rapid response of Helheim Glacier in Greenland to climate variability over the past century. *Nature Geoscience*, **5** (1), 37–41, doi:10.1038/ngeo1349.
- Andrews, A.J. et al., 2019: Boreal marine fauna from the Barents Sea disperse to Arctic Northeast Greenland. *Sci Rep*, **9** (1), 5799, doi:10.1038/s41598-019-42097-x.
- Andrews, J., D. Babb and D.G. Barber, 2018: Climate change and sea ice: Shipping in Hudson Bay, Hudson Strait, and Foxe Basin (1980–2016). *Elementa-Science of the Anthropocene*, **6** (1), p.19, doi:http://doi.org/10.1525/elementa.281.
- Angelopoulos, M. et al., 2019: Heat and Salt Flow in Subsea Permafrost Modeled with CryoGRID2. *Journal of Geophysical Research: Earth Surface*, **124** (4), 920–937, doi:10.1029/2018j004823.
- Anisimov, O.A., I.I. Borzenkova, S.A. Lavrov and J.G. Strelchenko, 2012: Dynamics of sub-aquatic permafrost and methane emission at eastern Arctic sea shelf under past and future climatic changes. *Ice and Snow*, **2**, 97–105, doi:10.1002/Ino.10307.
- Antarctic Treaty Meeting of Experts, 2010: *Co-Chairs' Report from Antarctic Treaty Meeting of Experts on Implications of Climate Change for Antarctic Management and Governance*. Antarctic Treaty Secretariat, Buenos Aires, Argentina.
- Anttila, K. et al., 2018: The role of climate and land use in the changes in surface albedo prior to snow melt and the timing of melt season of seasonal snow in northern land areas of 40°N–80°N during 1982–2015. *Remote Sensing*, **10** (10), 1619, doi:10.3390/rs10101619.
- Arblaster, J.M. et al., 2014: Stratospheric ozone changes and climate, Chapter 4 in Scientific Assessment of Ozone Depletion. [World Meteorological Organization, G.S. (ed.)], Geneva, iv + 57 pp; Global Ozone Research and Monitoring Project – Report No. 55.
- Arblaster, J.M. and G.A. Meehl, 2006: Contributions of External Forcings to Southern Annular Mode Trends. *Journal of Climate*, **19** (12), 2896–2905, doi:10.1175/jcli3774.1.
- Arctic Council, 2015a: *Arctic Marine Tourism Project (AMTP): best practices guidelines*. Protection of the Arctic Marine Environment (PAME), Iceland, 17 pp [Available at: <https://oaarchive.arctic-council.org/bitstream/handle/11374/414/AMTP%20Best%20Practice%20Guidelines.pdf?sequence=1&isAllowed=y>; Access Date: 10 October 2018].
- Arctic Council, 2015b: *Framework for a Pan-Arctic Network of Marine Protected Areas*. Protection of the Arctic Marine Environment (PAME), Iceland, 52 pp [Available at: <https://oaarchive.arctic-council.org/handle/11374/417>; Access Date: 28 March 2019].
- Arctic Council, 2017: *Expert Group on Black Carbon and Methane: Summary of progress and recommendations*. Expert Group on Black Carbon and Methane (EGBCM), 49 pp [Available at: <https://oaarchive.arctic-council.org/handle/11374/1936>; Access Date: 28 March 2019].
- Ardyna, M. et al., 2017: Shelf-basin gradients shape ecological phytoplankton niches and community composition in the coastal Arctic Ocean (Beaufort Sea). *Limnology and Oceanography*, **62** (5), 2113–2132, doi:10.1002/lno.10554.
- Armitage, D. et al., 2011: Co-management and the co-production of knowledge: Learning to adapt in Canada's Arctic. *Global Environmental Change*, **21** (3), 995–1004, doi:10.1016/j.gloenvcha.2011.04.006.
- Armitage, D.R. et al., 2009: Adaptive co-management for social–ecological complexity. *Frontiers in Ecology and the Environment*, **7** (2), 95–102, doi:10.1890/070089.
- Armitage, T.W. et al., 2017: Arctic Ocean surface geostrophic circulation 2003–2014. *The Cryosphere*, **11** (4), 1767, doi:10.5194/tc-11-1767-2017.
- Armitage, T.W. et al., 2016: Arctic sea surface height variability and change from satellite radar altimetry and GRACE, 2003–2014. *Journal of Geophysical Research: Oceans*, **121** (6), 4303–4322, doi:10.1002/2015JC011579.
- Armour, K.C. et al., 2011: The reversibility of sea ice loss in a state-of-the-art climate model. *Geophysical Research Letters*, **38** (16), L16705, doi:10.1029/2011gl048739.
- Armour, K.C. et al., 2016: Southern Ocean warming delayed by circumpolar upwelling and equatorward transport. *Nature Geoscience*, **9** (7), 549, doi:10.1038/Ngeo2731.
- Aronson, R.B. et al., 2015: No barrier to emergence of bathyal king crabs on the Antarctic shelf. *Proc Natl Acad Sci U S A*, **112** (42), 12997–13002, doi:10.1073/pnas.1513962112.
- Arp, C.D. et al., 2016: Threshold sensitivity of shallow Arctic lakes and sublake permafrost to changing winter climate. *Geophysical Research Letters*, **43** (12), 6358–6365, doi:10.1002/2016gl068506.
- Arp, C.D. et al., 2015: Depth, ice thickness, and ice-out timing cause divergent hydrologic responses among Arctic lakes. *Water Resources Research*, **51** (12), 9379–9401, doi:10.1002/2015wr017362.
- Arp, C.D. et al., 2019: Ice roads through lake-rich Arctic watersheds: Integrating climate uncertainty and freshwater habitat responses into adaptive management. *Arctic, Antarctic, and Alpine Research*, **51** (1), 9–23, doi:10.1080/15230430.2018.1560839.
- ARR, 2016: *Arctic Resilience Report* [Carson, M. and G. Peterson (eds.)]. Arctic Council, Stockholm Environment Institute and Stockholm Resilience Centre, Stockholm.
- Arrigo, K.R. et al., 2014: Phytoplankton blooms beneath the sea ice in the Chukchi sea. *Deep Sea Research Part II: Topical Studies in Oceanography*, **105** (Supplement C), 1–16, doi:10.1016/j.dsr2.2014.03.018.
- Arrigo, K.R. et al., 2012: Massive phytoplankton blooms under sea ice. *Science*, **336**, 1408, doi:10.1126/science.1215065.
- Arrigo, K.R. and G.L. van Dijken, 2004: Annual cycles of sea ice and phytoplankton in Cape Bathurst polynya, southeastern Beaufort Sea, Canadian Arctic. *Geophysical Research Letters*, **31** (8), doi:10.1029/2003gl018978.
- Arrigo, K.R. and G.L. van Dijken, 2011: Secular trends in Arctic Ocean net primary production. *J. Geophys. Res.*, **116** (C9), C09011, doi:10.1029/2011jc007151.
- Arrigo, K.R. and G.L. van Dijken, 2015: Continued increases in Arctic Ocean primary production. *Progress in Oceanography*, **136**, 60–70, doi:10.1016/j.pocean.2015.05.002.
- Arrigo, K.R. et al., 2017a: Early Spring Phytoplankton Dynamics in the Western Antarctic Peninsula. *Journal of Geophysical Research-Oceans*, **122** (12), 9350–9369, doi:10.1002/2017jc013281.
- Arrigo, K.R., G.L. van Dijken and S. Bushinsky, 2008: Primary production in the Southern Ocean, 1997–2006. *Journal of Geophysical Research: Oceans*, **113** (C8), doi:10.1029/2007JC004551.
- Arrigo, K.R. et al., 2017b: Melting glaciers stimulate large summer phytoplankton blooms in southwest Greenland waters. *Geophysical Research Letters*, **44** (12), 6278–6285, doi:10.1002/2017gl073583.
- Arrigo, K.R., G.L. van Dijken and A.L. Strong, 2015: Environmental controls of marine productivity hot spots around Antarctica. *Journal of Geophysical Research: Oceans*, **120** (8), 5545–5565, doi:10.1002/2015jc010888.
- Årthun, M., T. Eldevik and L.H. Smedsrud, 2019: The role of Atlantic heat transport in future Arctic winter sea ice loss. *Journal of Climate*, **32** (11), 3327–3341, doi:10.1175/jcli-d-18-0750.1.
- Arthun, M. et al., 2012: Quantifying the Influence of Atlantic Heat on Barents Sea Ice Variability and Retreat. *Journal of Climate*, **25** (13), 4736–4743, doi:10.1175/Jcli-D-11-00466.1.

- Asselin, N.C. et al., 2011: Beluga (*Delphinapterus leucas*) habitat selection in the eastern Beaufort Sea in spring, 1975–1979. *Polar Biology*, **34** (12), 1973–1988, doi:10.1007/s00300-011-0990-5.
- Assmy, P. et al., 2017: Leads in Arctic pack ice enable early phytoplankton blooms below snow-covered sea ice. *Scientific Reports*, **7**, 40850, doi:10.1038/srep40850.
- ATCM, 2016: Final Report of the Thirty-Ninth Antarctic Treaty Consultative Meeting. In: *Antarctic Treaty Consultative Meeting XXXIX*, 23 May – 1 June 2016, Santiago, Chile [Secretariat, A.T. (ed.)], 406 pp.
- ATCM, 2017: Final Report of the Fortieth Antarctic Treaty Consultative Meeting. In: *Antarctic Treaty Consultative Meeting XL*, 22 May – 1 June 2017, Beijing, China [Secretariat, A.T. (ed.)], 285 pp.
- ATCM, 2018: *IAATO Overview of Antarctic Tourism: 2017–18 Season and Preliminary Estimates for 2018–19 Season*. ATCM, Buenos Aires [Available at: <https://iaato.org/documents/10157/2398215/IAATO+overview/bc34db24-e1dc-4eab-997a-4401836b7033>].
- Atkinson, A. et al., 2019: Krill (*Euphausia superba*) distribution contracts southward during rapid regional warming. *Nature Climate Change*, **9** (2), 142–147, doi:10.1038/s41558-018-0370-z.
- Atkinson, A., V. Siegel, E. Pakhomov and P. Rothery, 2004: Long-term decline in krill stock and increase in salps within the Southern Ocean. *Nature*, **432** (7013), 100–103, doi:10.1038/nature0299.
- Åtland, K., 2013: The Security Implications of Climate Change in the Arctic Ocean. In: *Environmental Security in the Arctic Ocean*, Dordrecht, [Berkman, P. and A. Vylegzhanin (eds.)], Springer Netherlands, 205–216.
- Attard, C.R. et al., 2015: Low genetic diversity in pygmy blue whales is due to climate-induced diversification rather than anthropogenic impacts. *Biology Letters*, **11** (5), 20141037, doi:10.1098/rsbl.2014.1037.
- Austin, S.E. et al., 2015: Public health adaptation to climate change in Canadian jurisdictions. *International Journal of Environmental Research and Public Health*, **12** (1), 623–651, doi:10.3390/ijerph120100623.
- Ayarzaguena, B. and J.A. Screen, 2016: Future Arctic sea ice loss reduces severity of cold air outbreaks in midlatitudes. *Geophysical Research Letters*, **43** (6), 2801–2809, doi:10.1002/2016gl068092.
- Ayles, B., L. Porta and R.M. Clarke, 2016: Development of an integrated fisheries co-management framework for new and emerging commercial fisheries in the Canadian Beaufort Sea. *Marine Policy*, **72**, 246–254, doi:10.1016/j.marpol.2016.04.032.
- Azaneu, M., R. Kerr, M.M. Mata and C.A. Garcia, 2013: Trends in the deep Southern Ocean (1958–2010): Implications for Antarctic Bottom Water properties and volume export. *Journal of Geophysical Research: Oceans*, **118** (9), 4213–4227.
- Azetsu-Scott, K., M. Starr, Z. Mei and M. Granskog, 2014: Low calcium carbonate saturation state in an Arctic inland sea having large and varying fluvial inputs: The Hudson Bay system. *Journal of Geophysical Research-Oceans*, **119** (9), 6210–6220, doi:10.1002/2014jc009948.
- Bader, J. et al., 2013: Atmospheric winter response to a projected future Antarctic sea-ice reduction: a dynamical analysis. *Climate Dynamics*, **40** (11), 2707–2718, doi:10.1007/s00382-012-1507-9.
- Bailey, A. et al., 2017: Early life stages of the Arctic copepod *Calanus glacialis* are unaffected by increased seawater pCO₂. *ICES Journal of Marine Science*, **74** (4), 996–1004, doi:10.1093/icesjms/fsw066.
- Baird, J., R. Plummer and Ö. Bodin, 2016: Collaborative governance for climate change adaptation in Canada: experimenting with adaptive co-management. *Regional Environmental Change*, **16** (3), 747–758, doi:10.1007/s10113-015-0790-5.
- Bajzak, C.E., M.O. Hammill, G.B. Stenson and S. Prinsenberg, 2011: Drifting away: implications of changes in ice conditions for a pack-ice-breeding phocid, the harp seal (*Pagophilus groenlandicus*). *Canadian Journal of Zoology*, **89** (11), 1050–1062, doi:10.1139/z11-081.
- Baker, B. and B. Yeager, 2015: Coordinated Ocean Stewardship in the Arctic: Needs, Challenges and Possible Models for an Arctic Ocean Coordinating Agreement. *Transnational Environmental Law*, **4** (2), 359–394, doi:10.1017/S2047102515000151.
- Ballinger, T.J. et al., 2018: Greenland coastal air temperatures linked to Baffin Bay and Greenland Sea ice conditions during autumn through regional blocking patterns. *Climate Dynamics*, **50** (1), 83–100, doi:10.1007/s00382-017-3583-3.
- Balser, A.W., J.B. Jones and R. Gens, 2014: Timing of retrogressive thaw slump initiation in the Noatak Basin, northwest Alaska, USA. *Journal of Geophysical Research: Earth Surface*, **119** (5), 1106–1120, doi:10.1002/2013JF002889.
- Balshi, M.S. et al., 2009: Vulnerability of carbon storage in North American boreal forests to wildfires during the 21st century. *Global Change Biology*, **15** (6), 1491–1510, doi:10.1111/j.1365-2486.2009.01877.x.
- Bamber, J.L., R.M. Westaway, B. Marzeion and B. Wouters, 2018: The land ice contribution to sea level during the satellite era. *Environmental Research Letters*, **13** (6), 063008, doi:10.1088/1748-9326/aac2f0/meta.
- Ban, N.C. et al., 2014: Systematic Conservation Planning: A Better Recipe for Managing the High Seas for Biodiversity Conservation and Sustainable Use. *Conservation Letters*, **7** (1), 41–54, doi:10.1111/conl.12010.
- Barber, D. et al., 2017: Arctic Sea Ice. In: *Snow, Water, Ice and Permafrost in the Arctic (SWIPA)*. Arctic Monitoring and Assessment Programme, Oslo, 103–136.
- Barber, D.G. et al., 2012: Consequences of change and variability in sea ice on marine ecosystem and biogeochemical processes during the 2007–2008 Canadian International Polar Year program. *Climatic Change*, **115** (1), 135–159, doi:10.1007/s10584-012-0482-9.
- Barber, D.G. and R.A. Massom, 2007: Chapter 1 The Role of Sea Ice in Arctic and Antarctic Polynyas. In: *Elsevier Oceanography Series* [Smith, W.O. and D.G. Barber (eds.)]. Elsevier, **74**, 1–54.
- Barletta, V.R. et al., 2018: Observed rapid bedrock uplift in Amundsen Sea Embayment promotes ice-sheet stability. *Science*, **360** (6395), 1335–1339, doi:10.1126/science.aao1447.
- Barnes, D.K.A., 2017: Polar zoobenthos blue carbon storage increases with sea ice losses, because across-shelf growth gains from longer algal blooms outweigh ice scour mortality in the shallows. *Glob Chang Biol*, **23** (12), 5083–5091, doi:10.1111/gcb.13772.
- Barnes, D.K.A. et al., 2018: Icebergs, sea ice, blue carbon and Antarctic climate feedbacks. *Philos Trans A Math Phys Eng Sci*, **376** (2122), doi:10.1098/rsta.2017.0176.
- Barnes, E.A. and L.M. Polvani, 2015: CMIP5 Projections of Arctic Amplification, of the North American/North Atlantic Circulation, and of Their Relationship. *Journal of Climate*, **28** (13), 5254–5271, doi:10.1175/jcli-d-14-00589.1.
- Barnhart, K.R., C.R. Miller, I. Overeem and J.E. Kay, 2015: Mapping the future expansion of Arctic open water. *Nature Climate Change*, **6**, 280, doi:10.1038/nclimate2848.
- Barret, J., 2016: Securing the Polar Regions through International Law. In: *Security and International Law* [Footer, M.E., J. Schmidt, N.D. White and L. Davies (eds.)]. Bright, Oxford and Portland, Oregon, USA. Barret, J.H. et al., 2011: Interpreting the expansion of sea fishing in medieval Europe using stable isotope analysis of archaeological cod bones. *Journal of Archaeological Science*, **38** (7), 1516–1524, doi:10.1016/j.jas.2011.02.017.
- Bartsch, A., T. Kumpula, B.C. Forbes and F. Stammer, 2010: Detection of snow surface thawing and refreezing in the Eurasian Arctic with QuikSCAT: implications for reindeer herding. *Ecological Applications*, **20** (8), 2346–2358, doi:10.1890/09-1927.1.
- Bartsch, A. et al., 2017: Circumpolar Mapping of Ground-Fast Lake Ice. *Frontiers in Earth Science*, **5**, 12, doi:10.3389/feart.2017.00012.
- Bates, N.R. et al., 2014: Sea-ice melt CO₂-carbonate chemistry in the western Arctic Ocean: meltwater contributions to air-sea CO₂ gas exchange, mixed-layer properties and rates of net community production under sea ice. *Biogeosciences*, **11** (23), 6769–6789, doi:10.5194/bg-11-6769-2014.
- Bauch, D. et al., 2012: Impact of Siberian coastal polynyas on shelf-derived Arctic Ocean halocline waters. *Journal of Geophysical Research: Oceans*, **117** (C9), doi:10.1029/2011JC007282.

- Bauch, D. et al., 2011: Origin of freshwater and polynya water in the Arctic Ocean halocline in summer 2007. *Progress in Oceanography*, **91** (4), 482–495, doi:10.1016/j.pocean.2011.07.017.
- Baztan, J. et al., 2017: Life on thin ice: Insights from Uummannaq, Greenland for connecting climate science with Arctic communities. *Polar Science*, **13**, 100–108, doi:10.1016/j.polar.2017.05.002.
- Beaumier, M.C., J.D. Ford and S. Tagalik, 2015: The food security of Inuit women in Arviat, Nunavut: the role of socio-economic factors and climate change. *Polar Record*, **51** (5), 550–559, doi:10.1017/s0032247414000618.
- Beck, P.S.A. and S.J. Goetz, 2011: Satellite observations of high northern latitude vegetation productivity changes between 1982 and 2008: ecological variability and regional differences. *Environmental Research Letters*, **6** (4), 049501.
- Beers, J.M. and N. Jayasundara, 2015: Antarctic notothenioid fish: what are the future consequences of 'losses' and 'gains' acquired during long-term evolution at cold and stable temperatures? *J Exp Biol*, **218** (Pt 12), 1834–45, doi:10.1242/jeb.116129.
- Behrenfeld, M.J. et al., 2016: Annual boom–bust cycles of polar phytoplankton biomass revealed by space-based lidar. *Nature Geoscience*, **10**, 118, doi:10.1038/ngeo2861.
- Beier, P. et al., 2015: *Guiding Principles and Recommended Practices for Co-Producing Actionable Science*. A How-to Guide for DOI Climate Science Centers and the National Climate Change and Wildlife Science Center. Report to the Secretary of the Interior Advisory Committee on Climate Change and Natural Resource Science, Washington, DC. Bélanger, S., M. Babin and J.-É. Tremblay, 2013: Increasing cloudiness in Arctic damps the increase in phytoplankton primary production due to sea ice receding. *Biogeosciences*, **10** (6), 4087, doi:10.5194/bg-10-4087-2013.
- Belchier, M. and M.A. Collins, 2008: Recruitment and body size in relation to temperature in juvenile Patagonian toothfish (*Dissostichus eleginoides*) at South Georgia. *Marine Biology*, **155** (5), 493, doi:10.1007/s00227-008-1047-3.
- Bell, R.E., 2008: The role of subglacial water in ice-sheet mass balance. *Nature Geoscience*, **1**, 297, doi:10.1038/ngeo186.
- Bell, R.E. et al., 2017: Antarctic ice shelf potentially stabilized by export of meltwater in surface river. *Nature*, **544** (7650), 344–348, doi:10.1038/nature22048.
- Belleflamme, A., X. Fettweis and M. Erpicum, 2015: Recent summer Arctic atmospheric circulation anomalies in a historical perspective. *The Cryosphere*, **9** (1), 53–64, doi:10.5194/tc-9-53-2015.
- Bellerby, R. et al., 2018: *Arctic Ocean acidification: an update*. AMAP Assessment 2018 Arctic Monitoring and Assessment Programme (AMAP), AMAP, Tromsø, Norway., vi+187 pp.
- Belshe, E.F., E.A.G. Schuur and B.M. Bolker, 2013: Tundra ecosystems observed to be CO₂ sources due to differential amplification of the carbon cycle. *Ecology Letters*, **16** (10), 1307–1315, doi:10.1111/ele.12164.
- Bendtsen, J., J. Mortensen, K. Lennert and S. Rysgaard, 2015: Heat sources for glacial ice melt in a west Greenland tidewater outlet glacier fjord: The role of subglacial freshwater discharge. *Geophysical Research Letters*, **42** (10), 4089–4095, doi:10.1002/2015GL063846.
- Bengtsson, J. et al., 2003: Reserves, resilience and dynamic landscapes. *AMBIO*, **32** (6), 389–96, doi:10.1579/0044-7447-32.6.389.
- Benn, D.I. et al., 2017: Melt-under-cutting and buoyancy-driven calving from tidewater glaciers: new insights from discrete element and continuum model simulations. *Journal of Glaciology*, **63** (240), 691–702, doi:10.1017/jog.2017.41.
- Berchet, A. et al., 2016: Atmospheric constraints on the methane emissions from the East Siberian Shelf. *Atmos. Chem. Phys.*, **16** (6), 4147–4157, doi:10.5194/acp-16-4147-2016.
- Berdahl, M. et al., 2014: Arctic cryosphere response in the Geoengineering Model Intercomparison Project G3 and G4 scenarios. *Journal of Geophysical Research: Atmospheres*, **119** (3), 1308–1321, doi:10.1002/2013jd020627.
- Berge, J. et al., 2015: First Records of Atlantic Mackerel (*Scomber scombrus*) from the Svalbard Archipelago, Norway, with Possible Explanations for the Extension of Its Distribution. *Arctic*, **68** (1), 54–61, doi:10.14430/arctic4455.
- Berkes, F., 2017: Environmental Governance for the Anthropocene? Social-Ecological Systems, Resilience, and Collaborative Learning. *Sustainability*, **9** (7), 1232, doi:10.3390/su9071232.
- Berkman, A. and A. Vylegzhanin, 2013: *Environmental Security in the Arctic Ocean*. NATO Science for Peace and Security Series -C: Environmental Security., Springer.
- Berkman, P.A. and A.N. Vylegzhanin, 2010: Environmental Security in the Arctic Ocean. In: *Environmental Security in the Arctic Ocean*, Dordrecht, [Berkman, P.A. and A.N. Vylegzhanin (eds.)], Springer Netherlands.
- Berman, M., G. Kofinas and S. BurnSilver, 2017: Measuring Community Adaptive and Transformative Capacity in the Arctic Context. In: Northern Sustainabilities: Understanding and Addressing Change in the Circumpolar World [Fondahl, G. and G.N. Wilson. (eds.)]. Springer International Publishing, Inc., Cham, Switzerland, 59–75.
- Berman, M. and J.I. Schmidt, 2019: Economic Effects of Climate Change in Alaska. *Weather, Climate, and Society*, **11** (2), 245–258, doi:10.1175/wcas-d-18-0056.1.
- Bernardello, R. et al., 2014: Impact of Weddell Sea deep convection on natural and anthropogenic carbon in a climate model. *Geophysical Research Letters*, **41** (20), 7262–7269, doi:10.1002/2014gl061313.
- Bester, M.N., H. Bornemann and T. McIntyre, 2017: *Sea Ice, Third Edition* [Thomas, D.N. (ed.)]. Antarctic marine mammals and sea ice, John Wiley & Sons, Ltd.
- Bezeau, P., M. Sharp and G. Gascon, 2014: Variability in summer anticyclonic circulation over the Canadian Arctic Archipelago and west Greenland in the late 20th/early 21st centuries and its effect on glacier mass balance. *International Journal of Climatology*, **35** (4), 540–557, doi:10.1002/joc.4000.
- Bhatia, M.P. et al., 2013: Erratum: Greenland meltwater as a significant and potentially bioavailable source of iron to the ocean. *Nature Geoscience*, **6** (6), 503–503, doi:10.1038/ngeo1833.
- Bhatt, U. et al., 2017: Changing seasonality of panarctic tundra vegetation in relationship to climatic variables. *Environmental Research Letters*, **12** (5), doi:10.1088/1748-9326/aa6b0b.
- Biggs, R., G.D. Peterson and J.C. Rocha, 2018: The Regime Shifts Database: a framework for analyzing regime shifts in social-ecological systems. *Ecology and Society*, **23** (3), doi:10.5751/es-10264-230309.
- Biggs, R. et al., 2012: Toward Principles for Enhancing the Resilience of Ecosystem Services. *Annual Review of Environment and Resources*, Vol 37, **37** (1), 421–448, doi:10.1146/annurev-environ-051211-123836.
- Bintanja, R. and F.M. Selten, 2014: Future increases in Arctic precipitation linked to local evaporation and sea-ice retreat. *Nature*, **509**, 479, doi:10.1038/nature13259.
- Bintanja, R. et al., 2013: Important role for ocean warming and increased ice-shelf melt in Antarctic sea-ice expansion. *Nature Geoscience*, **6** (5), 376–379, doi:10.1038/Ngeo1767.
- Bintanja, R., G.J. Van Oldenborgh and C.A. Katsman, 2015: The effect of increased fresh water from Antarctic ice shelves on future trends in Antarctic sea ice. *Annals of Glaciology*, **56** (69), 120–126, doi:10.3189/2015AoG69A001.
- Birchenough, S.N.R. et al., 2015: Climate change and marine benthos: a review of existing research and future directions in the North Atlantic. *Wiley Interdisciplinary Reviews: Climate Change*, **6** (2), 203–223, doi:10.1002/wcc.330.
- Biskaborn, B.K. et al., 2019: Permafrost is warming at a global scale. *Nat Commun*, **10** (1), 264, doi:10.1038/s41467-018-08240-4.
- Bjerke, J. et al., 2017: Understanding the drivers of extensive plant damage in boreal and Arctic ecosystems: Insights from field surveys in the

- aftermath of damage. *Science of the Total Environment*, **599**, 1965–1976, doi:10.1016/j.scitotenv.2017.05.050.
- Bjørk, A.A. et al., 2018: Changes in Greenland's peripheral glaciers linked to the North Atlantic Oscillation. *Nature Climate Change*, **8** (1), 48–52, doi:10.1038/s41558-017-0029-1.
- Bjorndal, K.A. et al., 2017: Ecological regime shift drives declining growth rates of sea turtles throughout the West Atlantic. *Global Change Biology*, **23** (11), 4556–4568, doi:10.1111/gcb.13712.
- Bockheim, J. et al., 2013: Climate warming and permafrost dynamics in the Antarctic Peninsula region. *Global and Planetary Change*, **100**, 215–223, doi:10.1016/j.gloplacha.2012.10.018.
- Boetius, A. et al., 2013: Export of Algal Biomass from the Melting Arctic Sea Ice. *Science*, **339** (6126), 1430–1432, doi:10.1126/science.1231346.
- Boisvert, L.N., A.A. Petty and J.C. Stroeve, 2016: The Impact of the Extreme Winter 2015/16 Arctic Cyclone on the Barents–Kara Seas. *Monthly Weather Review*, **144** (11), 4279–4287, doi:10.1175/mwr-d-16-0234.1.
- Boisvert, L.N. et al., 2018: Intercomparison of Precipitation Estimates over the Arctic Ocean and Its Peripheral Seas from Reanalyses. *Journal of Climate*, **31** (20), 8441–8462, doi:10.1175/jcli-d-18-0125.1.
- Bolch, T. et al., 2013: Mass loss of Greenland's glaciers and ice caps 2003–2008 revealed from ICESat laser altimetry data. *Geophysical Research Letters*, **40** (5), 875–881, doi:10.1002/grl.50270.
- Bond, T.C. et al., 2013: Bounding the role of black carbon in the climate system: A scientific assessment. *Journal of Geophysical Research: Atmospheres*, **118** (11), 5380–5552, doi:10.1002/jgrd.50171.
- Bost, C.A. et al., 2009: The importance of oceanographic fronts to marine birds and mammals of the southern oceans. *Journal of Marine Systems*, **78** (3), 363–376, doi:10.1016/j.jmarsys.2008.11.022.
- Bost, C.A. et al., 2015: Large-scale climatic anomalies affect marine predator foraging behaviour and demography. *Nat Commun*, **6**, 8220, doi:10.1038/ncomms9220.
- Bouchard, F. et al., 2013: Vulnerability of shallow subarctic lakes to evaporate and desiccate when snowmelt runoff is low. *Geophysical Research Letters*, **40** (23), 6112–6117, doi:10.1002/2013gl058635.
- Bourgeois, S. et al., 2016: Glacier inputs influence organic matter composition and prokaryotic distribution in a high Arctic fjord (Kongsfjorden, Svalbard). *Journal of Marine Systems*, **164**, 112–127, doi:10.1016/j.jmarsys.2016.08.009.
- Box, J.E., 2013: Greenland ice sheet mass balance reconstruction. Part II: Surface mass balance (1840–2010). *Journal of Climate*, **26** (18), 6974–6989, doi:10.1175/JCLI-D-12-00518.1.
- Box, J.E. et al., 2019: Key indicators of Arctic climate change: 1971–2017. *Environmental Research Letters*, **14** (4), 045010, doi:10.1088/1748-9326/aafc1b.
- Box, J.E. et al., 2018: Global sea-level contribution from Arctic land ice: 1971–2017. *Environmental Research Letters*, **13** (12), 125012, doi:10.1088/1748-9326/aaf2ed.
- Box, J.E. et al., 2012: Greenland ice sheet albedo feedback: thermodynamics and atmospheric drivers. *The Cryosphere*, **6** (4), 821–839, doi:10.5194/tc-6-821-2012.
- Boy, M. et al., 2019: Interactions between the atmosphere, cryosphere, and ecosystems at northern high latitudes. *Atmospheric Chemistry and Physics*, **19** (3), 2015–2061, doi:10.5194/acp-19-2015-2019.
- Bracegirdle, T.J., P. Hyder and C.R. Holmes, 2018: CMIP5 Diversity in Southern Westerly Jet Projections Related to Historical Sea Ice Area: Strong Link to Strengthening and Weak Link to Shift. *Journal of Climate*, **31** (1), 195–211, doi:10.1175/jcli-d-17-0320.1.
- Bracegirdle, T.J. et al., 2013: Assessment of surface winds over the Atlantic, Indian, and Pacific Ocean sectors of the Southern Ocean in CMIP5 models: historical bias, forcing response, and state dependence. *Journal of Geophysical Research: Atmospheres*, **118** (2), 547–562, doi:10.1002/jgrd.50153.
- Bracegirdle, T.J., D.B. Stephenson, J. Turner and T. Phillips, 2015: The importance of sea ice area biases in 21st century multimodel projections of Antarctic temperature and precipitation. *Geophysical Research Letters*, **42** (24), 10832–10839, doi:10.1002/2015gl067055.
- Braithwaite, J.E., J.J. Meeuwig and M.R. Hipsey, 2015a: Optimal migration energetics of humpback whales and the implications of disturbance. *Conserv Physiol*, **3** (1), doi:10.1093/conphys/cov001.
- Braithwaite, J.E. et al., 2015b: From sea ice to blubber: linking whale condition to krill abundance using historical whaling records. *Polar Biology*, **38** (8), 1195–1202, doi:10.1007/s00300-015-1685-0.
- Breed, G.A. et al., 2017: Sustained disruption of narwhal habitat use and behavior in the presence of Arctic killer whales. *Proceedings of the National Academy of Sciences*, **114** (10), 2628–2633, doi:10.1073/pnas.1611707114.
- Bret-Harte, M.S. et al., 2013: The response of Arctic vegetation and soils following an unusually severe tundra fire. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **368** (1624), doi:10.1098/rstb.2012.0490.
- Brinkman, T.J. et al., 2016: Arctic communities perceive climate impacts on access as a critical challenge to availability of subsistence resources. *Climatic Change*, **139** (3), 413–427, doi:10.1007/s10584-016-1819-6.
- Bromaghin, J.F. et al., 2015: Polar bear population dynamics in the southern Beaufort Sea during a period of sea ice decline. *Ecological Applications*, **25** (3), 634–651, doi:10.1890/14-1129.1.
- Bronen, R., 2015: Climate-induced community relocations: using integrated social-ecological assessments to foster adaptation and resilience. *Ecology and Society*, **20** (3), doi:10.5751/es-07801-200336.
- Bronen, R., 2017: The Human Rights of Climate-Induced community relocation. In: Climate change, migration, and human rights [Mano, D., A. Baldwin, D. Cubie, A. Mihr and T. Thorp (eds.)]. Routledge Press., Abingdon UK, 129–148.
- Bronen, R. and F.S. Chapin, 3rd, 2013: Adaptive governance and institutional strategies for climate-induced community relocations in Alaska. *Proc Natl Acad Sci U S A*, **110** (23), 9320–5, doi:10.1073/pnas.1210508110.
- Bronselaer, B. et al., 2018: Change in future climate due to Antarctic meltwater. *Nature*, **564** (7734), 53–58, doi:10.1038/s41586-018-0712-z.
- Brooks, C.M. et al., 2018: Antarctic fisheries: factor climate change into their management. *Nature*, **558** (7709), 177–180, doi:10.1038/d41586-018-05372-x.
- Brower, A.A. et al., 2017: Gray whale distribution relative to benthic invertebrate biomass and abundance: Northeastern Chukchi Sea 2009–2012. *Deep Sea Research Part II: Topical Studies in Oceanography*, **144**, 156–174, doi:10.1016/j.dsr2.2016.12.007.
- Brown, L.C. and C.R. Duguay, 2011: The fate of lake ice in the North American Arctic. *The Cryosphere*, **5** (4), 869–892, doi:10.5194/tc-5-869-2011.
- Brown, R. and C. Derksen, 2013: Is Eurasian October snow cover extent increasing? *Environmental Research Letters*, **8**, doi:10.1088/1748-9326/8/2/024006.
- Brown, R. et al., 2017: Arctic terrestrial snow cover. In: Snow, Water, Ice and Permafrost in the Arctic (SWIPA) 2017 Assessment. Arctic Monitoring and Assessment Programme, Oslo, Norway.
- Brubaker, M., J. Berner, R. Chavan and J. Warren, 2011: Climate change and health effects in Northwest Alaska. *Global Health Action*, **4** (1), 8445, doi:10.3402/gha.v4i0.8445.
- Brubaker, M., J. Berner and M. Tcheripanoff, 2013: LEO, the Local Environmental Observer Network: a community-based system for surveillance of climate, environment, and health events. *International Journal of Circumpolar Health*, **72**, 513–514.
- Brutel-Vuilmet, C., M. Ménégoz and G. Krinner, 2013: An analysis of present and future seasonal Northern Hemisphere land snow cover simulated by CMIP5 coupled climate models. *The Cryosphere*, **7** (1), 67–80, doi:10.5194/tc-7-67-2013.

- Bullard, J.E. et al., 2016: High-latitude dust in the Earth system. *Reviews of Geophysics*, **54** (2), 447–485, doi:10.1002/2016rg000518.
- Bullock, R., S. Aggarwal, R.A. Perkins and W. Schnabel, 2017: *Scale-up considerations for surface collecting agent assisted in-situ burn crude oil spill response experiments in the Arctic: Laboratory to field-scale investigations*.
- Bulygina, O.N., P.Y. Groisman, V.N. Razuvaev and N.N. Korshunova, 2011: Changes in snow cover characteristics over Northern Eurasia since 1966. *Environmental Research Letters*, **6** (4), 045204, doi:10.1088/1748-9326/6/4/045204.
- Bunce, A. and J. Ford, 2015: How is adaptation, resilience, and vulnerability research engaging with gender? *Environmental Research Letters*, **10** (12), 123003, doi:10.1088/1748-9326/10/12/123003/meta.
- Bunce, A. et al., 2016: Vulnerability and adaptive capacity of Inuit women to climate change: a case study from Iqaluit, Nunavut. *Natural Hazards*, **83** (3), 1419–1441, doi:10.1007/s11069-016-2398-6.
- Burgard, C. and D. Notz, 2017: Drivers of Arctic Ocean warming in CMIP5 models. *Geophysical Research Letters*, **44** (9), 4263–4271, doi:10.1002/2016GL072342.
- Burgos, J., B. Ernst, D. Armstrong and J. Orensanz, 2013: Fluctuations in Range and Abundance of Snow Crab (*Chionoecetes Opilio*) from the Eastern Bering Sea: What Role for Pacific Cod (*Gadus Macrocephalus*) Predation? *Bulletin of Marine Science*, **89** (1), 57–81, doi:10.5343/bms.2011.1137.
- Burke, E.J. et al., 2017a: Quantifying uncertainties of permafrost carbon–climate feedbacks. *Biogeosciences*, **14** (12), 3051–3066, doi:10.5194/bg-14-3051-2017.
- Burke, E.J., C.D. Jones and C.D. Koven, 2013: Estimating the permafrost-carbon climate response in the CMIP5 climate models using a simplified approach. *Journal of Climate*, **26** (14), 4897–4909, doi:10.1175/jcli-d-12-00550.1.
- Burke, J.L., J. Bohlmann and A.L. Carroll, 2017b: Consequences of distributional asymmetry in a warming environment: invasion of novel forests by the mountain pine beetle. *Ecosphere*, **8** (4), e01778, doi:10.1002/ecs2.1778.
- BurnSilver, S. et al., 2016: Are Mixed Economies Persistent or Transitional? Evidence Using Social Networks from Arctic Alaska. *American Anthropologist*, **118** (1), 121–129, doi:10.1111/aman.12447.
- Burton-Johnson, A., M. Black, P.T. Fretwell and J. Kaluza-Gilbert, 2016: An automated methodology for differentiating rock from snow, clouds and sea in Antarctica from Landsat 8 imagery: a new rock outcrop map and area estimation for the entire Antarctic continent. *The Cryosphere*, **10** (4), 1665–1677, doi:10.5194/tc-10-1665-2016.
- Busch, D.S. et al., 2016: Climate science strategy of the US National Marine Fisheries Service. *Marine Policy*, **74**, 58–67, doi:10.1016/j.marpol.2016.09.001.
- CAFF, 2013a: *Arctic Biodiversity Assessment. Status and trends in Arctic biodiversity*. Conservation of Arctic Flora and Fauna (CAFF), Akureyri, Iceland, 28 pp [Available at: <http://arcticcc.org/assets/resources/ABA2013Science.pdf>; Access Date: 10 October 2018].
- CAFF, 2013b: *Arctic Biodiversity Assessment: Report for Policy Makers*. Conservation of Arctic Flora and Fauna (CAFF), Akureyri, Iceland, 678 pp.
- CAFF, 2015a: *The Economics of Ecosystems and Biodiversity (TEEB) Scoping Study for the Arctic*. Conservation of Arctic Flora and Fauna (CAFF), Akureyri, Iceland, 168 pp.
- CAFF, 2015b: *Traditional Knowledge & Community Based Monitoring Progress report 2015*. Conservation of Arctic Flora and Fauna (CAFF), Akureyri, Iceland, 4 pp [Available at: <https://oaarchive.arctic-council.org/handle/11374/397>; Access Date: 13 April 2019].
- CAFF, 2017: *State of the Arctic Marine Biodiversity Report*. Conservation of Arctic Flora and Fauna International Secretariat, Akureyri, Iceland, 200 pp.
- CAFF and PAME, 2017: *Arctic Invasive Alien Species: Strategy and Action Plan*. Conservation of Arctic Flora and Fauna and Protection of the Arctic Marine Environment Akureyri, Iceland, 20 pp.
- Cahalán, J., J. Gasper and J. Mondragon, 2014: *Catch sampling and estimation in the federal groundfish fisheries off Alaska, 2015 edition*. U.S. Dep. Commer., NOAA Tech. Memo., NMFS-AFSC-286, 46 p [Available at: www.afsc.noaa.gov/Publications/AFSC-TM/NOAA-TM-AFSC-286.pdf].
- Campbell, E.C. et al., 2019: Antarctic offshore polynyas linked to Southern Hemisphere climate anomalies. *Nature*, **in press**, doi:10.1038/s41586-019-1294-0.
- Camus, L. and M.G.D. Smit, 2019: Environmental effects of Arctic oil spills and spill response technologies, introduction to a 5 year joint industry effort. *Mar Environ Res*, **144**, 250–254, doi:10.1016/j.marenvres.2017.12.008.
- Canadian Forest Service, 2017: National Fire Database; Agency Fire Data., Edmonton, Alberta.
- Cape, M., R., M. Vernet, M. Kahru and G. Spreen, 2013: Polynya dynamics drive primary production in the Larsen A and B embayments following ice shelf collapse. *Journal of Geophysical Research: Oceans*, **119** (1), 572–594, doi:10.1002/2013jc009441.
- Cape, M.R. et al., 2018: Nutrient release to oceans from buoyancy-driven upwelling at Greenland tidewater glaciers. *Nature Geoscience*, **12** (1), 34–39, doi:10.1038/s41561-018-0268-4.
- Cape, M.R. et al., 2015: Foehn winds link climate-driven warming to ice shelf evolution in Antarctica. *Journal of Geophysical Research-Atmospheres*, **120** (21), 11037–11057, doi:10.1002/2015jd023465.
- Capotondi, A. et al., 2012: Enhanced upper ocean stratification with climate change in the CMIP3 models. *Journal of Geophysical Research: Oceans*, **117** (C4), C04031, doi:10.1029/2011JC007409.
- Carmack, E. et al., 2015: Toward Quantifying the Increasing Role of Oceanic Heat in Sea Ice Loss in the New Arctic. *Bulletin of the American Meteorological Society*, **96** (12), 2079–2105, doi:10.1175/Bams-D-13-00177.1.
- Carmack, E.C. et al., 2016: Freshwater and its role in the Arctic Marine System: Sources, disposition, storage, export, and physical and biogeochemical consequences in the Arctic and global oceans. *Journal of Geophysical Research: Biogeosciences*, **121** (3), 675–717, doi:10.1002/2015JG003140.
- Carr, J.R., C.R. Stokes and A. Veli, 2013: Recent progress in understanding marine-terminating Arctic outlet glacier response to climatic and oceanic forcing. *Progress in Physical Geography*, **37** (4), 436–467, doi:10.1177/0309133313483163.
- Carr, J.R. et al., 2017: Basal topographic controls on rapid retreat of Humboldt Glacier, northern Greenland. *Journal of Glaciology*, **61** (225), 137–150, doi:10.3189/2015JoG14J128.
- Carroll, M.L. et al., 2011: Shrinking lakes of the Arctic: Spatial relationships and trajectory of change. *Geophysical Research Letters*, **38** (20), doi:10.1029/2011GL049427.
- Carsey, F.D., 1980: Microwave Observation of the Weddell Polynya. *Monthly Weather Review*, **108** (12), 2032–2044, doi:10.1175/1520-0493(1980)108.
- Carson, M. and M. Sommerkorn, 2017: *A resilience approach to adaptation actions*. Chapter 8 of Adaptation Actions for a Changing Arctic: Perspectives from the Barents Area, Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway, 195–218 [Available at: www.amap.no/documents/doc/adaptation-actions-for-a-changing-arctic-perspectives-from-the-barents-area/1604].
- Carter, S.P. and H.A. Fricker, 2012: The supply of subglacial meltwater to the grounding line of the Siple Coast, West Antarctica. *Ann. Glaciol.*, **53**, 267–280, doi:10.3189/2012AoG60A119.
- Cassotta, S., K. Hossain, J. Ren and M.E. Goodsite, 2015: Climate Change and China as a Global Emerging Regulatory Sea Power in the Arctic Ocean: Is China a Threat for Arctic Ocean Security? *Beijing Law Review*, **6** (3), 119–207, doi:10.4236/blr.2015.63020.
- Cassotta, S., K. Hossain, J. Ren and M.E. Goodsite, 2016: Climate Change and Human Security in a Regulatory Multilevel and Multidisciplinary Dimension: The Case of the Arctic Environmental Ocean. In: Climate Change Adaptation, Resilience and Hazards [Leal Filho, W., H. Musa, G. Cavan, P. O'Hare and J. Seixas (eds.)]. Springer International Publishing, Cham, 71–91.
- Cavanagh, R.D. et al., 2017: A Synergistic Approach for Evaluating Climate Model Output for Ecological Applications. *Frontiers in Marine Science*, **4**, 1–12, doi:https://doi.org/10.3389/fmars.2017.00308.

- CAVM Team, 2003: Circumpolar Arctic Vegetation Map. Scale 1:7,500,000. Conservation of Arctic Flora and Fauna (CAFF) Map No. 1., Anchorage, Alaska.
- CCA, 2016: *Commercial Marine Shipping Accidents: Understanding the Risks in Canada*. Council of Canadian Academies (CCA), Ottawa (ON); Workshop Report, pp. 84 [Available at: https://clearseas.org/en/research_project/characterization-of-risk-of-marine-shipping-in-canadian-waters/].
- CCAMLR, 1982: *Convention on the Conservation of Antarctic Marine Living Resources, opened for signature 20 May 1980, 1329 UNTS 47 (entered into force 7 April 1982)* ('CCAMLR'). Canberra [Available at: <https://treaties.un.org/pages/showDetails.aspx?objid=08000002800dc364>; Access Date: 05 December 2018].
- CCAMLR, 2016a: *Commission for the Conservation of Antarctic Marine Living Resources: Report of the Thirty-fifth Meeting of the Commission*. Report of the meeting of the Commission, **35**, Hobart, Tasmania, Australia, 222.
- CCAMLR, 2016b: *The value of marine resources harvested in the CCAMLR Convention Area – an assessment of GVP*. Commission for the Conservation of Antarctic Marine Living Resources [Available at: www.ccamlr.org/en/ccamlr-xxxv/10; Access Date: 05 December, 2018].
- CCAMLR, 2017a: *Fishery Reports 2016*. Commission for the Conservation of Antarctic Marine Living Resources, Hobart, Tasmania [Available at: www.ccamlr.org/en/publications/fishery-reports-2016; Access Date: 05 December, 2018].
- CCAMLR, 2017b: *Krill Fishery Report 2016*. Commission for the Conservation of Antarctic Marine Living Resources, Hobart, Tasmania. [Available at: www.ccamlr.org/en/document/publications/krill-fishery-report-2016; Access Date: 05 December, 2018].
- CCAMLR, 2017c: *Map of the CAMLR Convention Area. 2017*, www.ccamlr.org/node/86816 [Available at: www.ccamlr.org/node/86816; Access Date: 05 December, 2018].
- CCAMLR, 2018: *Report of the thirty-seventh meeting of the commission*. Commission for the Conservation of Antarctic Marine Living Resources, Hobart, Australia [Available at: www.ccamlr.org/en/system/files/e-cc-xxxvii.pdf; Access Date: 05 December, 2018].
- Chambers, D.P., 2018: Using kinetic energy measurements from altimetry to detect shifts in the positions of fronts in the Southern Ocean. *Ocean Science*, **14** (1), 105, doi:10.5194/os-14-105-2018.
- Chapin III, F.S., G.P. Kofinas and C. Folke, Eds., 2009: *Principles of Ecosystem Stewardship: Resilience-Based Natural Resource Management in a Changing World*. Springer-Verlag, New York, USA., 401 pp.
- Chapin III, F.S. et al., 2010: Resilience of Alaska's boreal forest to climatic change. In: *The Dynamics of Change in Alaska's Boreal Forests: Resilience and Vulnerability in Response to Climate Warming*. Canadian Journal of Forest Research. NRC Research Press, **40**, 1360–1370.
- Chapin III, F.S., M. Sommerkorn, M.D. Robards and K. Hillmer-Pegram, 2015: Ecosystem stewardship: A resilience framework for arctic conservation. *Global Environmental Change*, **34**, 207–217, doi:doi.org/10.1016/j.gloenvcha.2015.07.003.
- Chapman, C.C., 2014: Southern Ocean jets and how to find them: Improving and comparing common jet detection methods. *Journal of Geophysical Research: Oceans*, **119** (7), 4318–4339, doi:10.1002/2014JC009810.
- Chapman, C.C., 2017: New perspectives on frontal variability in the Southern Ocean. *Journal of Physical Oceanography*, **47** (5), 1151–1168, doi:10.1175/JPO-D-16-0222.1.
- Charalampidis, C. et al., 2015: Changing surface–atmosphere energy exchange and refreezing capacity of the lower accumulation area, West Greenland. *The Cryosphere*, **9** (6), 2163–2181, doi:10.5194/tc-9-2163-2015.
- Charalampidis, C. et al., 2016: Thermal tracing of retained meltwater in the lower accumulation area of the Southwestern Greenland ice sheet. *Annals of Glaciology*, **57** (72), 1–10, doi:10.1017/aog.2016.2.
- Chen, H.W., F. Zhang and R.B. Alley, 2016a: The Robustness of Midlatitude Weather Pattern Changes due to Arctic Sea Ice Loss. *Journal of Climate*, **29** (21), 7831–7849, doi:10.1175/jcli-d-16-0167.1.
- Chen, M. et al., 2012: Temporal and spatial pattern of thermokarst lake area changes at Yukon Flats, Alaska. *Hydrological Processes*, **28** (3), 837–852, doi:10.1002/hyp.9642.
- Chen, X. et al., 2015: Observed contrast changes in snow cover phenology in northern middle and high latitudes from 2001–2014. *Scientific Reports*, **5**, 16820, doi:10.1038/srep16820.
- Chen, X.N., S.L. Liang and Y.F. Cao, 2016b: Satellite observed changes in the Northern Hemisphere snow cover phenology and the associated radiative forcing and feedback between 1982 and 2013. *Environmental Research Letters*, **11** (8), 084002, doi:10.1088/1748-9326/11/8/084002.
- Cheng, L. et al., 2017: Improved estimates of ocean heat content from 1960 to 2015. *Science Advances*, **3** (3), doi:10.1126/sciadv.1601545
- Chénier, R., L. Abado, O. Sabourin and L. Tardif, 2017: Northern marine transportation corridors: Creation and analysis of northern marine traffic routes in Canadian waters. *Transactions in GIS*, **21** (6), 1085–1097, doi:10.1111/tgis.12295.
- Chernova, N.V., 2011: Distribution patterns and chorological analysis of fish fauna of the Arctic Region. *Journal of Ichthyology*, **51** (10), 825–924, doi:10.1134/S0032945211100043.
- Chevallier, M. et al., 2017: Intercomparison of the Arctic sea ice cover in global ocean–sea ice reanalyses from the ORA-IP project. *Climate Dynamics*, **49** (3), 1107–1136, doi:10.1007/s00382-016-2985-y.
- Chidichimo, M.P., K.A. Donohue, D.R. Watts and K.L. Tracey, 2014: Baroclinic transport time series of the Antarctic Circumpolar Current measured in Drake Passage. *Journal of Physical Oceanography*, **44** (7), 1829–1853, doi:10.1175/JPO-D-13-071.1.
- Chin, K.S. et al., 2016: Permafrost thaw and intense thermokarst activity decreases abundance of stream benthic macroinvertebrates. *Glob Chang Biol*, **22** (8), 2715–28, doi:10.1111/gcb.13225.
- Chown, S.L., 2017: Antarctic environmental challenges in a global context. In: *The Handbook on the Politics of Antarctica* [Dodds, K. and A. Hemmings (eds.)]. Edward Elgar Publishing, Cheltenham, 523–539.
- Chown, S.L. et al., 2012: Continent-wide risk assessment for the establishment of nonindigenous species in Antarctica. *Proceedings of the National Academy of Sciences*, **109** (13), 4938, doi:10.1073/pnas.1119787109.
- Choy, E.S., B. Rosenberg, J.D. Roth and L.L. Loseto, 2017: Inter-annual variation in environmental factors affect the prey and body condition of beluga whales in the eastern Beaufort Sea. *Marine Ecology Progress Series*, **579**, 213–225, doi:10.3354/meps12256.
- Christensen, T.R. et al., 2019: Tracing the climate signal: mitigation of anthropogenic methane emissions can outweigh a large Arctic natural emission increase. *Sci Rep*, **9** (1), 1146, doi:10.1038/s41598-018-37719-9.
- Christiansen, J.S., 2017: No future for Euro-Arctic ocean fishes? *Marine Ecology Progress Series*, **575**, 217–227, doi:10.3354/meps12192.
- Christianson, K. et al., 2016: Sensitivity of Pine Island Glacier to observed ocean forcing. *Geophysical Research Letters*, **43** (20), 10817–10825, doi:10.1002/2016gl070500.
- Christie, F.D. et al., 2016: Four-decade record of pervasive grounding line retreat along the Bellingshausen margin of West Antarctica. *Geophysical Research Letters*, **43** (11), 5741–5749.
- Christie, K.S., T.E. Hollmen, H.P. Huntington and J.R. Lovvorn, 2018: Structured decision analysis informed by traditional ecological knowledge as a tool to strengthen subsistence systems in a changing Arctic. *Ecology and Society*, **23** (4), 42, doi:https://doi.org/10.5751/ES-10596-230442.
- Chuter, S.J., A. Martín-Español, B. Wouters and J.L. Bamber, 2017: Mass balance reassessment of glaciers draining into the Abbot and Getz Ice Shelves of West Antarctica. *Geophysical Research Letters*, **44** (14), 7328–7337, doi:10.1002/2017GL073087.
- Cimino, M.A., H.J. Lynch, V.S. Saba and M.J. Oliver, 2016: Projected asymmetric response of Adelie penguins to Antarctic climate change. *Sci Rep*, **6**, 28785, doi:10.1038/srep28785.

- Clark, D.G. et al., 2016a: The role of environmental factors in search and rescue incidents in Nunavut, Canada. *Public Health*, **137** (Supplement C), 44–49, doi:10.1016/j.puhe.2016.06.003.
- Clark, D.G., J.D. Ford, T. Pearce and L. Berrang-Ford, 2016b: Vulnerability to unintentional injuries associated with land-use activities and search and rescue in Nunavut, Canada. *Social Science and Medicine*, **169**, 18–26, doi:10.1016/j.socscimed.2016.09.026.
- Clark, G.F. et al., 2015: Vulnerability of Antarctic shallow invertebrate-dominated ecosystems. *Austral Ecology*, **40** (4), 482–491, doi:10.1111/aec.12237.
- Clark, G.F. et al., 2017: The Roles of Sea-Ice, Light and Sedimentation in Structuring Shallow Antarctic Benthic Communities. *Plos One*, **12** (1), e0168391, doi:10.1371/journal.pone.0168391.
- Clem, K.R., J.A. Renwick and J. McGregor, 2017: Relationship between eastern tropical Pacific cooling and recent trends in the Southern Hemisphere zonal-mean circulation. *Climate Dynamics*, **49** (1–2), 113–129, doi:10.1007/s00382-016-3329-7.
- Cochran, P. et al., 2013: Indigenous frameworks for observing and responding to climate change in Alaska. *Climatic Change*, **120** (3), 557–567, doi:10.1007/s10584-013-0735-2.
- Coetzee, B.W.T., P. Convey and S.L. Chown, 2017: Expanding the Protected Area Network in Antarctica is Urgent and Readily Achievable. *Conservation Letters*, **10** (6), 670–680, doi:10.1111/conl.12342.
- Coggins, J.H.J. and A.J. McDonald, 2015: The influence of the Amundsen Sea Low on the winds in the Ross Sea and surroundings: Insights from a synoptic climatology. *Journal of Geophysical Research-Atmospheres*, **120** (6), 2167–2189, doi:10.1002/2014JD022830.
- Cohen, J., K. Pfeiffer and J.A. Francis, 2018: Warm Arctic episodes linked with increased frequency of extreme winter weather in the United States. *Nature Communications*, **9** (1), 869, doi:10.1038/s41467-018-02992-9.
- Cohen, J., H. Ye and J. Jones, 2015: Trends and variability in rain-on-snow events. *Geophysical Research Letters*, **42** (17), 7115–7122, doi:10.1002/2015gl065320.
- Cohen, J.L. et al., 2012: Arctic warming, increasing snow cover and widespread boreal winter cooling. *Environmental Research Letters*, **7** (1), 014007, doi:10.1088/1748-9326/7/1/014007.
- Colgan, W. et al., 2015: Greenland high-elevation mass balance: inference and implication of reference period (1961–90) imbalance. *Annals of Glaciology*, **56** (70), 105–117, doi:10.3189/2015AoG70A967.
- Collins, M. et al., 2013: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Long-term climate change: Projections, commitments and irreversibility, Cambridge University Press, Cambridge, UK and New York, USA.
- Colombo, N. et al., 2018: Review: Impacts of permafrost degradation on inorganic chemistry of surface fresh water. *Global and Planetary Change*, **162**, 69–83, doi:10.1016/j.gloplacha.2017.11.017.
- Comiso, J.C. et al., 2017a: Positive Trend in the Antarctic Sea Ice Cover and Associated Changes in Surface Temperature. *Journal of Climate*, **30** (6), 2251–2267, doi:10.1175/JCLI-D-16-0408.1.
- Comiso, J.C., W.N. Meier and R. Gersten, 2017b: Variability and trends in the Arctic Sea ice cover: Results from different techniques. *Journal of Geophysical Research: Oceans*, **122** (8), 6883–6900, doi:10.1002/2017jc012768.
- Commane, R. et al., 2017: Carbon dioxide sources from Alaska driven by increasing early winter respiration from Arctic tundra. *Proceedings of the National Academy of Sciences USA*, **114** (21), 5361–5366, doi:10.1073/pnas.1618567114.
- Connon, R.F., W.L. Quinton, J.R. Craig and M. Hayashi, 2014: Changing hydrologic connectivity due to permafrost thaw in the lower Liard River valley, NWT, Canada. *Hydrological Processes*, **28** (14), 4163–4178, doi:10.1002/hyp.10206.
- Conrad, C.J. and N.S. Lovenduski, 2015: Climate-Driven Variability in the Southern Ocean Carbonate System. *Journal of Climate*, **28** (13), 5335–5350, doi:papers2://publication/doi/10.1175/JCLI-D-14-00481.1.
- Constable, A., J. Melbourne-Thomas, R. Trebilco and A.J. Press, 2017: *ACE CRC Position Analysis: Managing change in Southern Ocean ecosystems*. Centre, A.C.E.C.R., Hobart, 1–40 [Available at: <http://acecrc.org.au/wp-content/uploads/2017/10/2017-ACECRC-Position-Analysis-Southern-Ocean-Ecosystems.pdf>; Access Date: 05 December 2018].
- Constable, A.J., 2011: Lessons from CCAMLR on the implementation of the ecosystem approach to managing fisheries. *Fish and Fisheries*, **12** (2), 138–151, doi:10.1111/j.1467-2979.2011.00410.x.
- Constable, A.J. et al., 2016: Developing priority variables (“ecosystem Essential Ocean Variables” – eEOVs) for observing dynamics and change in Southern Ocean ecosystems. *Journal of Marine Systems*, **161**, 26–41, doi:10.1016/j.jmarsys.2016.05.003.
- Constable, A.J. et al., 2014: Climate change and Southern Ocean ecosystems I: how changes in physical habitats directly affect marine biota. *Global Change Biology*, **20** (10), 3004–3025, doi:10.1111/gcb.12623.
- Cook, A.J. et al., 2016: Ocean forcing of glacier retreat in the western Antarctic Peninsula. *Science*, **353** (6296), 283, doi:10.1126/science.aae0017.
- Cook, A.J., D.G. Vaughan, A.J. Luckman and T. Murray, 2014: A new Antarctic Peninsula glacier basin inventory and observed area changes since the 1940s. *Antarctic Science*, **26** (6), 614–624, doi:10.1017/S0954102014000200.
- Cook, J.A. et al., 2017: The Beringian Coevolution Project: holistic collections of mammals and associated parasites reveal novel perspectives on evolutionary and environmental change in the North. *Arctic Science*, **3** (3), 585–617, doi:10.1139/as-2016-0042.
- Cooley, S.W. and T.M. Pavelsky, 2016: Spatial and temporal patterns in Arctic river ice breakup revealed by automated ice detection from MODIS imagery. *Remote Sensing of Environment*, **175** (Supplement C), 310–322, doi:10.1016/j.rse.2016.01.004.
- Copland, L. and D. Mueller, 2017: *Arctic Ice Shelves and Ice Islands*. Springer Polar Sciences, Springer, Dordrecht.
- Coulombe, S. et al., 2019: Origin, burial and preservation of late Pleistocene-age glacier ice in Arctic permafrost (Bylot Island, NU, Canada). *The Cryosphere*, **13** (1), 97–111, doi:10.5194/tc-13-97-2019.
- Cowtan, K. and R.G. Way, 2014: Coverage bias in the HadCRUT4 temperature series and its impact on recent temperature trends. *Quarterly Journal of the Royal Meteorological Society*, **140** (683), 1935–1944, doi:10.1002/qj.2297.
- Cowton, T. et al., 2016: Controls on the transport of oceanic heat to Kangerdlugssuaq Glacier, East Greenland. *Journal of Glaciology*, **62** (236), 1167–1180, doi:10.1017/jog.2016.117.
- Cowton, T.R. et al., 2018: Linear response of east Greenland’s tidewater glaciers to ocean/atmosphere warming. *Proceedings of the National Academy of Sciences*, **115** (31), 7907, doi:10.1073/pnas.1801769115.
- Cox, M.J. et al., 2018: No evidence for a decline in the density of Antarctic krill *Euphausia superba* Dana, 1850, in the Southwest Atlantic sector between 1976 and 2016. *Journal of Crustacean Biology*, **38** (6), 656–661, doi:10.1093/jcbl/ruy072.
- Cozzetto, K. et al., 2013: Climate change impacts on the water resources of American Indians and Alaska Natives in the U.S. *Climatic Change*, **120** (3), 569–584, doi:10.1007/s10584-013-0852-y.
- Crépin, A.-S., Å. Gren, G. Engström and D. Ospina, 2017: Operationalising a social–ecological system perspective on the Arctic Ocean. *AMBIO*, **46** (3), 475–485, doi:10.1007/s13280-017-0960-4.
- Crill, P.M. and B.F. Thornton, 2017: Whither methane in the IPCC process? *Nature Climate Change*, **7**, 678, doi:10.1038/nclimate3403.
- Cristofari, R. et al., 2018: Climate-driven range shifts of the king penguin in a fragmented ecosystem. *Nature Climate Change*, **8** (3), 245–251, doi:10.1038/s41558-018-0084-2.
- Cullather, R.I. et al., 2016: Analysis of the warmest Arctic winter, 2015–2016. *Geophysical Research Letters*, **43** (20), 10,808–10,816, doi:10.1002/2016gl071228.

- Cumming, G.S., 2011: Spatial resilience: integrating landscape ecology, resilience, and sustainability. *Landscape Ecology*, **26** (7), 899–909, doi:10.1007/s10980-011-9623-1.
- Cunsolo, A. and N.R. Ellis, 2018: Ecological grief as a mental health response to climate change-related loss. *Nature Climate Change*, **8** (4), 275–281, doi:10.1038/s41558-018-0092-2.
- Cunsolo, A., I. Shiwak and M. Wood, 2017: “You Need to Be a Well-Rounded Cultural Person”: Youth Mentorship Programs for Cultural Preservation, Promotion, and Sustainability in the Nunatsiavut Region of Labrador. In: Northern Sustainabilities: Understanding and Addressing Change in the Circumpolar World [Fondahl, G. and G. Wilson (eds.)]. Springer Polar Sciences, Springer, 285–303.
- Cunsolo Willox, A. et al., 2013a: The land enriches the soul: On climatic and environmental change, affect, and emotional health and well-being in Rigolet, Nunatsiavut, Canada. *Emotion, Space and Society*, **6**, 14–24.
- Cunsolo Willox, A. et al., 2013b: Climate change and mental health: an exploratory case study from Rigolet, Nunatsiavut, Canada. *Climatic Change*, **121** (2), 255–270, doi:10.1007/s10584-013-0875-4.
- Cunsolo Willox, A. et al., 2012: From this place and of this place: “Climate change, sense of place, and health in Nunatsiavut, Canada. *Social Science & Medicine*, **75** (3), 538–547, doi:10.1016/j.socscimed.2012.03.043.
- Cunsolo Willox, A. et al., 2015: Examining relationships between climate change and mental health in the Circumpolar North. *Regional Environmental Change*, **15** (1), 169–182, doi:10.1007/s10113-014-0630-z.
- Dabros, A., M. Pyper and G. Castilla, 2018: Seismic lines in the boreal and arctic ecosystems of North America: environmental impacts, challenges, and opportunities. *Environmental Reviews*, **26** (2), 214–229, doi:10.1139/er-2017-0080.
- Dale, A. and D. Armitage, 2011: Marine mammal co-management in Canada’s Arctic: Knowledge co-production for learning and adaptive capacity. *Marine Policy*, **35** (4), 440–449, doi:10.1016/j.marpol.2010.10.019.
- Daley, K. et al., 2015: Water systems, sanitation, and public health risks in remote communities: Inuit resident perspectives from the Canadian Arctic. *Social Science & Medicine*, **135** (Supplement C), 124–132, doi:10.1016/j.socscimed.2015.04.017.
- Dalpadado, P. et al., 2016: Distribution and abundance of euphausiids and pelagic amphipods in Kongsfjorden, Isfjorden and Rijpfjorden (Svalbard) and changes in their relative importance as key prey in a warming marine ecosystem. *Polar Biology*, **39** (10), 1765–1784, doi:10.1007/s00300-015-1874-x.
- Damm, E. et al., 2018: The Transpolar Drift conveys methane from the Siberian Shelf to the central Arctic Ocean. *Sci Rep*, **8** (1), 4515, doi:10.1038/s41598-018-22801-z.
- Dannevig, H. and C. Aall, 2015: The regional level as boundary organization? An analysis of climate change adaptation governance in Norway. *Environmental Science & Policy*, **54**, 168–175, doi:10.1016/j.envsci.2015.07.001.
- Dätwyler, C. et al., 2017: Teleconnection stationarity, variability and trends of the Southern Annular Mode (SAM) during the last millennium. *Climate Dynamics*, **51** (5–6), 2321–2339, doi:10.1007/s00382-017-4015-0.
- Dawson, J., M.E. Johnston and E.J. Stewart, 2014: Governance of Arctic expedition cruise ships in a time of rapid environmental and economic change. *Ocean and Coastal Management*, **89**, 88–99, doi:10.1016/j.ocecoaman.2013.12.005.
- Dawson, J. et al., 2018: Temporal and Spatial Patterns of Ship Traffic in the Canadian Arctic from 1990 to 2015. *Arctic*, **71** (7), 15–26, doi:10.14430/arctic4698.
- de la Barre, S. et al., 2016: Tourism and Arctic Observation Systems: exploring the relationships. *Polar Research*, **35** (1), 24980, doi:10.3402/polar.v35.24980.
- de la Mare, W.K., 2009: Changes in Antarctic sea-ice extent from direct historical observations and whaling records. *Climatic Change*, **92** (3), 461–493, doi:10.1007/s10584-008-9473-2.
- de Lavergne, C. et al., 2014: Cessation of deep convection in the open Southern Ocean under anthropogenic climate change. *Nature Climate Change*, **4**, 278–282, doi:10.1038/nclimate2132.
- De Lucia, V., 2017: The Arctic environment and the BBNJ negotiations. Special rules for special circumstances? *Marine Policy*, **86**, 234–240, doi:10.1016/j.marpol.2017.09.011.
- De Robertis, A., K. Taylor, C.D. Wilson and E.V. Farley, 2017: Abundance and distribution of Arctic cod (*Boreogadus saida*) and other pelagic fishes over the U.S. Continental Shelf of the Northern Bering and Chukchi Seas. *Deep Sea Research Part II: Topical Studies in Oceanography*, **135**, 51–65, doi:10.1016/j.dsr2.2016.03.002.
- De Villiers, M.S. et al., 2006: Conservation management at Southern Ocean islands: towards the development of best-practice guidelines. *Polarforschung*, **75** (2/3), 113–131.
- Death, R. et al., 2014: Antarctic ice sheet fertilises the Southern Ocean. *Biogeosciences*, **11** (10), 2635–2643, doi:10.5194/bg-11-2635-2014.
- DeConto, R.M. and D. Pollard, 2016: Contribution of Antarctica to past and future sea-level rise. *Nature*, **531** (7596), 591–597, doi:10.1038/nature17145.
- deHart, P.A.P. and C.M. Picco, 2015: Stable oxygen and hydrogen isotope analyses of bowhead whale baleen as biochemical recorders of migration and arctic environmental change. *Polar Science*, **9** (2), 235–248, doi:https://doi.org/10.1016/j.polar.2015.03.002.
- Depoorter, M.A. et al., 2013: Calving fluxes and basal melt rates of Antarctic ice shelves. *Nature*, **502**, 89, doi:10.1038/nature12567.
- Deppeler, S. et al., 2018: Ocean acidification of a coastal Antarctic marine microbial community reveals a critical threshold for CO₂ tolerance in phytoplankton productivity. *Biogeosciences*, **15** (1), 209–231, doi:10.5194/bg-15-209-2018.
- Derksen, C. and R. Brown, 2012: Spring snow cover extent reductions in the 2008–2012 period exceeding climate model projections. *Geophysical Research Letters*, **39** (19), L19504, doi:10.1029/2012gl053387.
- Déry, S.J., T.A. Stadnyk, M.K. MacDonald and B. Gaulti-Sharma, 2016: Recent trends and variability in river discharge across northern Canada. *Hydrol. Earth Syst. Sci.*, **20** (12), 4801–4818, doi:10.5194/hess-20-4801-2016.
- Desbruyeres, D., E.L. McDonagh, B.A. King and V. Thierry, 2017: Global and Full-Depth Ocean Temperature Trends during the Early Twenty-First Century from Argo and Repeat Hydrography. *Journal of Climate*, **30** (6), 1985–1997, doi:10.1175/JCLI-D-16-0396.1.
- Descamps, S. et al., 2017: Circumpolar dynamics of a marine top-predator track ocean warming rates. *Global Change Biology*, **23** (9), 3770–3780, doi:10.1111/gcb.13715.
- Descamps, S. et al., 2015: Demographic effects of extreme weather events: snow storms, breeding success, and population growth rate in a long-lived Antarctic seabird. *Ecology and Evolution*, **5** (2), 314–325, doi:10.1002/ece3.1357.
- Desch, S.J. et al., 2017: Arctic ice management. *Earth’s Future*, **5** (1), 107–127, doi:10.1002/2016ef000410.
- DeVries, T., M. Holzer and F. Primeau, 2017: Recent increase in oceanic carbon uptake driven by weaker upper-ocean overturning. *Nature*, **542** (7640), 215, doi:10.1038/nature21068.
- Dewey, S. et al., 2018: Arctic Ice-Ocean Coupling and Gyre Equilibration Observed With Remote Sensing. *Geophysical Research Letters*, **45** (3), 1499–1508, doi:10.1002/2017gl076229.
- DFO, 2014: *Integrated Fisheries Management Plan Cambridge Bay Arctic Char Commercial Fishery, Nunavut Settlement Area Effective 2014. Arctic Char (Salvelinus alpinus)*. Fisheries and Oceans Canada, Central and Arctic Region, Resource Management and Aboriginal Affairs, 501 University Crescent, Winnipeg, MB, R3T 2N6, 38p.
- Díaz, S. et al., 2019: *Summary for policymakers of the global assessment report on biodiversity and ecosystem services – unedited advance version* [Manuela Carneiro da Cunha, Georgina Mace and Harold Mooney (eds.)]. The Intergovernmental Science-Policy Platform on Biodiversity and

- Ecosystem Services (IPBES) [Available at: www.ipbes.net/system/tdf/spm_global_unedited_advance.pdf?file=1&type=node&id=35245].
- Dibike, Y., T. Prowse, T. Saloranta and R. Ahmed, 2011: Response of Northern Hemisphere lake-ice cover and lake-water thermal structure patterns to a changing climate. *Hydrological Processes*, **25** (19), 2942–2953, doi:10.1002/hyp.8068.
- DiCosimo, J., S. Cunningham and D. Brannan, 2015: Pacific Halibut Bycatch Management in Gulf of Alaska Groundfish Trawl Fisheries. In: *Fisheries Bycatch: Global Issues and Creative Solutions* [Kruse, G.H., H.C. An, J. DiCosimo, C.A. Eischens, G.S. Gislason, D.N. McBride, C.S. Rose and C.E. Siddo (eds.)]. Alaska Sea Grant, University of Alaska Fairbanks, Fairbanks, Alaska, 19.
- Dilliplace, K.B., 2017: The effect of under ice crude oil spills on sympagic biota of the Arctic: a mesocosm approach. University of Alaska Fairbanks, Fairbanks, Alaska.
- Ding, Q. et al., 2017: Influence of high-latitude atmospheric circulation changes on summertime Arctic sea ice. *Nature Climate Change*, **7**, 289, doi:10.1038/nclimate3241
- Ding, Q. et al., 2018: Fingerprints of internal drivers of Arctic sea ice loss in observations and model simulations. *Nature Geoscience*, **12** (1), 28–33, doi:10.1038/s41561-018-0256-8.
- Ding, Q. et al., 2014: Tropical forcing of the recent rapid Arctic warming in northeastern Canada and Greenland. *Nature*, **509** (7499), 209–12, doi:10.1038/nature13260.
- Ding, Y.N. et al., 2016: Seasonal heat and freshwater cycles in the Arctic Ocean in CMIP5 coupled models. *Journal of Geophysical Research-Oceans*, **121** (4), 2043–2057, doi:10.1002/2015jc011124.
- Divoky, G.J., P.M. Lukacs and M.L. Druckenmiller, 2015: Effects of recent decreases in arctic sea ice on an ice-associated marine bird. *Progress in Oceanography*, **136**, 151–161, doi:10.1016/j.pocean.2015.05.010.
- Dodd, W. et al., 2018: Lived experience of a record wildfire season in the Northwest Territories, Canada. *Can J Public Health*, **109** (3), 327–337, doi:10.17269/s41997-018-0070-5.
- Dolant, C. et al., 2017: Meteorological inventory of rain-on-snow events in the Canadian Arctic Archipelago and satellite detection assessment using passive microwave data. *Physical Geography*, **39** (5), 428–444, doi:10.1080/02723646.2017.1400339.
- Domack, E. et al., 2005: Stability of the Larsen B ice shelf on the Antarctic Peninsula during the Holocene epoch. *Nature*, **436**, 681, doi:10.1038/nature03908.
- Donaldson, S.G. et al., 2010: Environmental contaminants and human health in the Canadian Arctic. *Science of the Total Environment*, **408** (22), 5165–5234, doi:10.1016/j.scitotenv.2010.04.059.
- Donohue, K. et al., 2016: Mean Antarctic Circumpolar Current transport measured in Drake Passage. *Geophysical Research Letters*, **43** (22).
- Dore, G., F.J. Niu and H. Brooks, 2016: Adaptation Methods for Transportation Infrastructure Built on Degrading Permafrost. *Permafrost and Periglacial Processes*, **27** (4), 352–364, doi:10.1002/ppp.1919.
- Dorresteyn, I. et al., 2012: Climate affects food availability to planktivorous least auklets *Aethia pusilla* through physical processes in the southeastern Bering Sea. *Marine Ecology Progress Series*, **454**, 207–220, doi:10.3354/meps09372.
- Douglas, V. et al., 2014: Reconciling traditional knowledge, food security, and climate change: experience from Old Crow, YT, Canada. *Progress in community health partnerships: research, education, and action*, **8** (1), 21–7, doi:10.1353/cpr.2014.0007.
- Dow, C.F. et al., 2018a: Basal channels drive active surface hydrology and transverse ice shelf fracture. *Sci Adv*, **4** (6), eaao7212, doi:10.1126/sciadv.aao7212.
- Dow, C.F. et al., 2018b: Dynamics of Active Subglacial Lakes in Recovery Ice Stream. *Journal of Geophysical Research: Earth Surface*, **123** (4), 837–850, doi:10.1002/2017jf004409.
- Downes, S., P. Spence and A. Hogg, 2018: Understanding variability of the Southern Ocean overturning circulation in CORE-II models. *Ocean Modelling*, **123**, 98–109, doi:10.1016/j.ocemod.2018.01.005.
- Downes, S.M. and A.M. Hogg, 2013: Southern Ocean circulation and eddy compensation in CMIP5 models. *Journal of Climate*, **26** (18), 7198–7220, doi:10.1175/JCLI-D-12-00504.1.
- Drewniak, M. et al., 2018: Geopolitics of Arctic shipping: the state of icebreakers and future needs. *Polar Geography*, **41** (2), 107–125, doi:10.1080/1088937x.2018.1455756.
- Driscoll, D.L. et al., 2016: Assessing the health effects of climate change in Alaska with community-based surveillance. *Climatic Change*, **137** (3), 455–466, doi:10.1007/s10584-016-1687-0.
- Drucker, R., S. Martin and R. Kwok, 2011: Sea ice production and export from coastal polynyas in the Weddell and Ross Seas. *Geophysical Research Letters*, **38**, L17502, doi:10.1029/2011gl048668.
- Du, J. et al., 2017: Satellite microwave assessment of Northern Hemisphere lake ice phenology from 2002 to 2015. *The Cryosphere*, **11** (1), 47–63, doi:10.5194/tc-11-47-2017.
- Duan, L., X. Man, B. Kurylyk and T. Cai, 2017: Increasing Winter Baseflow in Response to Permafrost Thaw and Precipitation Regime Shifts in Northeastern China. *Water*, **9** (1), 25, doi:10.3390/w9010025.
- Dudley, J.P., E.P. Hoberg, E.J. Jenkins and A.J. Parkinson, 2015: Climate Change in the North American Arctic: A One Health Perspective. *EcoHealth*, **12** (4), 713–725, doi:10.1007/s10393-015-1036-1.
- Duffy, G.A. et al., 2017: Barriers to globally invasive species are weakening across the Antarctic. *Diversity and Distributions*, **23** (9), 982–996, doi:10.1111/ddi.12593.
- Dugger, K.M. et al., 2014: AdĀlie penguins coping with environmental change: results from a natural experiment at the edge of their breeding range. *Frontiers in Ecology and Evolution*, **2**, 1–12, doi:10.3389/fevo.2014.00068.
- Dunn, M.J. et al., 2016: Population Size and Decadal Trends of Three Penguin Species Nesting at Signy Island, South Orkney Islands. *Plos One*, **11** (10), e0164025, doi:10.1371/journal.pone.0164025.
- Dunse, T. et al., 2015: Glacier-surge mechanisms promoted by a hydro-thermodynamic feedback to summer melt. *The Cryosphere*, **9** (1), 197–215, doi:10.5194/tc-9-197-2015.
- Duprat, L.P.A.M., G.R. Bigg and D.J. Wilton, 2016: Enhanced Southern Ocean marine productivity due to fertilization by giant icebergs. *Nature Geoscience*, **9**, 219, doi:10.1038/ngeo2633.
- Durkalec, A., C. Furgal, M.W. Skinner and T. Sheldon, 2014: Investigating environmental determinants of injury and trauma in the Canadian north. *Int J Environ Res Public Health*, **11** (2), 1536–1548, doi:10.3390/ijerph110201536.
- Durkalec, A., C. Furgal, M.W. Skinner and T. Sheldon, 2015: Climate change influences on environment as a determinant of Indigenous health: Relationships to place, sea ice, and health in an Inuit community. *Social Science and Medicine*, **136–137**, 17–26, doi:10.1016/j.socscimed.2015.04.026.
- Durner, G.M. et al., 2017: Increased Arctic sea ice drift alters adult female polar bear movements and energetics. *Global Change Biology*, **23** (9), 3460–3473, doi:10.1111/gcb.13746.
- Dutrieux, P. et al., 2014: Strong Sensitivity of Pine Island Ice-Shelf Melting to Climatic Variability. *Science*, **343** (6167), 174–178, doi:10.1126/science.1244341.
- Duyck, S., 2011: Participation of Non-State Actors in Arctic Environmental Governance *Nordia Geographical Publications*, **40** (4), 99–110.
- Easterling, D.R., K.E. Kunkel, M.F. Wehner and L. Sun, 2016: Detection and attribution of climate extremes in the observed record. *Weather and Climate Extremes*, **11**, 17–27, doi:10.1016/j.wace.2016.01.001.
- Edinburgh, T. and J.J. Day, 2016: Estimating the extent of Antarctic summer sea ice during the Heroic Age of Antarctic Exploration. *The Cryosphere*, **10** (6), 2721–2730, doi:10.5194/tc-10-2721-2016.

- Edwards, T.L. et al., 2019: Revisiting Antarctic ice loss due to marine ice-cliff instability. *Nature*, **566** (7742), 58–64, doi:10.1038/s41586-019-0901-4.
- Eguíluz, V.M., J. Fernández-Gracia, X. Irigoien and C.M. Duarte, 2016: A quantitative assessment of Arctic shipping in 2010–2014. *Scientific Reports*, **6**, 30682, doi:10.1038/srep30682.
- Eicken, H. et al., 2014: A framework and database for community sea ice observations in a changing Arctic: an Alaskan prototype for multiple users. *Polar Geography*, **37** (1), 5–27, doi:10.1080/1088937x.2013.873090.
- Eide, A., 2017: Climate change, fisheries management and fishing aptitude affecting spatial and temporal distributions of the Barents Sea cod fishery. *AMBIO*, **46** (Suppl 3), 387–399, doi:10.1007/s13280-017-0955-1.
- Eisner, W.R., K.M. Hinkel, C.J. Cuomo and R.A. Beck, 2013: Environmental, cultural, and social change in Arctic Alaska as observed by Iñupiat elders over their lifetimes: a GIS synthesis. *Polar Geography*, **36** (3), 221–231, doi:10.1080/1088937x.2012.724463.
- Elvidge, A.D. et al., 2015: Foehn jets over the Larsen C Ice Shelf, Antarctica. *Quarterly Journal of the Royal Meteorological Society*, **141** (688), 698–713, doi:10.1002/qj.2382.
- Enderlin, E.M. et al., 2014: An improved mass budget for the Greenland ice sheet. *Geophysical Research Letters*, **41** (3), doi:10.1002/2013GL059010.
- Enderlin, E.M., I.M. Howat and A. Vieli, 2013: High sensitivity of tidewater outlet glacier dynamics to shape. *Cryosphere*, **7** (3), 1007–1015, doi:10.5194/tc-7-1007-2013.
- England, M., L. Polvani and L. Sun, 2018: Contrasting the Antarctic and Arctic Atmospheric Responses to Projected Sea Ice Loss in the Late Twenty-First Century. *Journal of Climate*, **31** (16), 6353–6370, doi:10.1175/jcli-d-17-0666.1.
- England, M.R. et al., 2016: Robust response of the Amundsen Sea Low to stratospheric ozone depletion. *Geophysical Research Letters*, **43** (15), 8207–8213, doi:10.1002/2016gl070055.
- Ericson, Y. et al., 2014: Increasing carbon inventory of the intermediate layers of the Arctic Ocean. *Journal of Geophysical Research-Oceans*, **119** (4), 2312–2326, doi:10.1002/2013jc009514.
- Ernst, K.M. and M. van Riemsdijk, 2013: Climate change scenario planning in Alaska's National Parks: Stakeholder involvement in the decision-making process. *Applied Geography*, **45**, 22–28, doi:10.1016/j.apgeog.2013.08.004.
- Ershova, E.A., R.R. Hopcroft and K.N. Kosobokova, 2015: Inter-annual variability of summer mesozooplankton communities of the western Chukchi Sea: 2004–2012. *Polar Biology*, **38** (9), 1461–1481, doi:10.1007/s00300-015-1709-9.
- Escajeda, E. et al., 2018: Identifying shifts in maternity den phenology and habitat characteristics of polar bears (*Ursus maritimus*) in Baffin Bay and Kane Basin. *Polar Biology*, **41** (1), 87–100, doi:10.1007/s00300-017-2172-6.
- Essery, R., 2013: Large-scale simulations of snow albedo masking by forests. *Geophysical Research Letters*, **40** (20), 5521–5525, doi:10.1002/grl.51008.
- Estilow, T.W., A.H. Young and D.A. Robinson, 2015: A long-term Northern Hemisphere snow cover extent data record for climate studies and monitoring. *Earth System Science Data*, **7**, 137–142, doi:10.5194/essd-7-137-2015.
- Euskirchen, E.S. et al., 2016: Consequences of changes in vegetation and snow cover for climate feedbacks in Alaska and northwest Canada. *Environmental Research Letters*, **11** (10), 105003, doi:10.1088/1748-9326/11/10/105003.
- Evtushevsky, O.M., A.V. Grytsai and G.P. Milinevsky, 2018: Decadal changes in the central tropical Pacific teleconnection to the Southern Hemisphere extratropics. *Climate Dynamics*, **52** (7–8), 4027–4055, doi:10.1007/s00382-018-4354-5.
- Falkenberg, J. et al., 2018: *AMAP Assessment 2018: Arctic Ocean Acidification*. Biological responses to ocean acidification, Arctic Monitoring and Assessment Programme (AMAP), Tromsø, Norway, 187 [Available at: www.amap.no/documents/doc/AMAP-Assessment-2018-Arctic-Ocean-Acidification/1659].
- Fall, J., 2016: Regional Patterns of Fish and Wildlife Harvests in Contemporary Alaska. *Arctic*, **69** (1), 47–54, doi:10.14430/arctic4547.
- Fall, J.A. et al., 2013: Continuity and change in subsistence harvests in five Bering Sea communities: Akutan, Emmonak, Savoonga, St. Paul, and Togiak. *Deep-Sea Research Part II*, **94**, 274–291, doi:10.1016/j.dsr2.2013.03.010.
- Fauchald, P., V.H. Hausner, J.I. Schmidt and D.A. Clark, 2017a: Transitions of social-ecological subsistence systems in the Arctic. *International Journal of the Commons*, **11** (1), 275–329, doi:10.18352/ijc.698.
- Fauchald, P. et al., 2017b: Arctic greening from warming promotes declines in caribou populations. *Sci Adv*, **3** (4), e1601365, doi:10.1126/sciadv.1601365.
- Favier, L. et al., 2014: Retreat of Pine Island Glacier controlled by marine ice-sheet instability. *Nature Climate Change*, **4** (2), 117–121, doi:10.1038/Nclimate2094.
- Favier, V. et al., 2016: Atmospheric drying as the main driver of dramatic glacier wastage in the southern Indian Ocean. *Scientific Reports*, **6**, 32396, doi:10.1038/srep32396.
- Fay, A.R. et al., 2018: Utilizing the Drake Passage Time-series to understand variability and change in subpolar Southern Ocean pCO₂. *Biogeosciences*, **15** (12), 3841–3855, doi:10.5194/bg-15-3841-2018.
- Feng, Z. et al., 2018: Biogeographic responses of the copepod *Calanus glacialis* to a changing Arctic marine environment. *Glob Chang Biol*, **24** (1), e159–e170, doi:10.1111/gcb.13890.
- Fernández-Méndez, M. et al., 2015: Photosynthetic production in the central Arctic Ocean during the record sea-ice minimum in 2012. *Biogeosciences*, **12** (11), 3525–3549, doi:10.5194/bg-12-3525-2015.
- Fernández-Méndez, M. et al., 2018: Algal Hot Spots in a Changing Arctic Ocean: Sea-Ice Ridges and the Snow-Ice Interface. *Frontiers in Marine Science*, **5** (75), doi:10.3389/fmars.2018.00075.
- Fettweis, X. et al., 2017: Reconstructions of the 1900–2015 Greenland ice sheet surface mass balance using the regional climate MAR model. *The Cryosphere*, **11** (2), 1015–1033, doi:10.5194/tc-11-1015-2017.
- Fettweis, X. et al., 2013: Brief communication Important role of the mid-tropospheric atmospheric circulation in the recent surface melt increase over the Greenland ice sheet. *Cryosphere*, **7** (1), 241–248, doi:10.5194/tc-7-241-2013.
- Fieber, K.D. et al., 2018: Rigorous 3D change determination in Antarctic Peninsula glaciers from stereo WorldView-2 and archival aerial imagery. *Remote Sensing of Environment*, **205**, 18–31, doi:10.1016/j.rse.2017.10.042.
- Field, L. et al., 2018: Increasing Arctic Sea Ice Albedo Using Localized Reversible Geoengineering. *Earths Future*, **6** (6), 882–901, doi:10.1029/2018ef000820.
- Fielding, S. et al., 2014: Interannual variability in Antarctic krill (*Euphausia superba*) density at South Georgia, Southern Ocean: 1997–2013. *ICES Journal of Marine Science*, **71** (9), 2578–2588, doi:10.1093/icesjms/fts104.
- Fillinger, L., D. Janussen, T. Lundälv and C. Richter, 2013: Rapid Glass Sponge Expansion after Climate-Induced Antarctic Ice Shelf Collapse. *Current Biology*, **23** (14), 1330–1334, doi:10.1016/j.cub.2013.05.051.
- Fisher, D. et al., 2012: Recent melt rates of Canadian arctic ice caps are the highest in four millennia. *Global and Planetary Change*, **84–85**, 3–7, doi:10.1016/j.gloplacha.2011.06.005.
- Flament, T., E. Berthier and F. Rémy, 2014: Cascading water underneath Wilkes Land, East Antarctic ice sheet, observed using altimetry and digital elevation models. *The Cryosphere*, **8** (2), 673–687, doi:10.5194/tc-8-673-2014.
- Flanner, M.G. et al., 2011: Radiative forcing and albedo feedback from the Northern Hemisphere cryosphere between 1979 and 2008. *Nature Geoscience*, **4** (3), 151–155, doi:10.1038/ngeo1062.
- Flanner, M.G., C.S. Zender, J.T. Randerson and P.J. Rasch, 2007: Present-day climate forcing and response from black carbon in snow. *Journal of Geophysical Research*, **112** (D11), D11202, doi:10.1029/2006jd008003.
- Flannigan, M., B. Stocks, M. Turetsky and M. Wotton, 2009: Impacts of climate change on fire activity and fire management in the circumboreal forest. *Global Change Biology*, **15** (3), 549–560, doi:10.1111/j.1365-2486.2008.01660.x.

- Fleming, A.H. and N.D. Pyenson, 2017: How to Produce Translational Research to Guide Arctic Policy. *Bioscience*, **67** (6), 490–493, doi:10.1093/biosci/bix002.
- Fletcher, C.G., C.W. Thackeray and T.M. Burgers, 2015: Evaluating biases in simulated snow albedo feedback in two generations of climate models. *Journal of Geophysical Research: Atmospheres*, **120** (1), 12–26, doi:10.1002/2014jd022546.
- Fluhr, J. et al., 2017: Weakening of the subpolar gyre as a key driver of North Atlantic seabird demography: a case study with Brunnich's guillemots in Svalbard. *Marine Ecology Progress Series*, **563**, 1–11, doi:10.3354/meps11982.
- Flynn, M., J.D. Ford, T. Pearce and S.L. Harper, 2018: Participatory scenario planning and climate change impacts, adaptation and vulnerability research in the Arctic. *Environmental Science & Policy*, **79**, 45–53, doi:10.1016/j.envsci.2017.10.012.
- Fogt, R.L. and E.A. Zbacnik, 2014: Sensitivity of the Amundsen Sea Low to Stratospheric Ozone Depletion. *Journal of Climate*, **27** (24), 9383–9400, doi:10.1175/JCLI-D-13-00657.1.
- Fogwill, C.J. et al., 2016: Brief communication: Impacts of a developing polynya off Commonwealth Bay, East Antarctica, triggered by grounding of iceberg B09B. *The Cryosphere*, **10** (6), 2603–2609, doi:10.5194/tc-10-2603-2016.
- Forbes, B.C., 2013: Cultural Resilience of Social-ecological Systems in the Nenets and Yamal-Nenets Autonomous Okrugs, Russia: A Focus on Reindeer Nomads of the Tundra. *Ecology and Society*, **18** (4), doi:10.5751/ES-05791-180436.
- Forbes, B.C. et al., 2015: *Arctic Human Development Report II* [Larsen, J.N. and G. Fondal (eds.)]. Chapter 7 Resource Governanc, Denmark, 253–289.
- Forbes, B.C. et al., 2016: Sea ice, rain-on-snow and tundra reindeer nomadism in Arctic Russia. *Biology Letters*, **12** (11), doi:10.1098/rsbl.2016.0466.
- Forbis Jr, R. and K. Hayhoe, 2018: Does Arctic governance hold the key to achieving climate policy targets? *Environmental Research Letters*, **13** (2), 020201, doi:10.1088/1748-9326/aaa359.
- Forcada, J. and J.I. Hoffman, 2014: Climate change selects for heterozygosity in a declining fur seal population. *Nature*, **511** (7510), 462–5, doi:10.1038/nature13542.
- Ford, J.D., 2012: Indigenous health and climate change. *American Journal of Public Health*, **102** (7), 1260–1266, doi:10.2105/AJPH.2012.300752.
- Ford, J.D., L. Berrang-Ford, M. King and C. Furgal, 2010: Vulnerability of Aboriginal health systems in Canada to climate change. *Global Environmental Change*, **20** (4), 668–680, doi:10.1016/j.gloenvcha.2010.05.003.
- Ford, J.D. et al., 2012: Mapping Human Dimensions of Climate Change Research in the Canadian Arctic. *AMBIO*, **41** (8), 808–822, doi:10.1007/s13280-012-0336-8.
- Ford, J.D. et al., 2016: Including indigenous knowledge and experience in IPCC assessment reports. *Nature Climate Change*, **6**, 349, doi:10.1038/nclimate2954
- Ford, J.D. et al., 2019: Changing access to ice, land and water in Arctic communities. *Nature Climate Change*, **9** (4), 335–339, doi:10.1038/s41558-019-0435-7.
- Ford, J.D. and D. King, 2013: A framework for examining adaptation readiness. *Mitigation and Adaptation Strategies for Global Change*, **20** (4), 505–526, doi:10.1007/s11027-013-9505-8.
- Ford, J.D., G. McDowell and J. Jones, 2014a: The state of climate change adaptation in the Arctic. *Environmental Research Letters*, **9** (10), 104005, doi:10.1088/1748-9326/9/10/104005.
- Ford, J.D., G. McDowell and T. Pearce, 2015: The adaptation challenge in the Arctic. *Nature Climate Change*, **5**, 1046, doi:10.1038/nclimate2723.
- Ford, J.D. and T. Pearce, 2012: Climate change vulnerability and adaptation research focusing on the Inuit subsistence sector in Canada: Directions for future research. *The Canadian Geographer / Le Géographe canadien*, **56** (2), 275–287, doi:10.1111/j.1541-0064.2012.00418.x.
- Ford, J.D. et al., 2014b: Adapting to the Effects of Climate Change on Inuit Health. *American Journal of Public Health*, **104** (S3), e9–e17, doi:10.2105/AJPH.2013.301724.
- Ford, J.D. et al., 2013: The dynamic multiscale nature of climate change vulnerability: An Inuit harvesting example. *Annals of the Association of American Geographers*, **103** (5), 1193–1211, doi:10.1080/00045608.2013.776880.
- Forde, T. et al., 2016a: Genomic analysis of the multi-host pathogen *Erysipelothrix rhusiopathiae* reveals extensive recombination as well as the existence of three generalist clades with wide geographic distribution. *BMC Genomics*, **17**, 461, doi:10.1186/s12864-016-2643-0.
- Forde, T.L. et al., 2016b: Bacterial Genomics Reveal the Complex Epidemiology of an Emerging Pathogen in Arctic and Boreal Ungulates. *Frontiers in Microbiology*, **7**, 1759, doi:10.3389/fmicb.2016.01759.
- Forster, R.R. et al., 2013: Extensive liquid meltwater storage in firn within the Greenland ice sheet. *Nature Geoscience*, **7** (2), 95–98, doi:10.1038/ngeo2043.
- Forzieri, G., R. Alkama, D.G. Miralles and A. Cescatti, 2017: Satellites reveal contrasting responses of regional climate to the widespread greening of Earth. *Science*, **356** (6343), 1180–1184, doi:10.1126/science.aal1727.
- Fosheim, M. et al., 2015: Recent warming leads to a rapid borealization of fish communities in the Arctic. *Nature Climate Change*, **5**, 673, doi:10.1038/nclimate2647.
- Frainer, A. et al., 2017: Climate-driven changes in functional biogeography of Arctic marine fish communities. *Proc Natl Acad Sci U S A*, **114** (46), 12202–12207, doi:10.1073/pnas.1706080114.
- Francis, D., C. Eayrs, J. Cuesta and D. Holland, 2019: Polar Cyclones at the Origin of the Reoccurrence of the Maud Rise Polynya in Austral Winter 2017. *Journal of Geophysical Research-Atmospheres*, **124** (10), 5251–5267, doi:10.1029/2019jd030618.
- Francis, J.A., 2017: Why Are Arctic Linkages to Extreme Weather Still up in the Air? *Bulletin of the American Meteorological Society*, **98** (12), 2551–2557, doi:10.1175/bams-d-17-0006.1.
- Francis, J.A. and S.J. Vavrus, 2015: Evidence for a wavier jet stream in response to rapid Arctic warming. *Environmental Research Letters*, **10** (1), 014005, doi:10.1088/1748-9326/10/1/014005.
- Fransson, A. et al., 2017: Effects of sea-ice and biogeochemical processes and storms on under-ice water fCO₂ during the winter-spring transition in the high Arctic Ocean: Implications for sea-air CO₂ fluxes. *Journal of Geophysical Research-Oceans*, **122** (7), 5566–5587, doi:10.1002/2016jc012478.
- Fraser, A.D. et al., 2011: East Antarctic Landfast Sea Ice Distribution and Variability, 2000–08. *Journal of Climate*, **25** (4), 1137–1156, doi:10.1175/jcli-d-10-05032.1.
- Fraser, C.I., G.M. Kay, M. d. Plessis and P.G. Ryan, 2017: Breaking down the barrier: dispersal across the Antarctic Polar Front. *Ecography*, **40** (1), 235–237, doi:10.1111/ecog.02449.
- Fraser, C.I. et al., 2018: Antarctica's ecological isolation will be broken by storm-driven dispersal and warming. *Nature Climate Change*, **8**, 704–708, doi:10.1038/s41558-018-0209-7.
- Frederiksen, M., 2017: Synthesis: Status and trends of Arctic marine biodiversity and monitoring. In: CAFF State of the Arctic Marine Biodiversity Report. Conservation of Arctic Flora and Fauna International Secretariat Akureyri, Iceland, 175–195.
- Freeman, N.M. and N.S. Lovenduski, 2015: Decreased calcification in the Southern Ocean over the satellite record. *Nature Geoscience*, **42** (6), 1834–1840, doi:papers2://publication/uuid/E879F895-C356-42B6-B1DE-7E33D4676735.
- Freer, J.J. et al., 2018: Predicting ecological responses in a changing ocean: the effects of future climate uncertainty. *Mar Biol*, **165** (1), 7, doi:10.1007/s00227-017-3239-1.
- French, N.H. et al., 2015: Fire in Arctic tundra of Alaska: past fire activity, future fire potential, and significance for land management and ecology.

- International Journal of Wildland Fire*, **24** (8), 1045–1061, doi:10.1071/WF14167.
- Frenot, Y. et al., 2005: Biological invasions in the Antarctic: extent, impacts and implications. *Biological Reviews*, **80** (1), 45–72, doi:10.1017/s1464793104006542.
- Frey, K.E., J.W. McClelland, R.M. Holmes and L.C. Smith, 2007: Impacts of climate warming and permafrost thaw on the riverine transport of nitrogen and phosphorus to the Kara Sea. *Journal of Geophysical Research: Biogeosciences*, **112** (G4), G04S5, doi:10.1029/2006jg000369.
- Frezzotti, M. et al., 2013: A synthesis of the Antarctic surface mass balance during the last 800 yr. *Cryosphere*, **7** (1), 303–319, doi:10.5194/tc-7-303-2013.
- Fricker, H.A., T. Scambos, R. Bindshadler and L. Padman, 2007: An active subglacial water system in West Antarctica mapped from space. *Science*, **315** (5818), 1544–1548, doi:10.1126/science.1136897
- Fricker, H.A., M.R. Siegfried, S.P. Carter and T.A. Scambos, 2016: A decade of progress in observing and modelling Antarctic subglacial water systems. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **374** (2059), 20140294, doi:10.1098/rsta.2014.0294.
- Friedl, P. et al., 2018: Recent dynamic changes on Fleming Glacier after the disintegration of Wordie Ice Shelf, Antarctic Peninsula. *The Cryosphere*, **12** (4), 1347–1365, doi:10.5194/tc-12-1347-2018.
- Frölicher, T.L. et al., 2015: Dominance of the Southern Ocean in anthropogenic carbon and heat uptake in CMIP5 models. *Journal of Climate*, **28** (2), 862–886, doi:10.1175/JCLI-D-14-00117.1.
- Frost, G.V. and H.E. Epstein, 2014: Tall shrub and tree expansion in Siberian tundra ecotones since the 1960s. *Global Change Biology*, **20** (4), 1264–1277, doi:10.1111/gcb.12406.
- Fujiwara, A. et al., 2016: Influence of timing of sea ice retreat on phytoplankton size during marginal ice zone bloom period on the Chukchi and Bering shelves. *Biogeosciences*, **13** (1115–131), doi:10.5194/bg-13-115-2016.
- Fünfgeld, H., 2015: Facilitating local climate change adaptation through transnational municipal networks. *Current Opinion in Environmental Sustainability*, **12**, 67–73, doi:10.1016/j.cosust.2014.10.011.
- Fürst, J.J. et al., 2016: The safety band of Antarctic ice shelves. *Nature Climate Change*, **6**, 479, doi:10.1038/nclimate2912.
- Fyfe, J.C. et al., 2013: One hundred years of Arctic surface temperature variation due to anthropogenic influence. *Scientific Reports*, **3**, 2645, doi:10.1038/srep02645
- Fyke, J. et al., 2018: An Overview of Interactions and Feedbacks Between Ice Sheets and the Earth System. *Reviews of Geophysics*, **56** (2), 361–408, doi:10.1029/2018rg000600.
- Gagné, M.-È. et al., 2017: Aerosol-driven increase in Arctic sea ice over the middle of the twentieth century. *Geophysical Research Letters*, **44** (14), 7338–7346, doi:10.1002/2016gl071941.
- Gagné, M.È., N.P. Gillett and J.C. Fyfe, 2015: Observed and simulated changes in Antarctic sea ice extent over the past 50 years. *Geophysical Research Letters*, **42** (1), 90–95, doi:10.1002/2014gl062231.
- Gagnon-Lebrun, F. and S. Agrawala, 2007: Implementing adaptation in developed countries: an analysis of progress and trends. *Climate Policy*, **7** (5), 37–41, doi:10.1080/14693062.2007.9685664.
- Galicía, M.P. et al., 2016: Dietary habits of polar bears in Foxe Basin, Canada: possible evidence of a trophic regime shift mediated by a new top predator. *Ecology and Evolution*, **6** (16), 6005–6018, doi:10.1002/ece3.2173.
- Gall, A.E., T.C. Morgan, R.H. Day and K.J. Kuletz, 2017: Ecological shift from piscivorous to planktivorous seabirds in the Chukchi Sea, 1975–2012. *Polar Biology*, **40** (1), 61–78, doi:10.1007/s00300-016-1924-z.
- Gallaher, D.W., G.G. Campbell and W.N. Meier, 2014: Anomalous Variability in Antarctic Sea Ice Extents During the 1960s With the Use of Nimbus Data. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, **7**, 881–887, doi:10.1109/jstars.2013.2264391.
- Galley, R. et al., 2012: Landfast sea ice conditions in the Canadian Arctic, 1983–2009. *Arctic*, **65** (2), 133–144, doi:10.14430/arctic4195.
- Ganz, P. et al., 2018: *Deployment performance review of the 2017 North Pacific Observer Program*. U.S. Dep. Commer., NOAA Tech. Memo., NMFS-AFSC-379, 68p [Available at: www.afsc.noaa.gov/publications/AFSC-TM/NOAA-TM-AFSC-379.pdf].
- Gao, L., S.R. Rintoul and W. Yu, 2018: Recent wind-driven change in Subantarctic Mode Water and its impact on ocean heat storage. *Nature Climate Change*, **8** (1), 58, doi:10.1038/s41558-017-0022-8.
- Gao, X. et al., 2013: Permafrost degradation and methane: low risk of biogeochemical climate-warming feedback. *Environmental Research Letters*, **8** (3), 035014, doi:10.1088/1748-9326/8/3/035014.
- Gardner, A.S. et al., 2013: A reconciled estimate of glacier contributions to sea level rise: 2003 to 2009. *Science*, **340** (6134), 852–857, doi:10.1126/science.1234532.
- Gardner, A.S. et al., 2018: Increased West Antarctic and unchanged East Antarctic ice discharge over the last 7 years. *The Cryosphere*, **12** (2), 521–547, doi:10.5194/tc-12-521-2018.
- Garrett, R.A., T.C. Sharkey, M. Grabowski and W.A. Wallace, 2017: Dynamic resource allocation to support oil spill response planning for energy exploration in the Arctic. *European Journal of Operational Research*, **257** (1), 272–286, doi:10.1016/j.ejor.2016.07.023.
- Gascon, G. et al., 2013a: Changes in accumulation-area firn stratigraphy and meltwater flow during a period of climate warming: Devon Ice Cap, Nunavut, Canada. *Journal of Geophysical Research: Earth Surface*, **118** (4), 2380–2391, doi:10.1002/2013JF002838.
- Gascon, G., M. Sharp and A. Bush, 2013b: Changes in melt season characteristics on Devon Ice Cap, Canada, and their association with the Arctic atmospheric circulation. *Annals of Glaciology*, **54** (63), 101–110, doi:10.3189/2013AoG63A601.
- Gaston, A.J. and K.H. Elliott, 2014: Seabird diet changes in northern Hudson Bay, 1981–2013, reflect the availability of schooling prey. *Marine Ecology Progress Series*, **513**, 211–223, doi:10.3354/meps10945.
- Gaston, A.J., P.A. Smith and J.F. Provencher, 2012: Discontinuous change in ice cover in Hudson Bay in the 1990s and some consequences for marine birds and their prey. *ICES Journal of Marine Science*, **69** (7), 1218–1225, doi:10.1093/icesjms/fss040.
- Gauthier, S. et al., 2015: Boreal forest health and global change. *Science*, **349** (6250), 819–22, doi:10.1126/science.aaa9092.
- Ge, S., D. Yang and D.L. Kane, 2013: Yukon River Basin long-term (1977–2006) hydrologic and climatic analysis. *Hydrological Processes*, **27**, 2475–2484, doi:10.1002/hyp.9282.
- Gearheard, S. et al., 2006: “It’s Not that Simple”: A Collaborative Comparison of Sea Ice Environments, Their Uses, Observed Changes, and Adaptations in Barrow, Alaska, USA, and Clyde River, Nunavut, Canada. *AMBIO: A Journal of the Human Environment*, **35** (4), 203–211, doi:10.1579/0044-7447(2006)35[203:intsac]2.0.co;2.
- Gearheard, S.F. et al., 2013: *The meaning of ice: People and sea ice in three Arctic communities*. International Polar Institute, Montreal.
- Geilfus, N.X. et al., 2016: Estimates of ikaite export from sea ice to the underlying seawater in a sea ice-seawater mesocosm. *Cryosphere*, **10** (5), 2173–2189, doi:10.5194/tc-10-2173-2016.
- Gelfan, A. et al., 2016: Climate change impact on the water regime of two great Arctic rivers: modeling and uncertainty issues. *Climatic Change*, **141** (3), 499–515, doi:10.1007/s10584-016-1710-5.
- Gent, P.R., 2016: Effects of Southern Hemisphere wind changes on the meridional overturning circulation in ocean models. *Annual Review of Marine Science*, **8**, 79–94, doi:10.1146/annurev-marine-122414-033929.
- Gerlach, C., P.A. Loring, G. Kofinas and H. Penn, 2017: *Resilience to rapid change in Bering, Chukchi, and Beaufort communities*. Chapter 6 of *Adaptation Actions for a Changing Arctic: Perspectives from the Bering-Chukchi-Beaufort Region, Arctic Monitoring and Assessment Programme (AMAP)*, Oslo, Norway, 155–176 [Available at: www.amap.no/documents/doc/]

- Adaptation-Actions-for-a-Changing-Arctic-Perspectives-from-the-Bering-Chukchi-Beaufort-Region/1615].
- Gerland, S. et al., 2008: Decrease of sea ice thickness at Hopen, Barents Sea, during 1966–2007. *Geophysical Research Letters*, **35** (6), doi:10.1029/2007gl032716.
- Gerringa, L.J.A. et al., 2012: Iron from melting glaciers fuels the phytoplankton blooms in Amundsen Sea (Southern Ocean): Iron biogeochemistry. *Deep Sea Research Part II: Topical Studies in Oceanography*, **71–76**, 16–31, doi:10.1016/j.dsr2.2012.03.007.
- Gerringa, L.J.A. et al., 2015: Sources of iron in the Ross Sea Polynya in early summer. *Marine Chemistry*, **177**, 447–459, doi:10.1016/j.marchem.2015.06.002.
- Gibson, C.M. et al., 2018: Wildfire as a major driver of recent permafrost thaw in boreal peatlands. *Nat Commun*, **9** (1), 3041, doi:10.1038/s41467-018-05457-1.
- Giglio, L., J.T. Randerson and G.R. van der Werf, 2013: Analysis of daily, monthly, and annual burned area using the fourth-generation global fire emissions database (GFED4). *Journal of Geophysical Research: Biogeosciences*, **118** (1), 317–328, doi:10.1002/jgrg.20042.
- Gilbert, A. et al., 2017: The projected demise of Barnes Ice Cap: Evidence of an unusually warm 21st century Arctic. *Geophysical Research Letters*, **44** (6), 2810–2816, doi:10.1002/2016gl072394.
- Gilg, O. et al., 2012: Climate change and the ecology and evolution of Arctic vertebrates. *Annals of the New York Academy of Sciences*, **1249** (1), 166–190, doi:10.1111/j.1749-6632.2011.06412.x.
- Gille, S.T., 2014: Meridional displacement of the Antarctic Circumpolar Current. *Phil. Trans. R. Soc. A*, **372** (2019), 20130273, doi:10.1098/rsta.2013.0273.
- Gillett, N.P., 2004: Detecting the effect of climate change on Canadian forest fires. *Geophysical Research Letters*, **31** (18), L18211, doi:10.1029/2004gl020876.
- Gladish, C.V., D.M. Holland and C.M. Lee, 2015: Oceanic Boundary Conditions for Jakobshavn Glacier. Part I: Variability and Renewal of Ilulissat Icefjord Waters, 2001–14*. *Journal of Physical Oceanography*, **45** (2003), 33–63, doi:10.1175/JPO-D-14-0045.1.
- Goldhar, C., T. Bell and J. Wolf, 2013: Rethinking Existing Approaches to Water Security in Remote Communities: An Analysis of Two Drinking Water Systems in Nunatsiavut, Labrador, Canada. *Water Alternatives*, **6** (3), 462–486.
- Goldhar, C., T. Bell and J. Wolf, 2014: Vulnerability to Freshwater Changes in the Inuit Settlement Region of Nunatsiavut, Labrador: A Case Study from Rigolet. *Arctic*, **67** (1), 71–83, doi:10.14430/arctic4365.
- Golledge, N.R. et al., 2014: Antarctic contribution to meltwater pulse 1A from reduced Southern Ocean overturning. *Nature Communications*, **5** (5107), 1–10, doi:10.1038/ncomms6107.
- Golovnev, A., 2017: Challenges to Arctic Nomadism: Yamal Nenets Facing Climate Change Era Calamities. *Arctic Anthropology*, **54**, 40–51.
- Gomez, N., D. Pollard and D. Holland, 2015: Sea-level feedback lowers projections of future Antarctic Ice-Sheet mass loss. *Nature Communications*, **6**, 8798, doi:10.1038/ncomms9798.
- Goodwin, B.P. et al., 2016: Accumulation variability in the Antarctic Peninsula: The role of large-scale atmospheric oscillations and their interactions. *Journal of Climate*, **29** (7), 2579–2596, doi:10.1175/JCLI-D-15-0354.1.
- Goosse, H. et al., 2018: Quantifying climate feedbacks in polar regions. *Nature Communications*, **9** (1), 1919, doi:10.1038/s41467-018-04173-0.
- Goosse, H. and V. Zunz, 2014: Decadal trends in the Antarctic sea ice extent ultimately controlled by ice-ocean feedback. *The Cryosphere*, **8**, 453–470, doi:10.5194/tc-8-435-2014.
- Graeter, K.A. et al., 2018: Ice Core Records of West Greenland Melt and Climate Forcing. *Geophysical Research Letters*, **45** (7), 3164–3172, doi:10.1002/2017gl076641.
- Graham, R.M. et al., 2017: Increasing frequency and duration of Arctic winter warming events. *Geophysical Research Letters*, **44** (13), 6974–6983, doi:10.1002/2017gl073395.
- Grange, L.J. and C.R. Smith, 2013: Megafaunal communities in rapidly warming fjords along the West Antarctic Peninsula: hotspots of abundance and beta diversity. *Plos One*, **8** (12), e77917, doi:10.1371/journal.pone.0077917.
- Granskog, M.A., I. Fer, A. Rinke and H. Steen, 2018: Atmosphere-Ice-Ocean-Ecosystem Processes in a Thinner Arctic Sea Ice Regime: The Norwegian Young Sea ICE (N-ICE2015) Expedition. *Journal of Geophysical Research: Oceans*, **123** (3), 1586–1594, doi:10.1002/2017jc013328.
- Gray, A.R. et al., 2018: Autonomous Biogeochemical Floats Detect Significant Carbon Dioxide Outgassing in the High-Latitude Southern Ocean. *Geophysical Research Letters*, **45** (17), 9049–9057, doi:10.1029/2018gl078013.
- Greaves, W., 2016: Arctic (in)security and Indigenous peoples: Comparing Inuit in Canada and Sámi in Norway. *Security Dialogue*, **47** (6), 461–480, doi:10.1177/0967010616665957.
- Grebmeier, J.M., 2012: Shifting patterns of life in the Pacific Arctic and sub-Arctic Seas. *Annual Reviews in Marine Science*, **2012** (4), 63–78, doi:10.1146/annurev-marine-120710-100926.
- Grebmeier, J.M. et al., 2015: Ecosystem characteristics and processes facilitating persistent macrobenthic biomass hotspots and associated benthivory in the Pacific Arctic. *Progress in Oceanography*, **136** (Supplement C), 92–114, doi:10.1016/j.pocean.2015.05.006.
- Grebmeier, J.M. and L.W. Cooper, 2016: The Saint Lawrence Island Polynya: A 25-Year Evaluation of an Analogue for Climate Change in Polar Regions. In: Aquatic Microbial Ecology and Biogeochemistry: A Dual Perspective [Glibert, P.M. and T.M. Kana (eds.)]. Springer International Publishing, Cham, 171–183.
- Greene, C.A. et al., 2017: Wind causes Totten Ice Shelf melt and acceleration. *Sci Adv*, **3** (11), e1701681, doi:10.1126/sciadv.1701681.
- Greene, S. et al., 2014: Modeling the impediment of methane ebullition bubbles by seasonal lake ice. *Biogeosciences*, **11** (23), 6791–6811, doi:10.5194/bg-11-6791-2014.
- Gregor, L., S. Kok and P.M.S. Monteiro, 2017: Empirical methods for the estimation of Southern Ocean CO₂: support vector and random forest regression. *Biogeosciences*, **14** (23), 5551–5569, doi:10.1002/2016GB005541.
- Gregory, R. et al., 2012: *Structured Decision Making*. John Wiley & Sons Ltd, Chichester, United Kingdom.
- Griffith, D.L., L. Alessa and A. Kliskey, 2018: Community-based observing for social-ecological science: lessons from the Arctic. *Frontiers in Ecology and the Environment*, **16** (S1), S44–S51, doi:10.1002/fee.1798.
- Griffiths, H.J., A.J.S. Meijers and T.J. Bracegirdle, 2017a: More losers than winners in a century of future Southern Ocean seafloor warming. *Nature Climate Change*, **7** (10), 749–754, doi:10.1038/nclimate3377.
- Griffiths, H.J. et al., 2013: Antarctic Crabs: Invasion or Endurance? *Plos One*, **8** (7), e66981, doi:10.1371/journal.pone.0066981.
- Griffiths, K. et al., 2017b: Ice-cover is the principal driver of ecological change in High Arctic lakes and ponds. *Plos One*, **12** (3), e0172989, doi:10.1371/journal.pone.0172989.
- Groeneveld, R.A. et al., 2018: Defining scenarios of future vectors of change in marine life and associated economic sectors. *Estuarine, Coastal and Shelf Science*, **201**, 164–171, doi:10.1016/j.ecss.2015.10.020.
- Grosse, G. et al., 2011: Vulnerability of high-latitude soil organic carbon in North America to disturbance. *Journal of Geophysical Research*, **116** (G4), G00K06, doi:10.1029/2010jg001507.
- Grosse, G., B. Jones and C. Arp, 2013: Thermokarst lakes, drainage, and drained basins. *Treatise on Geomorphology*, **8**, 325–353, doi:10.1016/b978-0-12-374739-6.00216-5.
- Grosvenor, D.P., J.C. King, T.W. Choularton and T. Lachlan-Cope, 2014: Downslope föhn winds over the antarctic peninsula and their effect on the larsen ice shelves. *Atmospheric Chemistry and Physics*, **14** (18), 9481–9509, doi:10.5194/acp-14-9481-2014.
- Grotjahn, R. et al., 2016: North American extreme temperature events and related large scale meteorological patterns: a review of statistical methods,

- dynamics, modeling, and trends. *Climate Dynamics*, **46** (3–4), 1151–1184, doi:10.1007/s00382-015-2638-6.
- Gruber, N. et al., 2019a: The oceanic sink for anthropogenic CO₂ from 1994 to 2007. *Science*, **363** (6432), 1193–1199, doi:10.1126/science.aau5153.
- Gruber, N., P. Landschutzer and N.S. Lovenduski, 2019b: The Variable Southern Ocean Carbon Sink. *Ann Rev Mar Sci*, **11**, 159–186, doi:10.1146/annurev-marine-121916-063407.
- Gruber, S., 2012: Derivation and analysis of a high-resolution estimate of global permafrost zonation. *The Cryosphere*, **6** (1), 221–233, doi:10.5194/tc-6-221-2012.
- Guerry, A.D. et al., 2015: Natural capital and ecosystem services informing decisions: From promise to practice. *Proceedings of the National Academy of Sciences*, **112** (24), 7348, doi:10.1073/pnas.1503751112.
- Gullestad, P. et al., 2017: Towards ecosystem-based fisheries management in Norway – Practical tools for keeping track of relevant issues and prioritising management efforts. *Marine Policy*, **77**, 104–110, doi:10.1016/j.marpol.2016.11.032.
- Gunn, A., 2016: Rangifer tarandus. The IUCN Red List of Threatened Species 2016:e.T29742A22167140;www.iucnredlist.org/species/29742/22167140.
- Gunn, A. et al., 2011: Understanding the cumulative effects of human activities on barren-ground caribou. In: Cumulative Effects in Wildlife Management: Impact Mitigation [Krausman, P.R. and L.K. Harris (eds.)]. CRC Press, Boca Raton, 113–134.
- Gunn, A. et al., 2013: CARMA's approach for the collaborative and inter-disciplinary assessment of cumulative effects. *Rangifer*, **33** (2), 161–166, doi:10.7557/2.33.2.2540.
- Gurarie, E. et al., 2017: Distribution, density and abundance of Antarctic ice seals off Queen Maud Land and the eastern Weddell Sea. *Polar Biology*, **40** (5), 1149–1165, doi:10.1007/s00300-016-2029-4.
- Gutt, J. et al., 2011: Biodiversity change after climate-induced ice-shelf collapse in the Antarctic. *Deep Sea Research Part II: Topical Studies in Oceanography*, **58** (1), 74–83, doi:10.1016/j.dsr2.2010.05.024.
- Gutt, J. et al., 2015: The Southern Ocean ecosystem under multiple climate change stresses--an integrated circumpolar assessment. *Glob Chang Biol*, **21** (4), 1434–53, doi:10.1111/gcb.12794.
- Gutt, J. et al., 2018: Cross-disciplinarity in the advance of Antarctic ecosystem research. *Mar Genomics*, **37**, 1–17, doi:10.1016/j.margen.2017.09.006.
- Haas, C. et al., 2017: Ice and Snow Thickness Variability and Change in the High Arctic Ocean Observed by In Situ Measurements. *Geophysical Research Letters*, **44** (20), 10,462–10,469, doi:10.1002/2017gl075434.
- Haine, T.W.N. et al., 2015: Arctic freshwater export: Status, mechanisms, and prospects. *Global and Planetary Change*, **125** (Supplement C), 13–35, doi:10.1016/j.gloplacha.2014.11.013.
- Haine, T.W.N. and T. Martin, 2017: The Arctic-Subarctic sea ice system is entering a seasonal regime: Implications for future Arctic amplification. *Sci Rep*, **7** (1), 4618, doi:10.1038/s41598-017-04573-0.
- Häkkinen, S., P.B. Rhines and D.L. Worthen, 2013: Northern North Atlantic sea surface height and ocean heat content variability. *Journal of Geophysical Research: Oceans*, **118** (7), 3670–3678, doi:10.1002/jgrc.20268.
- Halfar, J. et al., 2013: Arctic sea-ice decline archived by multicentury annual-resolution record from crustose coralline algal proxy. *Proc Natl Acad Sci U S A*, **110** (49), 19737–41, doi:10.1073/pnas.1313775110.
- Hall, D.K. et al., 2013: Variability in the surface temperature and melt extent of the Greenland ice sheet from MODIS. *Geophysical Research Letters*, **40** (10), 2114–2120, doi:10.1002/grl.50240.
- Halliday, W.D. et al., 2017: Potential impacts of shipping noise on marine mammals in the western Canadian Arctic. *Marine Pollution Bulletin*, **123** (1), 73–82, doi:10.1016/j.marpolbul.2017.09.027.
- Hamilton, C.D. et al., 2017: An Arctic predator–prey system in flux: climate change impacts on coastal space use by polar bears and ringed seals. *Journal of Animal Ecology*, **86** (5), 1054–1064, doi:10.1111/1365-2656.12685.
- Hamilton, C.D., C. Lydersen, R.A. Ims and K.M. Kovacs, 2015: Predictions replaced by facts: a keystone species' behavioural responses to declining arctic sea-ice. *Biology Letters*, **11** (11), doi:10.1098/rsbl.2015.0803.
- Hamilton, C.D. et al., 2019: Contrasting changes in space use induced by climate change in two Arctic marine mammal species. *Biol Lett*, **15** (3), 20180834, doi:10.1098/rsbl.2018.0834.
- Hamilton, L.C. et al., 2016: Climigration? Population and climate change in Arctic Alaska. *Population and Environment*, **38** (2), 115–133, doi:10.1007/s11111-016-0259-6.
- Hancock, A.M. et al., 2017: Ocean acidification changes the structure of an Antarctic coastal protistan community. *Biogeosciences Discussions*, **2017**, 1–32, doi:10.5194/bg-2017-224.
- Hanes, C.C. et al., 2019: Fire-regime changes in Canada over the last half century. *Canadian Journal of Forest Research*, **49** (3), 256–269, doi:10.1139/cjfr-2018-0293.
- Hanna, E., T.E. Cropper, R.J. Hall and J. Cappelen, 2016: Greenland Blocking Index 1851–2015: a regional climate change signal. *International Journal of Climatology*, **36** (15), 4847–4861, doi:10.1002/joc.4673.
- Hanna, E. et al., 2015: Recent seasonal asymmetric changes in the NAO (a marked summer decline and increased winter variability) and associated changes in the AO and Greenland Blocking Index. *International Journal of Climatology*, **35** (9), 2540–2554, doi:10.1002/joc.4157.
- Hanna, E. et al., 2014: Atmospheric and oceanic climate forcing of the exceptional Greenland ice sheet surface melt in summer 2012. *International Journal of Climatology*, **34** (4), 1022–1037, doi:10.1002/joc.3743.
- Hanna, E., S.H. Mernild, J. Cappelen and K. Steffen, 2012: Recent warming in Greenland in a long-term instrumental (1881–2012) climatic context: I. Evaluation of surface air temperature records. *Environmental Research Letters*, **7** (4), 045404–045404, doi:10.1088/1748-9326/7/4/045404.
- Hanna, E. et al., 2013: Ice-sheet mass balance and climate change. *Nature*, **498** (7452), 51–59, doi:10.1038/nature12238.
- Hansen, B., B. et al., 2014: Warmer and wetter winters: characteristics and implications of an extreme weather event in the High Arctic. *Environmental Research Letters*, **9** (11), 114021, doi:10.1088/1748-9326/9/11/114021.
- Hansen, B.B. et al., 2013: Climate Events Synchronize the Dynamics of a Resident Vertebrate Community in the High Arctic. *Science*, **339** (6117), 313, doi:10.1126/science.1226766.
- Hansen, H.S.B., 2016: Three major challenges in managing non-native sedentary Barents Sea snow crab (*Chionoecetes opilio*). *Marine Policy*, **71**, 38–43, doi:10.1016/j.marpol.2016.05.013.
- Harder, M.T. and G.W. Wenzel, 2012: Inuit subsistence, social economy and food security in Clyde River, Nunavut. *Arctic*, **65** (3), 305–318.
- Harper, S.L., V.L. Edge, A. Cunsolo Willox and G. Rigolet Inuit Community, 2012: 'Changing climate, changing health, changing stories' profile: Using an EcoHealth approach to explore impacts of climate change on inuit health. *EcoHealth*, **9** (1), 89–101, doi:10.1007/s10393-012-0762-x.
- Harper, S.L. et al., 2011: Weather, Water Quality and Infectious Gastrointestinal Illness in Two Inuit Communities in Nunatsiavut, Canada: Potential Implications for Climate Change. *EcoHealth*, **8** (1), 93–108, doi:10.1007/s10393-011-0690-1.
- Hartmann, D.L. et al., 2013: Observations: atmosphere and surface. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. [Stocker, T.F., D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press.
- Hatta, M. et al., 2017: The relative roles of modified circumpolar deep water and benthic sources in supplying iron to the recurrent phytoplankton blooms above Pennell and Mawson Banks, Ross Sea, Antarctica. *Journal of Marine Systems*, **166**, 61–72, doi:10.1016/j.jmarsys.2016.07.009.

- Hauck, J. and C. Volker, 2015: Rising atmospheric CO₂ leads to large impact of biology on Southern Ocean CO₂ uptake via changes of the Revelle factor. *Geophys Res Lett*, **42** (5), 1459–1464, doi:10.1002/2015GL063070.
- Haug, T. et al., 2017: Future harvest of living resources in the Arctic Ocean north of the Nordic and Barents Seas: A review of possibilities and constraints. *Fisheries Research*, **188**, 38–57, doi:10.1016/j.fishres.2016.12.002.
- Haumann, F.A. et al., 2016: Sea-ice transport driving Southern Ocean salinity and its recent trends. *Nature*, **537** (7618), 89–92, doi:10.1038/nature19101.
- Haumann, F.A., D. Notz and H. Schmidt, 2014: Anthropogenic influence on recent circulation-driven Antarctic sea ice changes. *Geophysical Research Letters*, **41** (23), 8429–8437, doi:10.1002/2014gl061659.
- Hauquier, F., L. Ballesteros-Redondo, J. Gutt and A. Vanreusel, 2016: Community dynamics of nematodes after Larsen ice-shelf collapse in the eastern Antarctic Peninsula. *Ecol Evol*, **6** (1), 305–17, doi:10.1002/ece3.1869.
- Hauri, C., T. Friedrich and A. Timmermann, 2015: Abrupt onset and prolongation of aragonite undersaturation events in the Southern Ocean. *Nature Climate Change*, **6** (2), 172–176, doi:10.1038/nclimate2844.
- Hauser, D.D.W., K.L. Laird and H.L. Stern, 2018: Vulnerability of Arctic marine mammals to vessel traffic in the increasingly ice-free Northwest Passage and Northern Sea Route. *Proceedings of the National Academy of Sciences*, **115** (29), 7617, doi:10.1073/pnas.1803543115.
- Hawkings, J. et al., 2016: The Greenland Ice Sheet as a hot spot of phosphorus weathering and export in the Arctic. *Global Biogeochemical Cycles*, **30** (2), 191–210, doi:10.1002/2015GB005237.
- Hawkings, J.R. et al., 2017: Ice sheets as a missing source of silica to the polar oceans. *Nat Commun*, **8**, 14198, doi:10.1038/ncomms14198.
- Hawkings, J.R. et al., 2015: The effect of warming climate on nutrient and solute export from the Greenland Ice Sheet. *Geochemical Perspectives Letters*, **1** (0), 94–104, doi:10.7185/geochemlet.1510.
- Hawkings, J.R. et al., 2014: Ice sheets as a significant source of highly reactive nanoparticulate iron to the oceans. *Nat Commun*, **5**, 3929, doi:10.1038/ncomms4929.
- Hawkins, E. and R. Sutton, 2012: Time of emergence of climate signals. *Geophysical Research Letters*, **39** (1), doi:10.1029/2011gl050087.
- Haynes, T.B. et al., 2014: Patterns of lake occupancy by fish indicate different adaptations to life in a harsh Arctic environment. *Freshwater Biology*, **59** (9), 1884–1896, doi:10.1111/fwb.12391.
- Haynie, A.C. and L. Pfeiffer, 2012: Why economics matters for understanding the effects of climate change on fisheries. *ICES Journal of Marine Science*, **69** (7), 1160–1167, doi:10.1093/icesjms/fss021.
- Hedger, R.D. et al., 2013: Predicting climate change effects on subarctic-Arctic populations of Atlantic salmon (*Salmo salar*). *Canadian Journal of Fisheries and Aquatic Sciences*, **70** (2), 159–168, doi:10.1139/cjfas-2012-0205.
- Hegyí, B.M. and Y. Deng, 2016: Dynamical and Thermodynamical Impacts of High- and Low-Frequency Atmospheric Eddies on the Initial Melt of Arctic Sea Ice. *Journal of Climate*, **30** (3), 865–883, doi:10.1175/jcli-d-15-0366.1.
- Hegyí, B.M. and P.C. Taylor, 2018: The Unprecedented 2016–2017 Arctic Sea Ice Growth Season: The Crucial Role of Atmospheric Rivers and Longwave Fluxes. *Geophysical Research Letters*, **45** (10), 5204–5212, doi:10.1029/2017gl076717.
- Heim, K.C. et al., 2016: Seasonal cues of Arctic grayling movement in a small Arctic stream: the importance of surface water connectivity. *Environmental Biology of Fishes*, **99** (1), 49–65, doi:10.1007/s10641-015-0453-x.
- Heininen, L. and M. Finger, 2017: The “Global Arctic” as a New Geopolitical Context and Method. *Journal of Borderlands Studies*, **33** (2), 199–202, doi:10.1080/08865655.2017.1315605.
- Heleniak, T., 2014: Arctic Populations and Migration. In: Arctic Human Development Report: Regional Processes and Global Linkages [Nyman Larsen, J. and G. Fondhal (eds.)]. Nordic Council of Ministers, Copenhagen, 53–104.
- Helm, V., A. Humbert and H. Miller, 2014: Elevation and elevation change of Greenland and Antarctica derived from CryoSat-2. *The Cryosphere*, **8** (4), 1539–1559, doi:10.5194/tc-8-1539-2014.
- Héon, J., D. Arseneault and M.A. Parisien, 2014: Resistance of the boreal forest to high burn rates. *Proc Natl Acad Sci U S A*, **111** (38), 13888–93, doi:10.1073/pnas.1409316111.
- Hermann, A.J. et al., 2016: Projected future biophysical states of the Bering Sea. *Deep Sea Research Part II: Topical Studies in Oceanography*, **134** (Supplement C), 30–47, doi:10.1016/j.dsr2.2015.11.001.
- Hermann, A.J. et al., 2019: Projected biophysical conditions of the Bering Sea to 2100 under multiple emission scenarios. *ICES Journal of Marine Science*, **76** (5), 1280–1304, doi:10.1093/icesjms/fsz043.
- Hernández-Henríquez, M., S. Déry and C. Derksen, 2015: Polar amplification and elevation-dependence in trends of Northern Hemisphere snow cover extent. *Environmental Research Letters*, **10**, 044010, doi:10.1088/1748-9326/10/4/044010.
- Herraiz-Borreguero, L. et al., 2016: Large flux of iron from the Amery Ice Shelf marine ice to Prydz Bay, East Antarctica. *Journal of Geophysical Research: Oceans*, **121** (8), 6009–6020, doi:10.1002/2016jc011687.
- Heuzé, C., K.J. Heywood, D.P. Stevens and J.K. Ridley, 2015: Changes in global ocean bottom properties and volume transports in CMIP5 models under climate change scenarios. *Journal of Climate*, **28** (8), 2917–2944, doi:10.1175/JCLI-D-14-00381.1.
- Hill, S.L., T. Phillips and A. Atkinson, 2013: Potential Climate Change Effects on the Habitat of Antarctic Krill in the Weddell Quadrant of the Southern Ocean. *Plos One*, **8** (8), e72246, doi:10.1371/journal.pone.0072246.
- Hillenbrand, C.-D. et al., 2017: West Antarctic Ice Sheet retreat driven by Holocene warm water incursions. *Nature*, **547**, 43, doi:10.1038/nature22995.
- Hindell, M.A. et al., 2016: Circumpolar habitat use in the southern elephant seal: implications for foraging success and population trajectories. *Ecosphere*, **7** (5), e01213, doi:10.1002/ecs2.1213.
- Hinke, J.T. et al., 2017a: Identifying Risk: Concurrent Overlap of the Antarctic Krill Fishery with Krill-Dependent Predators in the Scotia Sea. *Plos One*, **12** (1), e0170132, doi:10.1371/journal.pone.0170132.
- Hinke, J.T., S.G. Trivelpiece and W.Z. Trivelpiece, 2017b: Variable vital rates and the risk of population declines in Adelle penguins from the Antarctic Peninsula region. *Ecosphere*, **8** (1), 1–13, doi:10.1002/ecs2.1666.
- Hjort, J. et al., 2018: Degrading permafrost puts Arctic infrastructure at risk by mid-century. *Nat Commun*, **9** (1), 5147, doi:10.1038/s41467-018-07557-4.
- Hobbs, W., M. Curran, N. Abram and E.R. Thomas, 2016a: Century-scale perspectives on observed and simulated Southern Ocean sea ice trends from proxy reconstructions. *Journal of Geophysical Research: Oceans*, **121** (10), 7804–7818, doi:10.1002/2016jc012111.
- Hobbs, W.R., N.L. Bindoff and M.N. Raphael, 2015: New Perspectives on Observed and Simulated Antarctic Sea Ice Extent Trends Using Optimal Fingerprinting Techniques. *Journal of Climate*, **28** (4), 1543–1560, doi:10.1175/Jcli-D-14-00367.1.
- Hobbs, W.R. et al., 2016b: A review of recent changes in Southern Ocean sea ice, their drivers and forcings. *Global and Planetary Change*, **143**, 228–250, doi:10.1016/j.gloplacha.2016.06.008.
- Hoberg, e. a. Arctic Biodiversity Assessment 2013: Chapter 15, Parasites. [Available at: www.caff.is/assessment-series/arctic-biodiversity-assessment/220-arctic-biodiversity-assessment-2013-chapter-15-parasites]
- Hoberg, E.P. and D.R. Brooks, 2015: Evolution in action: climate change, biodiversity dynamics and emerging infectious disease. *Philos Trans R Soc Lond B Biol Sci*, **370** (1665), 20130553, doi:10.1098/rstb.2013.0553.
- Hoberg, E.P. et al., 2017: Arctic systems in the Quaternary: ecological collision, faunal mosaics and the consequences of a wobbling climate. *J Helminthol*, **91** (4), 409–421, doi:10.1017/S0022149X17000347.
- Hodgson, D.A. et al., 2014: Terrestrial and submarine evidence for the extent and timing of the Last Glacial Maximum and the onset of deglaciation

- on the maritime-Antarctic and sub-Antarctic islands. *Quaternary Science Reviews*, **100**, 137–158, doi:10.1016/j.quascirev.2013.12.001.
- Hodgson, D.A. and J.P. Smol, 2008: High latitude paleolimnology. In: In Polar lakes and rivers – Limnology of Arctic and Antarctic aquatic ecosystems [Vincent, W.F. and J. Laybourn-Parry (eds.)]. Oxford University Press, Oxford, 43–64.
- Hodson, A. et al., 2017: Climatically sensitive transfer of iron to maritime Antarctic ecosystems by surface runoff. *Nat Commun*, **8**, 14499, doi:10.1038/ncomms14499.
- Hodson, A.J., 2014: Understanding the dynamics of black carbon and associated contaminants in glacial systems. *Wiley Interdisciplinary Reviews: Water*, **1** (2), 141–149, doi:10.1002/wat2.1016.
- Hodson, D.L.R. et al., 2013: Identifying uncertainties in Arctic climate change projections. *Climate Dynamics*, **40** (11), 2849–2865, doi:10.1007/s00382-012-1512-z.
- Hofer, S., A.J. Tedstone, X. Fettweis and J.L. Bamber, 2017: Decreasing cloud cover drives the recent mass loss on the Greenland Ice Sheet. *Sci Adv*, **3** (6), e1700584, doi:10.1126/sciadv.1700584.
- Hogg, A.E. et al., 2017: Increased ice flow in Western Palmer Land linked to ocean melting. *Geophysical Research Letters*, **44** (9), 4159–4167, doi:10.1002/2016GL072110.
- Hogg, A.M. et al., 2015: Recent trends in the Southern Ocean eddy field. *Journal of Geophysical Research: Oceans*, **120** (1), 257–267, doi:10.1002/2014JC010470.
- Holland, D.M., 2001: Explaining the Weddell Polynya – a large ocean eddy shed at Maud Rise. *Science*, **292** (5522), 1697–1700, doi:10.1126/science.1059322.
- Holland, D.M. et al., 2008: Acceleration of Jakobshavn Isbræ triggered by warm subsurface ocean waters. *Nature Geoscience*, **1**, 659, doi:10.1038/ngeo316.
- Holland, P.R., 2014: The seasonality of Antarctic sea ice trends. *Geophysical Research Letters*, **41**, 4230–4237, doi:10.1002/2014GL060172.
- Holland, P.R. et al., 2014: Modeled trends in Antarctic sea ice thickness. *Journal of Climate*, **27**, 3784–3801, doi:10.1175/JCLI-D-13-00301.1.
- Holland, P.R. and R. Kwok, 2012: Wind-driven trends in Antarctic sea-ice drift. *Nature Geoscience*, **5** (12), 872–875, doi:10.1038/Ngeo1627.
- Holmes, R.M. et al., 2018: *River Discharge* [Jeffries, M.O., J. Richter-Menge and J.E. Overland (eds.)]. Arctic Report Card, Update for 2018 [Available at: www.arctic.noaa.gov/Report-Card/Report-Card-2018/ArtMID/7878/ArticleID/786/River-Discharge].
- Holmes, R.M. et al., 2015: *River Discharge* [Jeffries, M.O., J. Richter-Menge and J.E. Overland (eds.)]. Arctic Report Card, 2015, 60–65 [Available at: <https://arctic.noaa.gov/Report-Card/Report-Card-2015/ArtMID/5037/ArticleID/227/River-Discharge>].
- Holsman, K. et al., 2018: Chapter 6: Climate change impacts, vulnerabilities and adaptations: North Pacific and Pacific Arctic marine fisheries. In: Impacts of climate change on fisheries and aquaculture: synthesis of current knowledge, adaptation and mitigation options. FAO Fisheries and Aquaculture Technical Paper No. 627. [Barange, M., T. Bahri, M.C.M. Beveridge, K.L. Cochrane, S. Funge-Smith and F. Poulain (eds.)], Rome.
- Holsman, K. et al., 2017: An ecosystem-based approach to marine risk assessment. *Ecosystem Health and Sustainability*, **3** (1), e01256, doi:10.1002/ehs2.1256.
- Holsman, K.K. et al., 2019: Towards climate resiliency in fisheries management. *ICES Journal of Marine Science*, **76** (5), 1368–1378, doi:10.1093/icesjms/fsz031.
- Holsman, K.K. et al., 2016: A comparison of fisheries biological reference points estimated from temperature-specific multi-species and single-species climate-enhanced stock assessment models. *Deep Sea Research Part II: Topical Studies in Oceanography*, **134** (Supplement C), 360–378, doi:10.1016/j.dsr2.2015.08.001.
- Holst-Andersen, J.P. et al., 2017: Impact of Arctic Met ocean Conditions on Oil Spill Response: Results of the First Circumpolar Response Viability Analysis. *International Oil Spill Conference Proceedings*, **2017** (1), 2017172, doi:10.7901/2169-3358-2017.1.000172.
- Honda, M., J. Inoue and S. Yamane, 2009: Influence of low Arctic sea-ice minima on anomalously cold Eurasian winters. *Geophysical Research Letters*, **36** (8), L08707, doi:10.1029/2008gl037079.
- Hood, E. et al., 2015: Storage and release of organic carbon from glaciers and ice sheets. *Nature Geosci*, **8** (2), 91–96, doi:10.1038/ngeo2331.
- Hop, H. and H. Gjosæter, 2013: Polar cod (*Boreogadus saida*) and capelin (*Mallotus villosus*) as key species in marine food webs of the Arctic and the Barents Sea. *Marine Biology Research*, **9** (9), 878–894, doi:10.1080/17451000.2013.775458.
- Hope, A.G. et al., 2013: Future distribution of tundra refugia in northern Alaska. *Nature Climate Change*, **3**, 931, doi:10.1038/nclimate1926.
- Hoppe, C.J.M. et al., 2018: Compensation of ocean acidification effects in Arctic phytoplankton assemblages. *Nature Climate Change*, **8** (6), 529–533, doi:10.1038/s41558-018-0142-9.
- Hopwood, M.J. et al., 2018: Non-linear response of summertime marine productivity to increased meltwater discharge around Greenland. *Nat Commun*, **9** (1), 3256, doi:10.1038/s41467-018-05488-8.
- Horgan, H.J. et al., 2013: Estuaries beneath ice sheets. *Geology*, **41** (11), 1159–1162, doi:10.1130/G34654.1.
- Hori, M. et al., 2017: A 38-year (1978–2015) Northern Hemisphere daily snow cover extent product derived using consistent objective criteria from satellite-borne optical sensors. *Remote Sensing of Environment*, **191**, 402–418, doi:10.1016/j.rse.2017.01.023.
- Hori, Y. et al., 2018: Implications of projected climate change on winter road systems in Ontario's Far North, Canada. *Climatic Change*, **148** (1–2), 109–122, doi:10.1007/s10584-018-2178-2.
- Horstkotte, T. et al., 2017: Human–animal agency in reindeer management: Sámi herders' perspectives on vegetation dynamics under climate change. *Ecosphere*, **8** (9), e01931, doi:10.1002/ecs2.1931.
- Horvat, C. et al., 2017: The frequency and extent of sub-ice phytoplankton blooms in the Arctic Ocean. *Science Advances*, **3** (3), e1601191, doi:10.1126/sciadv.1601191.
- Hossain, K., 2015: Governance of Arctic Ocean Marine Resources. In: Climate Change Impacts on Ocean and Coastal Law: U.S. and International Perspectives [Abate, R.S. (ed.)]. Oxford Scholarship Online, New York.
- Howell, S.E.L. et al., 2016: Landfast ice thickness in the Canadian Arctic Archipelago from observations and models. *The Cryosphere*, **10** (4), 1463–1475, doi:10.5194/tc-10-1463-2016.
- Howell, S.E.L. et al., 2013: Recent changes in the exchange of sea ice between the Arctic Ocean and the Canadian Arctic Archipelago. *Journal of Geophysical Research: Oceans*, **118** (7), 3595–3607, doi:10.1002/jgrc.20265.
- Howes, E., F. Joos, M. Eakin and J.-P. Gattuso, 2015: An updated synthesis of the observed and projected impacts of climate change on the chemical, physical and biological processes in the oceans. *Frontiers in Marine Science*, **2** (36), doi:10.3389/fmars.2015.00036.
- Hu, F.S. et al., 2015: Arctic tundra fires: natural variability and responses to climate change. *Frontiers in Ecology and the Environment*, **13** (7), 369–377, doi:10.1890/150063.
- Hu, F.S. et al., 2010: Tundra burning in Alaska: Linkages to climatic change and sea ice retreat. *Journal of Geophysical Research: Biogeosciences*, **115** (G4), G04002, doi:10.1029/2009JG001270.
- Huang, X. et al., 2018: Improved Representation of Surface Spectral Emissivity in a Global Climate Model and Its Impact on Simulated Climate. *Journal of Climate*, **31** (9), 3711–3727, doi:10.1175/jcli-d-17-0125.1.
- Huebert, R., 2013: Cooperation or Conflict in the New Arctic? Too Simple of a Dichotomy! In: *Environmental Security in the Arctic Ocean*, Dordrecht, [P., B. and V.A. (eds.)], Springer Netherlands, 195–203.

- Huet, C. et al., 2017: Food insecurity and food consumption by season in households with children in an Arctic city: a cross-sectional study. *BMC Public Health*, **17** (1), 578, doi:10.1186/s12889-017-4393-6.
- Hugelius, G. et al., 2014: Estimated stocks of circumpolar permafrost carbon with quantified uncertainty ranges and identified data gaps. *Biogeosciences*, **11** (23), 6573–6593, doi:10.5194/bg-11-6573-2014.
- Hughes, K.A., L.R. Pertierra, M.A. Molina-Montenegro and P. Convey, 2015: Biological invasions in terrestrial Antarctica: what is the current status and can we respond? *Biodiversity and Conservation*, **24** (5), 1031–1055, doi:10.1007/s10531-015-0896-6.
- Huiskes, A.H.L. et al., 2014: Aliens in Antarctica: Assessing transfer of plant propagules by human visitors to reduce invasion risk. *Biological Conservation*, **171**, 278–284, doi:10.1016/j.biocon.2014.01.038.
- Humphrey, N.F., J.T. Harper and W.T. Pfeffer, 2012: Thermal tracking of meltwater retention in Greenland's accumulation area. *Journal of Geophysical Research: Earth Surface*, **117** (1), 1–11, doi:10.1029/2011JF002083.
- Hunt, B.P.V. et al., 2014: Zooplankton community structure and dynamics in the Arctic Canada Basin during a period of intense environmental change (2004–2009). *Journal of Geophysical Research: Oceans*, **119** (4), 2518–2538, doi:10.1002/2013JC009156.
- Hunt, G.L. et al., 2016: Advection in polar and sub-polar environments: Impacts on high latitude marine ecosystems. *Progress in Oceanography*, **149**, 40–81, doi:10.1016/j.pocean.2016.10.004.
- Hunt, G.L. et al., 2018: Timing of sea-ice retreat affects the distribution of seabirds and their prey in the southeastern Bering Sea. *Marine Ecology Progress Series*, **593**, 209–230, doi:10.3354/meps12383.
- Huntington, H.P. et al., 2015: Vessels, risks, and rules: Planning for safe shipping in Bering Strait. *Marine Policy*, **51**, 119–127, doi:10.1016/j.marpol.2014.07.027.
- Huntington, H.P. et al., 2018: Staying in place during times of change in Arctic Alaska: the implications of attachment, alternatives, and buffering. *Regional Environmental Change*, **18** (2), 489–499, doi:10.1007/s10113-017-1221-6.
- Huntington, H.P., L.T. Quakenbush and M. Nelson, 2017: Evaluating the Effects of Climate Change on Indigenous Marine Mammal Hunting in Northern and Western Alaska Using Traditional Knowledge. *Frontiers in Marine Science*, **4**, 319, doi:10.3389/fmars.2017.00319.
- Huskey, L., 2018: An Arctic development strategy? The North Slope Inupiat and the resource curse. *Canadian Journal of Development Studies / Revue canadienne d'études du développement*, **39** (1), 89–100, doi:10.1080/02255189.2017.1391067.
- Huskey, L., I. Maenpaa and A. Pelyasov, 2014: Economic Systems. In: Arctic Human Development Report [Nyman Larson, J. and G. Fondahl (eds.)]. Nordic Council of Ministers, Copenhagen, 151–184.
- Hutchins, D.A. and P.W. Boyd, 2016: Marine phytoplankton and the changing ocean iron cycle. *Nature Climate Change*, **6** (12), 1072, doi:10.1038/nclimate3147.
- Hyder, P. et al., 2018: Critical Southern Ocean climate model biases traced to atmospheric model cloud errors. *Nat Commun*, **9** (1), 3625, doi:10.1038/s41467-018-05634-2.
- Ianelli, J., K.K. Holsman, A.E. Punt and K. Aydin, 2016: Multi-model inference for incorporating trophic and climate uncertainty into stock assessments. *Deep Sea Research Part II: Topical Studies in Oceanography*, **134** (Supplement C), 379–389, doi:10.1016/j.dsr2.2015.04.002.
- ICC, 2012: *Food Security across the Arctic, Background paper of the Steering Committee of the Circumpolar Inuit Health Strategy Inuit Circumpolar Council*. Canada [Available at: www.inuitcircumpolar.com/uploads/3/0/5/4/30542564/icc_food_security_across_the_arctic_may_2012.pdf].
- Ignatowski, J. and J. Rosales, 2013: Identifying the exposure of two subsistence villages in Alaska to climate change using traditional ecological knowledge. *Climatic Change*, **121** (2), 285–299, doi:10.1007/s10584-013-0883-4.
- Ilicak, M. et al., 2016: An assessment of the Arctic Ocean in a suite of interannual CORE-II simulations. Part III: Hydrography and fluxes. *Ocean Modelling*, **100**, 141–161, doi:10.1016/j.ocemod.2016.02.004.
- IMO, 2017: *International Maritime Organisation, International Code for Ships Operating in Polar Waters ('Polar Code')*.
- Ingels, J., R.B. Aronson and C.R. Smith, 2018: The scientific response to Antarctic ice-shelf loss. *Nature Climate Change*, **8** (10), 848–851, doi:10.1038/s41558-018-0290-y.
- Ingvaldsen, R.B. and H. Gjørseter, 2013: Responses in spatial distribution of Barents Sea capelin to changes in stock size, ocean temperature and ice cover. *Marine Biology Research*, **9** (9), 867–877, doi:10.1080/17451000.2013.775450.
- Inuit Circumpolar Council-Alaska (ICC-AK), 2015: *Alaskan Inuit Food Security Conceptual Framework: How to Assess the Arctic from an Inuit Perspective -- Summary and Recommendations Report. Report created as part of 2015 Alaskan Inuit Food Security Conceptual Framework Technical Report*. [Available at: <https://tribalclimateguide.uoregon.edu/literature/inuit-circumpolar-council-alaska-icc-ak-2015-alaskan-inuit-food-security-conceptual/>].
- Inuit Circumpolar Council, 2014: *The Sea Ice Never Stops. Circumpolar Inuit Reflections on Sea Ice Use and Shipping in Inuit Nunaat*. (ICC), I.C.C., Canada [Available at: <http://hdl.handle.net/11374/1478>].
- Inuit Circumpolar Council Canada, 2014: *The Sea Ice Never Stops: Reflections on sea ice use and shipping in Inuit Nunaat*. Inuit Circumpolar Council – Canada, Ottawa, Canada [Available at: <https://oaarchive.arctic-council.org/handle/11374/410>].
- IPCC, 2013: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp [Available at: www.climatechange2013.org/report/full-report/].
- Irving, D.B., S. Wijffels and J.A. Church, 2019: Anthropogenic Aerosols, Greenhouse Gases, and the Uptake, transport, and Storage of Excess Heat in the Climate System. *Geophysical Research Letters*, **46** (9), 4894–4903, doi:10.1029/2019gl082015.
- Islam, D. and F. Berkes, 2016: Indigenous peoples' fisheries and food security: a case from northern Canada. *Food Security*, **8** (4), 815–826, doi:10.1007/s12571-016-0594-6.
- Itkin, P. et al., 2017: Thin ice and storms: Sea ice deformation from buoy arrays deployed during N-ICE2015. *Journal of Geophysical Research: Oceans*, **122** (6), 4661–4674, doi:10.1002/2016jc012403.
- Ivanov, V. et al., 2016: Arctic Ocean heat impact on regional ice decay: A suggested positive feedback. *Journal of Physical Oceanography*, **46** (5), 1437–1456, doi:10.1175/JPO-D-15-0144.1.
- Ivanova, D.P. et al., 2016: Moving beyond the Total Sea Ice Extent in Gauging Model Biases. *Journal of Climate*, **29** (24), 8965–8987, doi:10.1175/Jcli-D-16-0026.1.
- Iverson, J., 2013: Funding Alaska Village Relocation Caused by Climate Change and Preserving Cultural Values During Relocation. *Seattle Journal for Social Justice*, **12** (2), Article 12.
- Jabour, J., 2017: 25. Southern Ocean search and rescue: platforms and procedures. *Handbook on the Politics of Antarctica*, 392.
- Jacobs, S.S., 2004: Bottom water production and its links with the thermohaline circulation. *Antarctic Science*, **16** (4), 427–437, doi:10.1017/S095410200400224x.
- Jacobs, S.S., A. Jenkins, C.F. Giulivi and P. Dutrieux, 2011: Stronger ocean circulation and increased melting under Pine Island Glacier ice shelf. *Nature Geoscience*, **4** (8), 519, doi:10.1038/ngeo1188.
- Jahn, A., 2018: Reduced probability of ice-free summers for 1.5°C compared to 2°C warming. *Nature Climate Change*, **8** (5), 409–413, doi:10.1038/s41558-018-0127-8.

- Jahn, A., J.E. Kay, M.M. Holland and D.M. Hall, 2016: How predictable is the timing of a summer ice-free Arctic? *Geophysical Research Letters*, **43** (17), 9113–9120, doi:10.1002/2016gl070067.
- Jahn, A. et al., 2012: Late-Twentieth-Century Simulation of Arctic Sea Ice and Ocean Properties in the CCSM4. *Journal of Climate*, **25** (5), 1431–1452, doi:10.1175/jcli-d-11-00201.1.
- Jakobsen, I., 2014: Extractive Industries in Arctic: The International Legal Framework for the Protection of the Environment. *Nordic Environmental Law Journal I*, **1**, 39–52.
- Janout, M. et al., 2015: Episodic warming of near-bottom waters under the Arctic sea ice on the central Laptev Sea shelf. *Geophysical Research Letters*, **43** (1), 264–272, doi:10.1002/2015GL066565.
- Jansen, J. et al., 2017: Abundance and richness of key Antarctic seafloor fauna correlates with modelled food availability. *Nature Ecology & Evolution*, 1–13, doi:10.1038/s41559-017-0392-3.
- Jansen, T. et al., 2016: Ocean warming expands habitat of a rich natural resource and benefits a national economy. *Ecological Applications*, **26** (7), 2021–2032, doi:10.1002/eap.1384.
- Jarvis, D. et al., 2013: *Review of the evidence on Indicators, metrics and monitoring systems*. Department for International Development, UK Government [Available at: <http://r4d.dfid.gov.uk/Output/192446/Default.aspx>].
- Jena, B., M. Ravichandran and J. Turner, 2019: Recent Reoccurrence of Large Open-Ocean Polynya on the Maud Rise Seamount. *Geophysical Research Letters*, **46** (8), 4320–4329, doi:10.1029/2018gl081482.
- Jenkins, A. et al., 2018: West Antarctic Ice Sheet retreat in the Amundsen Sea driven by decadal oceanic variability. *Nature Geoscience*, **11** (10), 733–738, doi:10.1038/s41561-018-0207-4.
- Jenkins, E.J. et al., 2013: Tradition and transition: parasitic zoonoses of people and animals in Alaska, northern Canada, and Greenland. *Adv Parasitol*, **82**, 33–204, doi:10.1016/B978-0-12-407706-5.00002-2.
- Jenouvrier, S. et al., 2018: Climate change and functional traits affect population dynamics of a long-lived seabird. *Journal of Animal Ecology*, **87** (4), 906–920, doi:10.1111/1365-2656.12827.
- Jenouvrier, S. et al., 2014: Projected continent-wide declines of the emperor penguin under climate change. *Nature Climate Change*, **4** (8), 715–718, doi:10.1038/nclimate2280.
- Jenouvrier, S., C. Péron and H. Weimerskirch, 2015: Extreme climate events and individual heterogeneity shape life-history traits and population dynamics. *Ecological Monographs*, **85** (4), 605–624, doi:10.1890/14-1834.1.
- Jensen, A.J., B. Finstad and P. Fiske, 2018: Evidence for the linkage of survival of anadromous Arctic char and brown trout during winter to marine growth during the previous summer. *Canadian Journal of Fisheries and Aquatic Sciences*, **75** (5), 663–672, doi:10.1139/cjfas-2017-0077.
- Jepsen, S.M. et al., 2013: Linkages between lake shrinkage/expansion and sublacustrine permafrost distribution determined from remote sensing of interior Alaska, USA. *Geophysical Research Letters*, **40** (5), 882–887, doi:10.1002/grl.50187.
- Jepsen, S.M., M.A. Walvoord, C.I. Voss and J. Rover, 2015: Effect of permafrost thaw on the dynamics of lakes recharged by ice-jam floods: case study of Yukon Flats, Alaska. *Hydrological Processes*, **30** (11), 1782–1795, doi:10.1002/hyp.10756.
- Jin, M. et al., 2016: Ecosystem model intercomparison of under-ice and total primary production in the Arctic Ocean. *Journal of Geophysical Research: Oceans*, **121** (1), 934–948, doi:10.1002/2015JC011183.
- Jobbágy, E.G. and R.B. Jackson, 2000: The vertical distribution of soil organic carbon and its relation to climate and vegetation. *Ecological Applications*, **10** (2), 423–436, doi:10.1890/1051-0761.
- Johannesen, E. et al., 2017: Large-scale patterns in community structure of benthos and fish in the Barents Sea. *Polar Biology*, **40** (2), 237–246, doi:10.1007/s00300-016-1946-6.
- Johnson, N. et al., 2015a: The Contributions of Community-Based Monitoring and Traditional Knowledge to Arctic Observing Networks: Reflections on the State of the Field. *Arctic*, **68** (28–40), doi:10.14430/arctic4447.
- Johnson, N. et al., 2015b: *Community-Based Monitoring and Indigenous Knowledge in a Changing Arctic: A Review for the Sustaining Arctic Observing Networks*. Brown University's Voss Interdisciplinary Postdoctoral Fellowship, Brown University.
- Johnston, A., M.E. Johnston, J. Dawson and E.J. Stewart, 2012a: Challenges of changes in Arctic cruise tourism: perspectives of federal government stakeholders. *Journal of Maritime Law and Commerce*, **43** (3), 335–347.
- Johnston, A. et al., 2012b: Perspectives of decision makers and regulators on climate change and adaptation in expedition cruise ship tourism in Nunavut. *Northern Review*, **35**, 69–85.
- Johnston, D.W., M.T. Bowers, A.S. Friedlaender and D.M. Lavigne, 2012c: The Effects of Climate Change on Harp Seals (*Pagophilus groenlandicus*). *PLoS One*, **7** (1), e29158, doi:10.1371/journal.pone.0029158.
- Johnston, M., J. Dawson, E. De Souza and E.J. Stewart, 2017: Management challenges for the fastest growing marine shipping sector in Arctic Canada: pleasure crafts. *Polar Record*, **53** (1), 67–78, doi:10.1017/s0032247416000565.
- Johnstone, J. et al., 2009: Postfire seed rain of black spruce, a semiserotinous conifer, in forests of interior Alaska. *Canadian Journal of Forest Research*, **39** (8), 1575–1588, doi:10.1139/X09-068.
- Johnstone, J.F. et al., 2010: Fire, climate change, and forest resilience in interior Alaska: This article is one of a selection of papers from The Dynamics of Change in Alaska's Boreal Forests: Resilience and Vulnerability in Response to Climate Warming. *Canadian Journal of Forest Research*, **40** (7), 1302–1312, doi:10.1139/X10-061.
- Johnstone, J.F., T.S. Rupp, M. Olson and D. Verbyla, 2011: Modeling impacts of fire severity on successional trajectories and future fire behavior in Alaskan boreal forests. *Landscape Ecology*, **26** (4), 487–500, doi:10.1007/s10980-011-9574-6.
- Joli, N. et al., 2018: Need for focus on microbial species following ice melt and changing freshwater regimes in a Janus Arctic Gateway. *Scientific Reports*, **8** (1), 9405, doi:10.1038/s41598-018-27705-6.
- Jones, B. et al., 2009: Fire behavior, weather, and burn severity of the 2007 Anaktuvuk river tundra fire, North Slope, Alaska. *Arctic, Antarctic, and Alpine Research*, **41** (3), 309–316, doi:10.1657/1938-4246-41.3.309.
- Jones, B.M. et al., 2011: Modern thermokarst lake dynamics in the continuous permafrost zone, northern Seward Peninsula, Alaska. *Journal of Geophysical Research: Biogeosciences*, **116** (G2), G00M03, doi:10.1029/2011JG001666.
- Jones, B.M. et al., 2015a: Recent Arctic tundra fire initiates widespread thermokarst development. *Scientific Reports*, **5**, 15865, doi:10.1038/srep15865.
- Jones, J.M. et al., 2016: Assessing recent trends in high-latitude Southern Hemisphere surface climate. *Nature Climate Change*, **6**, 917, doi:10.1038/nclimate3103.
- Jones, R.S. et al., 2015b: Rapid Holocene thinning of an East Antarctic outlet glacier driven by marine ice sheet instability. *Nature Communications*, **6**, 8910, doi:10.1038/ncomms9910.
- Joughin, I., B.E. Smith and B. Medley, 2014: Marine Ice Sheet Collapse Potentially Under Way for the Thwaites Glacier Basin, West Antarctica. *Science*, **344** (6185), 735–738, doi:10.1126/science.1249055.
- Jourdain, N.C. et al., 2017: Ocean circulation and sea-ice thinning induced by melting ice shelves in the Amundsen Sea. *Journal of Geophysical Research: Oceans*, **122** (3), 2550–2573, doi:10.1002/2016JC012509.
- Ju, J. and J.G. Masek, 2016: The vegetation greenness trend in Canada and US Alaska from 1984–2012 Landsat data. *Remote Sensing of Environment*, **176**, 1–16, doi:10.1016/j.rse.2016.01.001.
- Jung, T. et al., 2015: Polar Lower-Latitude Linkages and Their Role in Weather and Climate Prediction. *Bulletin of the American Meteorological Society*, **96** (11), Es197–Es200, doi:10.1175/Bams-D-15-00121.1.
- Juul-Pedersen, T. et al., 2015: Seasonal and interannual phytoplankton production in a sub-Arctic tidewater outlet glacier fjord, SW Greenland. *Marine Ecology Progress Series*, **524**, 27–38, doi:10.3354/meps11174.

- Juvonen, S.-K. and A.E. Kuhmonen, 2013: Evaluation of the Protected Area Network in the Barents Region Using the Programme of Work on Protected Areas of the Convention on Biological Diversity as a Tool. In: Reports of the Finnish Environment Institute, Helsinki, 37.
- Kaartvedt, S. and J. Titelman, 2018: Planktivorous fish in a future Arctic Ocean of changing ice and unchanged photoperiod. *ICES Journal of Marine Science*, **75** (7), 2312–2318, doi:10.1093/icesjms/fsx248.
- Kafle, P. et al., 2018: Temperature-dependent development and freezing survival of protostrongylid nematodes of Arctic ungulates: implications for transmission. *Parasites & Vectors*, **11** (1), 400, doi:10.1186/s13071-018-2946-x.
- Kahru, M., V. Brotas, M. Manzano-Sarabia and B.G. Mitchell, 2011: Are phytoplankton blooms occurring earlier in the Arctic? *Global Change Biology*, **17** (4), 1733–1739, doi:10.1111/j.1365-2486.2010.02312.x.
- Kahru, M., Z. Lee, B.G. Mitchell and C.D. Nevison, 2016: Effects of sea ice cover on satellite-detected primary production in the Arctic Ocean. *Biology Letters*, **12** (11), doi:10.1098/rsbl.2016.0223.
- Kaiser, B.A. et al., 2015: Spatial issues in Arctic marine resource governance workshop summary and comment. *Marine Policy*, **58**, 1–5, doi:10.1016/j.marpol.2015.03.033.
- Kaján, E., 2014: Arctic Tourism and Sustainable Adaptation: Community Perspectives to Vulnerability and Climate Change. *Scandinavian Journal of Hospitality and Tourism*, **14** (1), 60–79, doi:10.1080/15022250.2014.886097.
- Kaleschke, L. et al., 2016: SMOS sea ice product: Operational application and validation in the Barents Sea marginal ice zone. *Remote Sensing of Environment*, **180**, 264–273, doi:10.1016/j.rse.2016.03.009.
- Kanevskiy, M. et al., 2013: Ground ice in the upper permafrost of the Beaufort Sea coast of Alaska. *Cold Regions Science and Technology*, **85**, 56–70, doi:10.1016/j.coldregions.2012.08.002.
- Kanna, N. et al., 2018: Upwelling of Macronutrients and Dissolved Inorganic Carbon by a Subglacial Freshwater Driven Plume in Bowdoin Fjord, Northwestern Greenland. *Journal of Geophysical Research: Biogeosciences*, **123** (5), 1666–1682, doi:10.1029/2017JG004248.
- Kapsch, M.-L., R.G. Graversen and M. Tjernström, 2013: Springtime atmospheric energy transport and the control of Arctic summer sea-ice extent. *Nature Climate Change*, **3**, 744, doi:10.1038/nclimate1884.
- Kapsch, M.-L., R.G. Graversen, M. Tjernström and R. Bintanja, 2016: The Effect of Downwelling Longwave and Shortwave Radiation on Arctic Summer Sea Ice. *Journal of Climate*, **29** (3), 1143–1159, doi:10.1175/jcli-d-15-0238.1.
- Karnovsky, N.J., K.A. Hobson, Z.W. Brown and G.L. Hunt, 2009: Distribution and diet of Ivory Gulls (*Pagophila eburnea*) in the North Water Polynya. *Arctic*, **62**, 65–74, doi:10.14430/arctic113
- Karpechko, A. et al., 2018: *Scientific Assessment of Ozone Depletion: 2018* [Cagnazzo, C. and L. Polvani (eds.)]. Stratospheric Ozone and Climate, Chapter 5, World Meteorological Organization, G.S., Geneva, Switzerland [Available at: www.esrl.noaa.gov/csd/assessments/ozone/2018/report/Chapter5_2018OzoneAssessment.pdf].
- Kasischke, E.S. and M.R. Turetsky, 2006: Recent changes in the fire regime across the North American boreal region – Spatial and temporal patterns of burning across Canada and Alaska. *Geophysical Research Letters*, **33** (9), L09703, doi:10.1029/2006gl025677.
- Kates, R.W., W.R. Travis and T.J. Wilbanks, 2012: Transformational adaptation when incremental adaptations to climate change are insufficient. *Proceedings of the National Academy of Sciences of the United States of America*, **109** (19), 7156–7161, doi:10.1073/pnas.1115521109.
- Kaufman, D.E. et al., 2017: Climate change impacts on southern Ross Sea phytoplankton composition, productivity, and export. *Journal of Geophysical Research: Oceans*, **122** (3), 2339–2359, doi:10.1002/2016jc012514.
- Kavanaugh, M.T. et al., 2015: Effect of continental shelf canyons on phytoplankton biomass and community composition along the western Antarctic Peninsula. *Marine Ecology Progress Series*, **524**, 11–26, doi:10.3354/meps11189.
- Kawaguchi, S. et al., 2013: Risk maps for Antarctic krill under projected Southern Ocean acidification. *Nature Climate Change*, **3**, 843, doi:10.1038/nclimate1937.
- Kawaguchi, S., S. Nicol and A.J. Press, 2009: Direct effects of climate change on the Antarctic krill fishery. *Fisheries Management and Ecology*, **16** (5), 424–427, doi:10.1111/j.1365-2400.2009.00686.x.
- Kay, J.E., M.M. Holland and A. Jahn, 2011: Inter-annual to multi-decadal Arctic sea ice extent trends in a warming world. *Geophysical Research Letters*, **38** (15), L15708, doi:10.1029/2011gl048008.
- Keil, K. and S.E. Knecht, 2017: *Governing Arctic Change: Global Perspectives*. Palgrave Macmillan, Basingstoke, UK.
- Kelly, R. et al., 2013: Recent burning of boreal forests exceeds fire regime limits of the past 10,000 years. *Proceedings of the National Academy of Sciences USA*, **110** (32), 13055–13060, doi:10.1073/pnas.1305069110.
- Kennicutt, M.C. et al., 2014a: Polar research: Six priorities for Antarctic science. *Nature*, (512), 23–25, doi:10.1038/512023a.
- Kennicutt, M.C. et al., 2014b: A roadmap for Antarctic and Southern Ocean science for the next two decades and beyond. *Antarctic Science*, **27** (1), 3–18, doi:10.1017/S0954102014000674.
- Keppler, L. and P. Landschutzer, 2019: Regional Wind Variability Modulates the Southern Ocean Carbon Sink. *Sci Rep*, **9** (1), 7384, doi:10.1038/s41598-019-43826-y.
- Kern, S. and B. Ozsoy-Çiçek, 2016: Satellite Remote Sensing of Snow Depth on Antarctic Sea Ice: An Inter-Comparison of Two Empirical Approaches. *Remote Sensing*, **8** (6), 450, doi:10.3390/rs8060450.
- Kessler, A. and J. Tjiputra, 2016: The Southern Ocean as a constraint to reduce uncertainty in future ocean carbon sinks. *Earth System Dynamics*, **7** (2), 295–312, doi:papers2://publication/doi/10.5194/esd-7-295-2016.
- Khan, S.A. et al., 2015: Greenland ice sheet mass balance: a review. *Reports on Progress in Physics*, **046801**, 1–26, doi:10.1088/0034-4885/78/4/046801.
- Kharin, V.V., F.W. Zwiers, X. Zhang and M. Wehner, 2013: Changes in temperature and precipitation extremes in the CMIP5 ensemble. *Climatic Change*, **119** (2), 345–357, doi:10.1007/s10584-013-0705-8.
- Khazendar, A. et al., 2016: Rapid submarine ice melting in the grounding zones of ice shelves in West Antarctica. *Nature Communications*, **7**, 13243, doi:10.1038/ncomms13243.
- Khazendar, A. et al., 2013: Observed thinning of Totten Glacier is linked to coastal polynya variability. *Nature Communications*, **4**, 2857, doi:10.1038/ncomms3857.
- Kiani, S. et al., 2018: Effects of recent temperature variability and warming on the Oulu-Hailuoto ice road season in the northern Baltic Sea. *Cold Regions Science and Technology*, **151**, 1–8, doi:10.1016/j.coldregions.2018.02.010.
- Kidston, J., A.S. Taschetto, D.W.J. Thompson and M.H. England, 2011: The influence of Southern Hemisphere sea-ice extent on the latitude of the mid-latitude jet stream. *Geophysical Research Letters*, **38**, 5, doi:10.1029/2011gl048056.
- Kim, B.-M. et al., 2017: Major cause of unprecedented Arctic warming in January 2016: Critical role of an Atlantic windstorm. *Scientific Reports*, **7**, 40051, doi:10.1038/srep40051.
- Kim, B.M. et al., 2014: Weakening of the stratospheric polar vortex by Arctic sea-ice loss. *Nat Commun*, **5**, 4646, doi:10.1038/ncomms5646.
- Kim, H. et al., 2018: Inter-decadal variability of phytoplankton biomass along the coastal West Antarctic Peninsula. *Philos Trans A Math Phys Eng Sci*, **376** (2122), 1–21, doi:10.1098/rsta.2017.0174.
- Kimmel, D.G., L.B. Eisner, M.T. Wilson and J.T. Duffy-Anderson, 2018: Copepod dynamics across warm and cold periods in the eastern Bering Sea: Implications for walleye pollock (*Gadus chalcogrammus*) and the Oscillating Control Hypothesis. *Fisheries Oceanography*, **27** (2), 143–158, doi:10.1111/fog.12241.
- Kimura, S. et al., 2017: Oceanographic Controls on the Variability of Ice-Shelf Basal Melting and Circulation of Glacial Meltwater in the Amundsen Sea Embayment, Antarctica. *Journal of Geophysical Research: Oceans*, **122** (12), 10131–10155, doi:10.1002/2017JC012926.

- King, M.D. et al., 2018: Seasonal to decadal variability in ice discharge from the Greenland Ice Sheet. *The Cryosphere*, **12** (12), 3813–3825, doi:10.5194/tc-12-3813-2018.
- Kingslake, J. et al., 2018: Extensive retreat and re-advance of the West Antarctic Ice Sheet during the Holocene. *Nature*, **558** (7710), 430–434, doi:10.1038/s41586-018-0208-x.
- Kinnard, C. et al., 2011: Reconstructed changes in Arctic sea ice over the past 1,450 years. *Nature*, **479** (7374), 509–12, doi:10.1038/nature10581.
- Kinzey, D., G.M. Watters and C.S. Reiss, 2015: Selectivity and two biomass measures in an age-based assessment of Antarctic krill (*Euphausia superba*). *Fisheries Research*, **168**, 72–84, doi:10.1016/j.fishres.2015.03.023.
- Kirkfeldt, T.S. et al., 2016: Why cumulative impacts assessments of hydrocarbon activities in the Arctic fail to meet their purpose. *Regional Environmental Change*, **17** (3), 725–737, doi:10.1007/s10113-016-1059-3.
- Kjeldsen, K.K. et al., 2015: Spatial and temporal distribution of mass loss from the Greenland Ice Sheet since AD 1900. *Nature*, **528**, 396, doi:10.1038/nature16183.
- Kjesbu, O.S. et al., 2014: Synergies between climate and management for Atlantic cod fisheries at high latitudes. *Proceedings of the National Academy of Sciences*, **111** (9), 3478–3483, doi:10.1073/pnas.1316342111.
- Klaczek, M.R., C.J. Johnson and H.D. Cluff, 2016: Wolf–caribou dynamics within the central Canadian Arctic. *The Journal of Wildlife Management*, **80** (5), 837–849, doi:10.1002/jwmg.1070.
- Klein, E.S. et al., 2018: Impacts of rising sea temperature on krill increase risks for predators in the Scotia Sea. *Plos One*, **13** (1), e0191011, doi:10.1371/journal.pone.0191011.
- Kleinen, T. and V. Brovkin, 2018: Pathway-dependent fate of permafrost region carbon. *Environmental Research Letters*, **13** (9), 094001, doi:10.1088/1748-9326/aad824.
- Klokov, K., 2012: Changes in reindeer population numbers in Russia: an effect of the political context or climate? *Rangifer*, **32** (1), 19, doi:10.7557/2.32.1.2234.
- Kloster, S., N.M. Mahowald, J.T. Randerson and P.J. Lawrence, 2012: The impacts of climate, land use, and demography on fires during the 21st century simulated by CLM-CN. *Biogeosciences*, **9** (1), 509–525, doi:10.5194/bg-9-509-2012.
- Kocho-Schellenberg, J.-E. and F. Berkes, 2014: Tracking the development of co-management: using network analysis in a case from the Canadian Arctic. *Polar Record*, **51** (4), 422–431, doi:10.1017/S0032247414000436.
- Koenig, L.S., C. Miège, R.R. Forster and L. Brucker, 2014: Initial in situ measurements of perennial meltwater storage in the Greenland firn aquifer. *Geophysical Research Letters*, **41** (1), 81–85, doi:10.1002/2013GL058083.
- Koenig, T. and L. Brodeau, 2014: Ocean heat transport into the Arctic in the twentieth and twenty-first century in EC-Earth. *Climate Dynamics*, **42** (11–12), 3101–3120, doi:10.1007/s00382-013-1821-x.
- Koenigstein, S. et al., 2018: Forecasting future recruitment success for Atlantic cod in the warming and acidifying Barents Sea. *Glob Chang Biol*, **24** (1), 526–535, doi:10.1111/gcb.13848.
- Kofinas, G. et al., 2016: Building resilience in the Arctic: From theory to practice. In: Arctic Resilience Report [Council, A. (ed.)][Carson, M. and G. Peterson (eds.)]. Stockholm Environment Institute and Stockholm Resilience Centre, Stockholm, 180–208.
- Kohlbach, D. et al., 2016: The importance of ice algae-produced carbon in the central Arctic Ocean ecosystem: Food web relationships revealed by lipid and stable isotope analyses. *Limnology and Oceanography*, **61** (6), 2027–2044, doi:10.1002/lno.10351.
- Kohnert, K. et al., 2017: Strong geologic methane emissions from discontinuous terrestrial permafrost in the Mackenzie Delta, Canada. *Scientific Reports*, **7** (1), 5828, doi:10.1038/s41598-017-05783-2.
- Koivuova, T., 2013: Gaps in International Regulatory Frameworks for the Arctic Ocean. In: *Environmental Security in the Arctic Ocean*, 2013//, Dordrecht, [Berkman, P.A. and A.N. Vylegzhanin (eds.)], Springer Netherlands, 139–155.
- Koivuova, T. and R. Caddell, 2018: Managing Biodiversity Beyond National Jurisdiction in the Changing Arctic. *The American Society of International Law*, **112**, 134–138, doi:10.1017/aju.2018.44.
- Kokelj, S.V. et al., 2013: Thawing of massive ground ice in mega slumps drives increases in stream sediment and solute flux across a range of watershed scales. *Journal of Geophysical Research: Earth Surface*, **118** (2), 681–692, doi:10.1002/jgrf.20063.
- Kokelj, S.V. et al., 2017: Climate-driven thaw of permafrost preserved glacial landscapes, northwestern Canada. *Geology*, **45** (4), 371–374, doi:10.1130/G38626.1.
- Kokelj, S.V. et al., 2015: Increased precipitation drives mega slump development and destabilization of ice-rich permafrost terrain, northwestern Canada. *Global and Planetary Change*, **129**, 56–68, doi:10.1016/j.gloplacha.2015.02.008.
- Kokubun, N. et al., 2018: Inter-annual climate variability affects foraging behavior and nutritional state of thick-billed murres breeding in the southeastern Bering Sea. *Marine Ecology Progress Series*, **593**, 195–208, doi:10.3354/meps12365.
- Kononova, N.K., 2012: The influence of atmospheric circulation on the formation of snow cover on the north eastern Siberia. *Ice and Snow*, **1**, 38/53, doi:10.15356/2076-6734-2012-1-38-53.
- Konrad, H. et al., 2017: Uneven onset and pace of ice-dynamical imbalance in the Amundsen Sea Embayment, West Antarctica. *Geophysical Research Letters*, **44** (2), 910–918, doi:10.1002/2016GL070733.
- Konrad, H. et al., 2018: Net retreat of Antarctic glacier grounding line. *Nature Geosciences*, **11**, 258–262, doi:10.1038/s41561-018-0082-z.
- Kooyman, G.L. and P.J. Ponganis, 2017: Rise and fall of Ross Sea emperor penguin colony populations: 2000 to 2012. *Antarctic Science*, **29** (3), 201–208, doi:10.1017/S0954102016000559.
- Kortsch, S. et al., 2012: Climate-driven regime shifts in Arctic marine benthos. *Proceedings of the National Academy of Sciences of the United States of America*, **109** (35), 14052–14057, doi:10.1073/pnas.1207509109.
- Kortsch, S. et al., 2015: Climate change alters the structure of arctic marine food webs due to poleward shifts of boreal generalists. *Proceedings of the Royal Society B: Biological Sciences*, **282** (1814), 20151546, doi:10.1098/rspb.2015.1546.
- Kouril, D., C. Furgal and T. Whillans, 2016: Trends and key elements in community-based monitoring: a systematic review of the literature with an emphasis on Arctic and Subarctic regions. *Environmental Reviews*, **24** (2), 151–163, doi:10.1139/er-2015-0041.
- Kovacs, K.M. et al., 2012: Global threats to pinnipeds. *Marine Mammal Science*, **28** (2), 414–436, doi:10.1111/j.1748-7692.2011.00479.x.
- Kovacs, K.M., P. Lemons, J.G. MacCracken and C. Lydersen, 2016: *Walrus in a time of climate change*. Arctic Report Card: Update for 2015 [Available at: www.arctic.noaa.gov/Report-Card].
- Koven, C.D., 2013: Boreal carbon loss due to poleward shift in low-carbon ecosystems. *Nature Geoscience*, **6** (6), 452–456, doi:10.1038/ngeo1801.
- Koven, C.D., W.J. Riley and A. Stern, 2013: Analysis of Permafrost Thermal Dynamics and Response to Climate Change in the CMIP5 Earth System Models. *Journal of Climate*, **26** (6), 1877–1900, doi:10.1175/jcli-d-12-00228.1.
- Koven, C.D. et al., 2011: Permafrost carbon-climate feedbacks accelerate global warming. *Proceedings of the National Academy of Sciences USA*, **108** (36), 14769–14774, doi:10.1073/pnas.1103910108.
- Koven, C.D. et al., 2015: A simplified, data-constrained approach to estimate the permafrost carbon–climate feedback. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **373** (2054), 20140423, doi:10.1098/rsta.2014.0423.
- Kraska, J., 2011: *Arctic Security in an Age of Climate Change* [Kraska, J. (ed.)]. Cambridge University Press, Cambridge.
- Krasting, J.P., A.J. Broccoli, K.W. Dixon and J.R. Lanzante, 2013: Future Changes in Northern Hemisphere Snowfall. *Journal of Climate*, **26** (20), 7813–7828, doi:10.1175/jcli-d-12-00832.1.

- Krause-Jensen, D. et al., 2016: Long photoperiods sustain high pH in Arctic kelp forests. *Science Advances*, **2** (12), 8, doi:10.1126/sciadv.1501938.
- Kretschmer, M., D. Coumou, J.F. Donges and J. Runge, 2016: Using Causal Effect Networks to Analyze Different Arctic Drivers of Midlatitude Winter Circulation. *Journal of Climate*, **29** (11), 4069–4081, doi:10.1175/jcli-d-15-0654.1.
- Krishfield, R.A. et al., 2014: Deterioration of perennial sea ice in the Beaufort Gyre from 2003 to 2012 and its impact on the oceanic freshwater cycle. *Journal of Geophysical Research: Oceans*, **119** (2), 1271–1305, doi:10.1002/2013JC008999.
- Krüger, L. et al., 2018: Projected distributions of Southern Ocean albatrosses, petrels and fisheries as a consequence of climatic change. *Ecography*, **41** (1), 195–208, doi:10.1111/ecog.02590.
- Krumpen, T. et al., 2019: Arctic warming interrupts the Transpolar Drift and affects long-range transport of sea ice and ice-rafted matter. *Sci Rep*, **9** (1), 5459, doi:10.1038/s41598-019-41456-y.
- Krumpen, T. et al., 2016: Recent summer sea ice thickness surveys in Fram Strait and associated ice volume fluxes. *The Cryosphere*, **10** (2), 523–534, doi:10.5194/tc-10-523-2016.
- Kug, J.S. et al., 2015: Two distinct influences of Arctic warming on cold winters over North America and East Asia. *Nature Geoscience*, **8** (10), 759, doi:10.1038/ngeo2517.
- Kullerud, L. et al., 2013: The Arctic Ocean and UNCLOS Article 76: Are There Any Commons? In: *Environmental Security in the Arctic Ocean*, Dordrecht, [Berkman, P. and A. Vylegzhanin (eds.)], Springer Netherlands, 185–194.
- Kumpula, J., M. Kurkilahti, T. Helle and A. Colpaert, 2014: Both reindeer management and several other land use factors explain the reduction in ground lichens (*Cladonia* spp.) in pastures grazed by semi-domesticated reindeer in Finland. *Regional Environmental Change*, **14** (2), 541–559, doi:10.1007/s10113-013-0508-5.
- Kurtz, N.T. and S.L. Farrell, 2011: Large-scale surveys of snow depth on Arctic sea ice from Operation IceBridge. *Geophysical Research Letters*, **38** (20), L20505, doi:10.1029/2011gl049216.
- Kusahara, K. et al., 2018: An ocean-sea ice model study of the unprecedented Antarctic sea ice minimum in 2016. *Environmental Research Letters*, **13** (8), 084020, doi:10.1088/1748-9326/aad624.
- Kusahara, K. et al., 2017: Roles of wind stress and thermodynamic forcing in recent trends in Antarctic sea ice and Southern Ocean SST: An ocean-sea ice model study. *Global and Planetary Change*, **158**, 103–118, doi:10.1016/j.gloplacha.2017.09.012.
- Kutz, S. et al., 2015: Erysipelothrix rhusiopathiae associated with recent widespread muskox mortalities in the Canadian Arctic. *Can Vet J*, **56** (6), 560–563.
- Kutz, S.J. et al., 2013: Invasion, establishment, and range expansion of two parasitic nematodes in the Canadian Arctic. *Glob Chang Biol*, **19** (11), 3254–62, doi:10.1111/gcb.12315.
- Kutz, S.J. et al., 2014: A walk on the tundra: Host-parasite interactions in an extreme environment. *Int J Parasitol Parasites Wildl*, **3** (2), 198–208, doi:10.1016/j.ijppaw.2014.01.002.
- Kvile, K.O. et al., 2018: Pushing the limit: Resilience of an Arctic copepod to environmental fluctuations. *Glob Chang Biol*, **24** (11), 5426–5439, doi:10.1111/gcb.14419.
- Kwiatkowski, L. and J.C. Orr, 2018: Diverging seasonal extremes for ocean acidification during the twenty-first century. *Nature Climate Change*, **8** (2), 141–145, doi:10.1038/s41558-017-0054-0.
- Kwok, R., 2018: Arctic sea ice thickness, volume, and multiyear ice coverage: losses and coupled variability (1958–2018). *Environmental Research Letters*, **13** (10), 105005, doi:10.1088/1748-9326/aae3ec.
- Kwok, R. and T. Maksym, 2014: Snow depth of the Weddell and Bellingshausen sea ice covers from IceBridge surveys in 2010 and 2011: An examination. *Journal of Geophysical Research: Oceans*, **119** (7), 4141–4167, doi:10.1002/2014jc009943.
- Kwok, R., G. Spreen and S. Pang, 2013: Arctic sea ice circulation and drift speed: Decadal trends and ocean currents. *Journal of Geophysical Research: Oceans*, **118** (5), 2408–2425, doi:10.1002/jgrc.20191.
- Kylling, A., C.D. Groot Zwaafink and A. Stohl, 2018: Mineral Dust Instantaneous Radiative Forcing in the Arctic. *Geophysical Research Letters*, **45** (9), 4290–4298, doi:10.1029/2018gl077346.
- Laaksonen, S. et al., 2017: Filarioid nematodes, threat to arctic food safety and security. In: Food safety and security [Paulsen, P., A. Bauer and F.J.M. Smulders (eds.)]. Wageningen Academic Publishers, 101–120.
- Labrecque, S. et al., 2009: Contemporary (1951–2001) evolution of lakes in the Old Crow Basin, Northern Yukon, Canada: Remote Sensing, numerical modeling, and stable isotope analysis. *Arctic*, **62**, 225–238, doi:10.14430/arctic13.
- Laidler, G., 2012: Societal Aspects of Changing Cold Environments. In: Changing Cold Environments: A Canadian Perspective [French, H. and O. Slaymaker (eds.)]. Wiley-Blackwell, Oxford, 267–300.
- Laidler, G.J., 2006: Inuit and Scientific Perspectives on the Relationship Between Sea Ice and Climate Change: The Ideal Complement? *Climatic Change*, **78** (2), 407, doi:10.1007/s10584-006-9064-z.
- Laidler, G.J. et al., 2010: *Mapping Sea-Ice Knowledge, Use, and Change in Nunavut, Canada (Cape Dorset, Igloolik, Pangnirtung)*. SIKU: Knowing Our Ice, Documenting Inuit Sea-Ice Knowledge and Use, Springer, Dordrecht.
- Lairde, K.L. et al., 2018: Range contraction and increasing isolation of a polar bear subpopulation in an era of sea-ice loss. *Ecology and Evolution*, **8** (4), 2062–2075, doi:10.1002/ece3.3809.
- Lairde, K.L. et al., 2016: Use of glacial fronts by narwhals (*Monodon monoceros*) in West Greenland. *Biol Lett*, **12** (10), doi:10.1098/rsbl.2016.0457.
- Lairde, K.L. et al., 2015: Arctic marine mammal population status, sea ice habitat loss, and conservation recommendations for the 21st century. *Conservation Biology*, **29** (3), 724–737, doi:10.1111/cobi.12474.
- Lainé, A., H. Nakamura, K. Nishii and T. Miyasaka, 2014: A diagnostic study of future evaporation changes projected in CMIP5 climate models. *Climate Dynamics*, **42** (9), 2745–2761, doi:10.1007/s00382-014-2087-7.
- Lalande, C. et al., 2014: Variability in under-ice export fluxes of biogenic matter in the Arctic Ocean. *Global Biogeochemical Cycles*, **28** (5), 571–583, doi:10.1002/2013GB004735.
- Lam, V.W.Y., W.W.L. Cheung and U.R. Sumaila, 2016: Marine capture fisheries in the Arctic: winners or losers under climate change and ocean acidification? *Fish and Fisheries*, **17** (2), 335–357, doi:10.1111/faf.12106.
- Lamers, M.A.J., E. Eijgelaar and B. Amelung, 2013: Last chance tourism in Antarctica Cruising for change? In: Last chance tourism: Adapting tourism opportunities in a changing world [Lemelin, R.H., J. Dawson and E.J. Stewart (eds.)]. Routledge, London, 24–41.
- Lammers, R.B., J.W. Pundsack and A.I. Shiklomanov, 2007: Variability in river temperature, discharge, and energy flux from the Russian pan-Arctic landmass. *Journal of Geophysical Research: Biogeosciences*, **112** (G4), G04S59, doi:10.1029/2006jg000370.
- Landa, C.S. et al., 2014: Recruitment, distribution boundary and habitat temperature of an arcto-boreal gadoid in a climatically changing environment: a case study on Northeast Arctic haddock (*Melanogrammus aeglefinus*). *Fisheries Oceanography*, **23** (6), 506–520, doi:10.1111/fog.12085.
- Landrum, L.L., M.M. Holland, M.N. Raphael and L.M. Polvani, 2017: Stratospheric Ozone Depletion: An Unlikely Driver of the Regional Trends in Antarctic Sea Ice in Austral Fall in the Late Twentieth Century. *Geophysical Research Letters*, **44** (21), 11062–11070, doi:10.1002/2017gl075618.
- Landschützer, P., N. Gruber, D.C.E. Bakker and U. Schuster, 2014: Recent variability of the global ocean carbon sink. *Global Biogeochemical Cycles*, **28** (9), 927–949, doi:10.1002/2014GB004853.
- Landschützer, P. et al., 2018: Strengthening seasonal marine CO₂ variations due to increasing atmospheric CO₂. *Nature Climate Change*, **8** (2), 146–150, doi:10.1038/s41558-017-0057-x.

- Landschützer, P. et al., 2015: The reinvigoration of the Southern Ocean carbon sink. *Science*, **349** (6253), 1221–1224, doi:10.1126/science.aab2620
- Lange, B.A. et al., 2017: Pan-Arctic sea ice-algal chl a biomass and suitable habitat are largely underestimated for multiyear ice. *Glob Chang Biol*, **23** (11), 4581–4597, doi:10.1111/gcb.13742.
- Langlais, C.E. et al., 2017: Stationary Rossby waves dominate subduction of anthropogenic carbon in the Southern Ocean. *Sci Rep*, **7** (1), 17076, doi:10.1038/s41598-017-17292-3.
- Lantuit, H. and W. Pollard, 2008: Fifty years of coastal erosion and retrogressive thaw slump activity on Herschel Island, southern Beaufort Sea, Yukon Territory, Canada. *Geomorphology*, **95** (1–2), 84–102, doi:10.1016/j.geomorph.2006.07.040.
- Lantz, T.C. and K.W. Turner, 2015: Changes in lake area in response to thermokarst processes and climate in Old Crow Flats, Yukon. *Journal of Geophysical Research: Biogeosciences*, **120** (3), 513–524, doi:10.1002/2014jg002744.
- Lara, M.J. et al., 2018: Reduced arctic tundra productivity linked with landform and climate change interactions. *Sci Rep*, **8** (1), 2345, doi:10.1038/s41598-018-20692-8.
- Larsen, J.N. et al., 2014: Polar regions. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change* [Barros, V.R., C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1567–1612.
- LaRue, M.A. et al., 2013: Climate change winners: receding ice fields facilitate colony expansion and altered dynamics in an Adelie penguin metapopulation. *Plos One*, **8** (4), e60568, doi:10.1371/journal.pone.0060568.
- Laske, S.M. et al., 2016: Surface water connectivity drives richness and composition of Arctic lake fish assemblages. *Freshwater Biology*, **61** (7), 1090–1104, doi:10.1111/fwb.12769.
- Lasserre, F. and S. Pelletier, 2011: Polar super seaways? Maritime transport in the Arctic: an analysis of shipowners' intentions. *Journal of Transport Geography*, **19** (6), 1465–1473, doi:10.1016/j.jtrangeo.2011.08.006.
- Lasserre, F. and P.-L. Têtu, 2015: The cruise tourism industry in the Canadian Arctic: analysis of activities and perceptions of cruise ship operators. *Polar Record*, **51** (1), 24–38, doi:10.1017/s0032247413000508.
- Laurel, B.J., L.A. Copeman, M. Spencer and P. Iseri, 2017: Temperature-dependent growth as a function of size and age in juvenile Arctic cod (*Boreogadus saida*). *ICES Journal of Marine Science*, **74** (6), 1614–1621, doi:10.1093/icesjms/fsx028.
- Lavrillier, A., 2013: Climate change among nomadic and settled Tungus of Siberia: continuity and changes in economic and ritual relationships with the natural environment. *Polar Record*, **49** (3), 260–271, doi:10.1017/s0032247413000284.
- Lavrillier, A. and S. Gabyshev, 2017: *An Arctic Indigenous Knowledge System of Landscape, Climate, and Human Interactions. Evenki Reindeer Herders and Hunters*. Fürstenberg/Havel: Verlag der Kulturstiftung Sibirien SEC Publications, Published online by Cambridge University Press, 467 pp.
- Lavrillier, A. and S. Gabyshev, 2018: An emic science of climate. Reindeer Evenki environmental knowledge and the notion of an "extreme process", *Études mongoles et sibériennes, centrasiatiques et tibétaines*. 49.
- Lavrillier, A., S. Gabyshev and M. Rojo, 2016: The Sable for Evenki Reindeer Herders in Southeastern Siberia: Interplaying Drivers of Changes on Biodiversity and Ecosystem Services. In: *Indigenous and Local Knowledge of Biodiversity and Ecosystems Services in Europe and Central Asia: Contributions to an IPBES regional assessment* [Roué, M. and Z. Molnar (eds.)]. UNESCO, Paris, 111–128.
- Lawrence, D.M. et al., 2015: Permafrost thaw and resulting soil moisture changes regulate projected high-latitude CO₂ and CH₄ emissions. *Environmental Research Letters*, **10** (9), 094011.
- Lawrence, D.M. et al., 2011: The CCSM4 Land Simulation, 1850–2005: Assessment of Surface Climate and New Capabilities. *Journal of Climate*, **25** (7), 2240–2260, doi:10.1175/jcli-d-11-00103.1.
- Laxon, S.W. et al., 2013: CryoSat-2 estimates of Arctic sea ice thickness and volume. *Geophysical Research Letters*, **40** (4), 732–737, doi:10.1002/grl.50193.
- Le Brocq, A.M., 2013: Evidence from ice shelves for channelizing meltwater flow beneath the Antarctic ice sheet. *Nat. Geosci.*, **6**, 945–948, doi:10.1038/ngeo1977.
- Le Moigne, F.A.C. et al., 2015: Carbon export efficiency and phytoplankton community composition in the Atlantic sector of the Arctic Ocean. *Journal of Geophysical Research: Oceans*, **120** (6), 3896–3912, doi:10.1002/2015JC010700.
- Le Quéré, C. et al., 2018: Global Carbon Budget 2018. *Earth System Science Data*, **10** (4), 2141–2194, doi:10.5194/essd-10-2141-2018.
- Le Quéré, C. et al., 2007: Saturation of the Southern Ocean CO₂ Sink Due to Recent Climate Change. *Science*, **316** (5832), 1735–1738, doi:10.1126/science.1136188
- Lecavalier, B.S. et al., 2017: High Arctic Holocene temperature record from the Agassiz ice cap and Greenland ice sheet evolution. *Proc Natl Acad Sci U S A*, **114** (23), 5952–5957, doi:10.1073/pnas.1616287114.
- Lee, J.R. et al., 2017a: Climate change drives expansion of Antarctic ice-free habitat. *Nature*, **547** (7661), 49, doi:10.1038/nature22996.
- Lee, S. et al., 2017b: Evidence of minimal carbon sequestration in the productive Amundsen Sea polynya. *Geophysical Research Letters*, **44** (15), 7892–7899, doi:10.1002/2017gl074646.
- Leibman, M. et al., 2011: Sulfur and carbon isotopes within atmospheric, surface and ground water, snow and ice as indicators of the origin of tabular ground ice in the Russian Arctic. *Permafrost and Periglacial Processes*, **22** (1), 39–48, doi:10.1002/ppp.716.
- Lemelin, H. et al., 2010: Last-chance tourism: the boom, doom, and gloom of visiting vanishing destinations. *Current Issues in Tourism*, **13** (5), 477–493, doi:10.1080/13683500903406367.
- Leppi, J.C., C.D. Arp and M.S. Whitman, 2016: Predicting Late Winter Dissolved Oxygen Levels in Arctic Lakes Using Morphology and Landscape Metrics. *Environmental Management*, **57** (2), 463–473, doi:10.1007/s00267-015-0622-x.
- Lesnikowski, A.C. et al., 2011: Adapting to health impacts of climate change: a study of UNFCCC Annex I parties. *Environmental Research Letters*, **6** (4), 044009, doi:10.1088/1748-9326/6/4/044009.
- Leung, S., A. Cabré and I. Marinov, 2015: A latitudinally banded phytoplankton response to 21st century climate change in the Southern Ocean across the CMIP5 model suite. *Biogeosciences*, **12** (19), 5715–5734, doi:10.5194/bg-12-5715-2015.
- Lewis, A. and R.C. Prince, 2018: Integrating Dispersants in Oil Spill Response in Arctic and Other Icy Environments. *Environ Sci Technol*, **52** (11), 6098–6112, doi:10.1021/acs.est.7b06463.
- Li, C., D. Notz, S. Tietsche and J. Marotzke, 2013: The Transient versus the Equilibrium Response of Sea Ice to Global Warming. *Journal of Climate*, **26** (15), 5624–5636, doi:10.1175/jcli-d-12-00492.1.
- Li, F. et al., 2016a: Impacts of Interactive Stratospheric Chemistry on Antarctic and Southern Ocean Climate Change in the Goddard Earth Observing System, Version 5 (GEOS-5). *Journal of Climate*, **29** (9), 3199–3218, doi:10.1175/jcli-d-15-0572.1.
- Li, X., D.M. Holland, E.P. Gerber and C. Yoo, 2014: Impacts of the north and tropical Atlantic Ocean on the Antarctic Peninsula and sea ice. *Nature*, **505**, 538, doi:10.1038/nature12945.
- Li, X., D.M. Holland, E.P. Gerber and C. Yoo, 2015a: Rossby Waves Mediate Impacts of Tropical Oceans on West Antarctic Atmospheric Circulation

- in Austral Winter. *Journal of Climate*, **28** (20), 8151–8164, doi:10.1175/jcli-d-15-0113.1.
- Li, X. et al., 2015b: Grounding line retreat of Totten Glacier, East Antarctica, 1996 to 2013. *Geophysical Research Letters*, **42** (19), 8049–8056, doi:10.1002/2015GL065701.
- Li, Y. et al., 2016b: Evaluating biases in simulated land surface albedo from CMIP5 global climate models. *Journal of Geophysical Research: Atmospheres*, **121** (11), 6178–6190, doi:10.1002/2016jd024774.
- Liggett, D., B. Frame, N. Gilbert and F. Morgan, 2017: Is it all going south? Four future scenarios for Antarctica. *Polar Record*, **53** (5), 459–478, doi:10.1017/S0032247417000390.
- Liljedahl, A.K. et al., 2016: Pan-Arctic ice-wedge degradation in warming permafrost and its influence on tundra hydrology. *Nature Geoscience*, **9** (4), 312–318, doi:10.1038/ngeo2674.
- Lilly, M.R., 2017: *Alaskan North Slope Oil & Gas Transportation Support*. United States [Available at: www.osti.gov/scitech/servlets/purl/1350972].
- Lin, G. et al., 2014: Radiative forcing of organic aerosol in the atmosphere and on snow: Effects of SOA and brown carbon. *Journal of Geophysical Research: Atmospheres*, **119** (12), 7453–7476, doi:10.1002/2013jd021186.
- Lind, S., R.B. Ingvaldsen and T. Furevik, 2018: Arctic warming hotspot in the northern Barents Sea linked to declining sea-ice import. *Nature Climate Change*, **8** (7), 634–639, doi:10.1038/s41558-018-0205-y.
- Lindgren, A., G. Hugelius and P. Kuhry, 2018: Extensive loss of past permafrost carbon but a net accumulation into present-day soils. *Nature*, **560** (7717), 219–222, doi:10.1038/s41586-018-0371-0.
- Lindsay, R. and A. Schweiger, 2015: Arctic sea ice thickness loss determined using subsurface, aircraft, and satellite observations. *The Cryosphere*, **9** (1), 269–283, doi:10.5194/tc-9-269-2015.
- Lindsay, R., M. Wensnahan, A. Schweiger and J. Zhang, 2014: Evaluation of Seven Different Atmospheric Reanalysis Products in the Arctic. *Journal of Climate*, **27** (7), 2588–2606, doi:10.1175/jcli-d-13-00014.1.
- Lindstad, H., R.M. Bright and A.H. Strømman, 2016: Economic savings linked to future Arctic shipping trade are at odds with climate change mitigation. *Transport Policy*, **45**, 24–30, doi:10.1016/j.tranpol.2015.09.002.
- Link, H., D. Piepenburg and P. Archambault, 2013: Are Hotspots Always Hotspots? The Relationship between Diversity, Resource and Ecosystem Functions in the Arctic. *Plos One*, **8** (9), e74077, doi:10.1371/journal.pone.0074077.
- Lipenkov, V., A.A. Ekaykin, E.V. Polyakova and D. Raynaud, 2016: Characterization of subglacial Lake Vostok as seen from physical and isotope properties of accreted ice. *Phil. Trans. R. Soc. A*, **374** (2059), 20140303, doi:10.1098/rsta.2014.0303.
- Lique, C. et al., 2016: Modeling the Arctic freshwater system and its integration in the global system: Lessons learned and future challenges. *Journal of Geophysical Research: Biogeosciences*, **121** (3), 540–566, doi:10.1002/2015jg003120.
- Lischka, S. and U. Riebesell, 2016: Metabolic response of Arctic pteropods to ocean acidification and warming during the polar night/twilight phase in Kongsfjord (Spitsbergen). *Polar Biology*, **40** (6), 1211–1227, doi:10.1007/s00300-016-2044-5.
- Liston, G. and C. Hiemstra, 2011: The changing cryosphere: pan-Arctic snow trends (1979–2009). *Journal of Climate*, **24**, 5691–5712, doi:10.1175/jcli-d-11-00081.1.
- Liu, B., D. Yang, B. Ye and S. Berezovskaya, 2005: Long-term open-water season stream temperature variations and changes over Lena River Basin in Siberia. *Global and Planetary Change*, **48** (1), 96–111, doi:10.1016/j.gloplacha.2004.12.007.
- Liu, J., M. Song, R.M. Horton and Y. Hu, 2013: Reducing spread in climate model projections of a September ice-free Arctic. *Proceedings of the National Academy of Sciences*, **110** (31), 12571–12576, doi:10.1073/pnas.1219716110.
- Liu, J., M. Song, M.H. Radley and Y. Hu, 2015a: Revisiting the potential of melt pond fraction as a predictor for the seasonal Arctic sea ice extent minimum. *Environmental Research Letters*, **10** (5), 054017, doi:10.1088/1748-9326/10/5/054017/meta.
- Liu, Y., H. Gupta, E. Springer and T. Wagener, 2008: Linking science with environmental decision making: Experiences from an integrated modeling approach to supporting sustainable water resources management. *Environmental Modelling & Software*, **23** (7), 846–858, doi:10.1016/j.envsoft.2007.10.007.
- Liu, Y. et al., 2015b: Evapotranspiration in Northern Eurasia: Impact of forcing uncertainties on terrestrial ecosystem model estimates. *Journal of Geophysical Research: Atmospheres*, **120** (7), 2647–2660, doi:10.1002/2014jd022531.
- Liu, Y. et al., 2014: Response of evapotranspiration and water availability to the changing climate in Northern Eurasia. *Climatic Change*, **126** (3), 413–427, doi:10.1007/s10584-014-1234-9.
- Loboda, T.V., 2014: Adaptation strategies to climate change in the Arctic: a global patchwork of reactive community-scale initiatives. *Environmental Research Letters*, **9** (11), 111006, doi:10.1088/1748-9326/9/11/111006.
- Loeb, V.J. and J.A. Santora, 2015: Climate variability and spatiotemporal dynamics of five Southern Ocean krill species. *Progress in Oceanography*, **134**, 93–122, doi:10.1016/j.pocean.2015.01.002.
- Logerwell, E., K. Rand, S. Danielson and L. Sousa, 2018: Environmental drivers of benthic fish distribution in and around Barrow Canyon in the northeastern Chukchi Sea and western Beaufort Sea. *Deep Sea Research Part II: Topical Studies in Oceanography*, **152**, 170–181, doi:10.1016/j.dsr2.2017.04.012.
- Loisel, J. et al., 2014: A database and synthesis of northern peatland soil properties and Holocene carbon and nitrogen accumulation. *The Holocene*, **24** (9), 1028–1042, doi:10.1177/0959683614538073.
- Lone, K. et al., 2018: Aquatic behaviour of polar bears (*Ursus maritimus*) in an increasingly ice-free Arctic. *Scientific Reports*, **8** (1), 9677, doi:10.1038/s41598-018-27947-4.
- Long, W.C., P. Pruisner, K.M. Swiney and R. Foy, 2019: Effects of ocean acidification on the respiration and feeding of juvenile red and blue king crabs. *ICES Journal of Marine Science*, **76** (5), 1335–1343, doi:https://doi.org/10.1093/icesjms/fsz090.
- Long, W.C., S.B. Van Sant and J.A. Haaga, 2015: Habitat, predation, growth, and coexistence: Could interactions between juvenile red and blue king crabs limit blue king crab productivity? *Journal of Experimental Marine Biology and Ecology*, **464**, 58–67, doi:10.1016/j.jembe.2014.12.011.
- Long, W.C. et al., 2017: Survival, growth, and morphology of blue king crabs: effect of ocean acidification decreases with exposure time. *ICES Journal of Marine Science*, **74** (4), 1033–1041, doi:10.1093/icesjms/fsw197.
- Lorant, M.M. et al., 2014: Vegetation controls on northern high latitude snow-albedo feedback: observations and CMIP5 model simulations. *Global Change Biology*, **20** (2), 594–606, doi:10.1111/gcb.12391.
- Lorentzen, G. et al., 2018: Current Status of the Red King Crab (*Paralithodes camtschaticus*) and Snow Crab (*Chionoecetes opilio*) Industries in Norway. *Reviews in Fisheries Science & Aquaculture*, **26** (1), 42–54, doi:10.1080/23308249.2017.1335284.
- Loring, P., S. Gerlach and H. Harrison, 2013: Seafood as Local Food: Food Security and Locally Caught Seafood on Alaska's Kenai Peninsula. *Journal of Agriculture, Food Systems, and Community Development*, **3** (3), 13–30, doi:10.5304/jafscd.2013.033.006.
- Loring, P.A., S.C. Gerlach and H.J. Penn, 2016: "Community Work" in a Climate of Adaptation: Responding to Change in Rural Alaska. *Human Ecology*, **44** (1), 119–128, doi:10.1007/s10745-015-9800-y.
- Lowther, A.D., A. Fisk, K.M. Kovacs and C. Lydersen, 2017: Interdecadal changes in the marine food web along the west Spitsbergen coast detected in the stable isotope composition of ringed seal (*Pusa hispida*) whiskers. *Polar Biology*, **40** (10), 2027–2033, doi:10.1007/s00300-017-2122-3.
- Luckman, A. et al., 2015: Calving rates at tidewater glaciers vary strongly with ocean temperature. *Nature Communications*, **6**, 8566, doi:10.1038/ncomms9566.

- Luckman, A. et al., 2014: Surface melt and ponding on Larsen C Ice Shelf and the impact of föhn winds. *Antarctic Science*, **26** (06), 625–635, doi:10.1017/S0954102014000339.
- Ludescher, J., N. Yuan and A. Bunde, 2018: Detecting the statistical significance of the trends in the Antarctic sea ice extent: an indication for a turning point. *Climate Dynamics*, **53** (1–2), 237–244, doi:10.1007/s00382-018-4579-3.
- Lund, M. et al., 2010: Variability in exchange of CO₂ across 12 northern peatland and tundra sites. *Global Change Biology*, **16** (9), 2436–2448, doi:10.1111/j.1365-2486.2009.02104.x.
- Lunn, N.J. et al., 2016: Demography of an apex predator at the edge of its range: impacts of changing sea ice on polar bears in Hudson Bay. *Ecological Applications*, **26** (5), 1302–1320, doi:10.1890/15-1256.
- Lydersen, C. et al., 2014: The importance of tidewater glaciers for marine mammals and seabirds in Svalbard, Norway. *Journal of Marine Systems*, **129**, 452–471, doi:10.1016/j.jmarsys.2013.09.006.
- Lydersen, C. et al., 2017: Novel terrestrial haul-out behaviour by ringed seals (*Pusa hispida*) in Svalbard, in association with harbour seals (*Phoca vitulina*). *Polar Research*, **36** (1), 1374124, doi:10.1080/17518369.2017.1374124.
- Lynch, H.J., R. Naveen and P. Casanovas, 2013: Antarctic Site Inventory breeding bird survey data, 1994–2013. *Ecology*, **94** (11), 2653–2653.
- Lynghamar, A. et al., 2013: Species richness and distribution of chondrichthyan fishes in the Arctic Ocean and adjacent seas. *Biodiversity*, **14** (1), 57–66, doi:10.1080/14888386.2012.706198.
- Lyver, P.O. et al., 2014: Trends in the Breeding Population of Adelie Penguins in the Ross Sea, 1981–2012: A Coincidence of Climate and Resource Extraction Effects. *Plos One*, **9** (3), 10, doi:10.1371/journal.pone.0091188.
- Macayeal, D.R. and O.V. Sergienko, 2013: The flexural dynamics of melting ice shelves. *Annals of Glaciology*, **54** (63), 1–10, doi:10.3189/2013AoG63A256.
- MacDonald, M.K. et al., 2018: Impacts of 1.5 and 2.0°C Warming on Pan-Arctic River Discharge Into the Hudson Bay Complex Through 2070. *Geophysical Research Letters*, **45** (15), 7561–7570, doi:10.1029/2018gl079147.
- MacDougall, A.H., C.A. Avis and A.J. Weaver, 2012: Significant contribution to climate warming from the permafrost carbon feedback. *Nature Geoscience*, **5** (10), 719–721, doi:10.1038/ngeo1573.
- MacDougall, A.H. and R. Knutti, 2016: Projecting the release of carbon from permafrost soils using a perturbed parameter ensemble modelling approach. *Biogeosciences*, **13** (7), 2123–2136, doi:10.5194/bg-13-2123-2016.
- MacGilchrist, G.A. et al., 2014: The Arctic Ocean carbon sink. *Deep-Sea Research Part I-Oceanographic Research Papers*, **86**, 39–55, doi:10.1016/j.dsr.2014.01.002.
- Macias-Fauria, M., S. Karlens and B. Forbes, 2017: Disentangling the coupling between sea ice and tundra productivity in Svalbard. *Scientific Reports*, **7** (1), 8586, doi:10.1038/s41598-017-06218-8.
- Mack, M.C. et al., 2011: Carbon loss from an unprecedented Arctic tundra wildfire. *Nature*, **475** (7357), 489–492, doi:10.1038/nature10283.
- Mahlstein, I. and R. Knutti, 2012: September Arctic sea ice predicted to disappear near 2°C global warming above present. *Journal of Geophysical Research: Atmospheres*, **117** (D6), D06104, doi:10.1029/2011jd016709.
- Mahoney, A.R., H. Eicken, A.G. Gaylord and R. Gens, 2014: Landfast sea ice extent in the Chukchi and Beaufort Seas: The annual cycle and decadal variability. *Cold Regions Science and Technology*, **103** (Supplement C), 41–56, doi:10.1016/j.coldregions.2014.03.003.
- Mäkelä, A., U. Witte and P. Archambault, 2017: Ice algae versus phytoplankton: resource utilization by Arctic deep sea macroinfauna revealed through isotope labelling experiments. *Marine Ecology Progressive Series*, **572**, 1–18, doi:10.3354/meps12157.
- Makki, M., 2012: Evaluating arctic dialogue: A case study of stakeholder relations for sustainable oil and gas development. *Journal of Sustainable Development*, **5** (3), 34–45, doi:10.5539/jsd.v5n3p34.
- Maksym, T. and T. Markus, 2008: Antarctic sea ice thickness and snow-to-ice conversion from atmospheric reanalysis and passive microwave snow depth. *Journal of Geophysical Research: Oceans*, **113** (C2), C02S12, doi:10.1029/2006jc004085.
- Malinauskaite, L. et al., 2019: Ecosystem services in the Arctic: a thematic review. *Ecosystem Services*, **36**, 100898, doi:10.1016/j.ecoser.2019.100898.
- Mallory, C.D. and M.S. Boyce, 2017: Observed and predicted effects of climate change on Arctic caribou and reindeer. *Environmental Reviews*, **26** (1), 13–25, doi:10.1139/er-2017-0032.
- Malpress, V. et al., 2017: Bio-physical characterisation of polynyas as a key foraging habitat for juvenile male southern elephant seals (*Mirounga leonina*) in Prydz Bay, East Antarctica. *Plos One*, **12** (9), e0184536, doi:10.1371/journal.pone.0184536.
- Mann, D.H., T. Scott Rupp, M.A. Olson and P.A. Duffy, 2012: Is Alaska's Boreal Forest Now Crossing a Major Ecological Threshold? *Arctic, Antarctic, and Alpine Research*, **44** (3), 319–331, doi:10.1657/1938-4246-44.3.319.
- Mann, M.E. et al., 2017: Influence of Anthropogenic Climate Change on Planetary Wave Resonance and Extreme Weather Events. *Scientific Reports*, **7** (1), 45242, doi:10.1038/srep45242.
- Manno, C. et al., 2017: Shelled pteropods in peril: Assessing vulnerability in a high CO₂ ocean. *Earth-Science Reviews*, **169**, 132–145, doi:10.1016/j.earscirev.2017.04.005.
- Manno, C., V.L. Peck and G.A. Tarling, 2016: Pteropod eggs released at high pCO₂ lack resilience to ocean acidification. *Sci Rep*, **6**, 25752, doi:10.1038/srep25752.
- Marelle, L. et al., 2016: Air quality and radiative impacts of Arctic shipping emissions in the summertime in northern Norway: from the local to the regional scale. *Atmospheric Chemistry and Physics*, **16** (4), 2359–2379, doi:10.5194/acp-16-2359-2016.
- Marino, E., 2012: The long history of environmental migration: Assessing vulnerability construction and obstacles to successful relocation in Shishmaref, Alaska. *Global Environmental Change*, **22** (2), 374–381, doi:10.1016/j.gloenvcha.2011.09.016.
- Marshall, G.J., 2004: Causes of exceptional atmospheric circulation changes in the Southern Hemisphere. *Geophysical Research Letters*, **31** (14), L1420, doi:10.1029/2004gl019952.
- Marshall, G.J., A. Orr, N.P.M. van Lipzig and J.C. King, 2006: The Impact of a Changing Southern Hemisphere Annular Mode on Antarctic Peninsula Summer Temperatures. *Journal of Climate*, **19** (20), 5388–5404, doi:10.1175/jcli3844.1.
- Marshall, G.J., D.W.J. Thompson and M.R. Van den Broeke, 2017: The signature of Southern Hemisphere atmospheric circulation patterns in Antarctic precipitation. *Geophysical Research Letters*, **44** (22), 11580–11589, doi:10.1002/2017GL075998.
- Martin-Español, A., J.L. Bamber and A. Zammit-Mangion, 2017: Constraining the mass balance of East Antarctica. *Geophysical Research Letters*, **44** (9), 4168–4175, doi:10.1002/2017GL072937.
- Martin-Español, A. et al., 2016: Spatial and temporal Antarctic Ice Sheet mass trends, glacio-isostatic adjustment, and surface processes from a joint inversion of satellite altimeter, gravity, and GPS data. *Journal of Geophysical Research: Earth Surface*, **121** (2), 182–200, doi:10.1002/2015JF003550.
- Martin, A. et al., 2017: Shrub growth and expansion in the Arctic tundra: an assessment of controlling factors using an evidence-based approach. *Environmental Research Letters*, **12** (8), 085007, doi:10.1088/1748-9326/aa7989.
- Masina, S. et al., 2019: Weather, environmental conditions, and waterborne Giardia and Cryptosporidium in Iqaluit, Nunavut. *J Water Health*, **17** (1), 84–97, doi:10.2166/wh.2018.323.
- Massom, R.A. et al., 2001: Snow on Antarctic sea ice. *Reviews of Geophysics*, **39** (3), 413–445, doi:10.1029/2000rg000085.
- Masson-Delmotte, V. et al., 2012: Greenland climate change: from the past to the future. *Wiley Interdisciplinary Reviews: Climate Change*, **3** (5), 427–449, doi:10.1002/wcc.186.
- Massonnet, F. et al., 2012: Constraining projections of summer Arctic sea ice. *The Cryosphere*, **6** (6), 1383–1394, doi:10.5194/tc-6-1383-2012.

- Massonnet, F. et al., 2013: A model reconstruction of the Antarctic sea ice thickness and volume changes over 1980–2008 using data assimilation. *Ocean Modelling*, **64**, 67–75, doi:DOI 10.1016/j.ocemod.2013.01.003.
- Massonnet, F. et al., 2018: Arctic sea-ice change tied to its mean state through thermodynamic processes. *Nature Climate Change*, **8** (7), 599–603, doi:10.1038/s41558-018-0204-z.
- Matear, R.J., T.J. O’Kane, J.S. Risbey and M. Chamberlain, 2015: Sources of heterogeneous variability and trends in Antarctic sea-ice. *Nature Communications*, **6**, 8656, doi:10.1038/Ncomms9656.
- Mathis, J.T. et al., 2015: Ocean acidification risk assessment for Alaska’s fishery sector. *Progress in Oceanography*, **136**, 71–91, doi:10.1016/j.pocean.2014.07.001.
- Matthews, T. and R. Potts, 2018: Planning for climigration: a framework for effective action. *Climatic Change*, **148** (4), 607–621, doi:10.1007/s10584-018-2205-3.
- McCall, A.G., N.W. Piffold, A.E. Derocher and N.J. Lunn, 2016: Seasonal habitat selection by adult female polar bears in western Hudson Bay. *Population Ecology*, **58** (3), 407–419, doi:10.1007/s10144-016-0549-y.
- McCarthy, A.H., L.S. Peck, K.A. Hughes and D.C. Aldridge, 2019: Antarctica: The final frontier for marine biological invasions. *Glob Chang Biol*, **25** (7), 2221–2241, doi:10.1111/gcb.14600.
- McCave, I.N. et al., 2013: Minimal change in Antarctic Circumpolar Current flow speed between the last glacial and Holocene. *Nature Geoscience*, **7**, 113, doi:10.1038/ngeo2037.
- McClelland, G.T.W. et al., 2017: Climate change leads to increasing population density and impacts of a key island invader. *Ecological Applications*, **28** (1), 212–224, doi:10.1002/eap.1642.
- McCormack, S.A. et al., 2017: Simplification of complex ecological networks – species aggregation in Antarctic food web models. In: *MODSIM2017, 22nd International Congress on Modelling and Simulation*, [Syme, G., D. Hatton MacDonald, E. Fulton and J. Piantadosi (eds.)], Modelling and Simulation Society of Australia and New Zealand, 264–270.
- McFarland, J.J., M.S. Wipfli and M.S. Whitman, 2017: Trophic pathways supporting Arctic grayling in a small stream on the Arctic Coastal Plain, Alaska. *Ecology of Freshwater Fish*, **27** (1), 184–197, doi:10.1111/eff.12336.
- McGillicuddy, D.J. et al., 2015: Iron supply and demand in an Antarctic shelf ecosystem. *Geophysical Research Letters*, **42** (19), 8088–8097, doi:10.1002/2015gl065727.
- McGrath, D. et al., 2013: Recent warming at Summit, Greenland: Global context and implications. *Geophysical Research Letters*, **40** (10), 2091–2096, doi:10.1002/grl.50456.
- McGuire, A.D. et al., 2012: An assessment of the carbon balance of Arctic tundra: comparisons among observations, process models, and atmospheric inversions. *Biogeosciences*, **9** (8), 3185–3204, doi:10.5194/bg-9-3185-2012.
- McGuire, A.D. et al., 2016: Variability in the sensitivity among model simulations of permafrost and carbon dynamics in the permafrost region between 1960 and 2009. *Global Biogeochemical Cycles*, **30** (7), 1015–1037, doi:10.1002/2016gb005405.
- McGuire, A.D. et al., 2018: Dependence of the evolution of carbon dynamics in the northern permafrost region on the trajectory of climate change. *Proc Natl Acad Sci U S A*, **115** (15), 3882–3887, doi:10.1073/pnas.1719903115.
- McKenna, C.M. et al., 2018: Arctic Sea Ice Loss in Different Regions Leads to Contrasting Northern Hemisphere Impacts. *Geophysical Research Letters*, **45** (2), 945–954, doi:10.1002/2017gl076433.
- McLaughlin, J.B. et al., 2005: Outbreak of *Vibrio parahaemolyticus* Gastroenteritis Associated with Alaskan Oysters. *New England Journal of Medicine*, **353** (14), 1463–1470, doi:10.1056/NEJMoa051594.
- McLeod, E., R. Salm, A. Green and J. Almany, 2009: Designing marine protected area networks to address the impacts of climate change. *Frontiers in Ecology and the Environment*, **7** (7), 362–370, doi:10.1890/070211.
- McLeod, J.T. and T.L. Mote, 2016: Linking interannual variability in extreme Greenland blocking episodes to the recent increase in summer melting across the Greenland ice sheet. *International Journal of Climatology*, **36** (3), 1484–1499, doi:10.1002/joc.4440.
- McMillan, M. et al., 2014a: Rapid dynamic activation of a marine-based Arctic ice cap. *Geophysical Research Letters*, **41** (24), 8902–8909, doi:10.1002/2014GL062255.
- McMillan, M. et al., 2014b: Increased ice losses from Antarctica detected by CryoSat-2. *Geophysical Research Letters*, **41** (11), 3899–3905, doi:10.1002/2014gl060111.
- McMinn, A., 2017: Reviews and syntheses: Ice acidification, the effects of ocean acidification on sea ice microbial communities. *Biogeosciences*, **14** (17), 3927–3935, doi:10.5194/bg-14-3927-2017.
- McNeil, B.I. and R.J. Matear, 2013: The non-steady state oceanic CO₂ signal: its importance, magnitude and a novel way to detect it. *Biogeosciences*, **10** (4), 2219–2228, doi:10.5194/bg-10-2219-2013.
- McNeil, B.I. and T.P. Sasse, 2016: Future ocean hypercapnia driven by anthropogenic amplification of the natural CO₂ cycle. *Nature*, **529** (7586), 383–6, doi:10.1038/nature16156.
- Meadow, A.M. et al., 2015: Moving toward the Deliberate Coproduction of Climate Science Knowledge. *Weather, Climate, and Society*, **7** (2), 179–191, doi:10.1175/WCAS-D-14-00050.1.
- Medley, B. and E.R. Thomas, 2018: Increased snowfall over the Antarctic Ice Sheet mitigated twentieth-century sea-level rise. *Nature Climate Change*, **9** (1), 34–39, doi:10.1038/s41558-018-0356-x.
- Meehl, G.A. et al., 2016: Antarctic sea-ice expansion between 2000 and 2014 driven by tropical Pacific decadal climate variability. *Nature Geoscience*, **9** (8), 590–595, doi:10.1038/Ngeo2751.
- Meehl, G.A. et al., 2019: Sustained ocean changes contributed to sudden Antarctic sea ice retreat in late 2016. *Nat Commun*, **10** (1), 14, doi:10.1038/s41467-018-07865-9.
- Meehl, G.A. et al., 2018: Tropical Decadal Variability and the Rate of Arctic Sea Ice Decrease. *Geophysical Research Letters*, **45** (20), 11,326–11,333, doi:10.1029/2018gl079989.
- Meijers, A. et al., 2016: Wind-driven export of Weddell Sea slope water. *Journal of Geophysical Research: Oceans*, **121** (10), 7530–7546, doi:10.1002/2016JC011757.
- Meijers, A.J.S. et al., 2019: The role of ocean dynamics in king penguin range estimation. *Nature Climate Change*, **9** (2), 120–121, doi:10.1038/s41558-018-0388-2.
- Meijers, A.J.S. et al., 2012: Representation of the Antarctic Circumpolar Current in the CMIP5 climate models and future changes under warming scenarios. *Journal of Geophysical Research: Oceans*, **117** (C12), 19 pp, doi:10.1029/2012JC008412.
- Meire, L. et al., 2016a: High export of dissolved silica from the Greenland Ice Sheet. *Geophysical Research Letters*, **43** (17), 9173–9182, doi:10.1002/2016GL070191.
- Meire, L. et al., 2017: Marine-terminating glaciers sustain high productivity in Greenland fjords. *Glob Chang Biol*, **23** (12), 5344–5357, doi:10.1111/gcb.13801.
- Meire, L. et al., 2016b: Spring bloom dynamics in a subarctic fjord influenced by tidewater outlet glaciers (Godthabsfjord, SW Greenland). *Journal of Geophysical Research-Biogeosciences*, **121** (6), 1581–1592, doi:10.1002/2015jg003240.
- Mekonnen, A., J.A. Renwick and A. Sánchez-Lugo, 2016: Regional climates [in “State of the Climate in 2015”]. *Bulletin of the American Meteorological Society*, **97** (8), S173–S226.
- Melbourne-Thomas, J. et al., 2016: Under ice habitats for Antarctic krill larvae: Could less mean more under climate warming? *Geophysical Research Letters*, **43** (19), 10,322–10,327, doi:10.1002/2016gl070846.
- Melia, N., K. Haines and E. Hawkins, 2016: Sea ice decline and 21st century trans-Arctic shipping routes. *Geophysical Research Letters*, **43** (18), 9720–9728, doi:10.1002/2016gl069315.

- Melvin, A.M. et al., 2017: Climate change damages to Alaska public infrastructure and the economics of proactive adaptation. *Proceedings of the National Academy of Sciences*, **114** (2), E122, doi:10.1073/pnas.1611056113.
- Mémin, A. et al., 2015: Interannual variation of the Antarctic Ice Sheet from a combined analysis of satellite gravimetry and altimetry data. *Earth and Planetary Science Letters*, **422**, 150–156, doi:10.1016/j.epsl.2015.03.045.
- Meneghello, G. et al., 2018: The Ice-Ocean Governor: Ice-Ocean Stress Feedback Limits Beaufort Gyre Spin-Up. *Geophysical Research Letters*, **45** (20), 11,293–11,299, doi:10.1029/2018gl080171.
- Meneghello, G., J. Marshall, S.T. Cole and M.-L. Timmermans, 2017: Observational Inferences of Lateral Eddy Diffusivity in the Halocline of the Beaufort Gyre. *Geophysical Research Letters*, **44** (24), 12,331–12,338, doi:10.1002/2017gl075126.
- Menezes, V.V., A.M. Macdonald and C. Schatzman, 2017: Accelerated freshening of Antarctic Bottom Water over the last decade in the Southern Indian Ocean. *Science Advances*, **3** (1), e1601426, doi:10.1126/sciadv.1601426.
- Mengerink, K., D. Roche and G. Swanson, 2017: Understanding Arctic Co-Management: The U.S. Marine Mammal Approach. *The Yearbook of Polar Law Online*, **8** (1), 76–102, doi:10.1163/22116427_008010007.
- Meredith, M.P. et al., 2013: The vision for a Southern Ocean Observing System. *Current Opinion in Environmental Sustainability*, **5** (3–4), 306–313, doi:10.1016/j.cosust.2013.03.002.
- Merino, N. et al., 2018: Impact of increasing antarctic glacial freshwater release on regional sea-ice cover in the Southern Ocean. *Ocean Modelling*, **121**, 76–89, doi:10.1016/j.ocemod.2017.11.009.
- Merkouriadi, I. et al., 2017: Critical Role of Snow on Sea Ice Growth in the Atlantic Sector of the Arctic Ocean. *Geophysical Research Letters*, **44** (20), 10,479–10,485, doi:10.1002/2017gl075494.
- Mernild, S.H. et al., 2015: Greenland precipitation trends in a long-term instrumental climate context (1890–2012): Evaluation of coastal and ice core records. *International Journal of Climatology*, **35** (2), 303–320, doi:10.1002/joc.3986.
- Mernild, S.H., T.L. Mote and G.E. Liston, 2017: Greenland ice sheet surface melt extent and trends: 1960–2010. *Journal of Glaciology*, **57** (204), 621–628, doi:10.3189/002214311797409712.
- Messori, G., R. Caballero and M. Gaetani, 2016: On cold spells in North America and storminess in western Europe. *Geophysical Research Letters*, **43** (12), 6620–6628, doi:10.1002/2016gl069392.
- Meyer, B. et al., 2017: The winter pack-ice zone provides a sheltered but food-poor habitat for larval Antarctic krill. *Nat Ecol Evol*, **1** (12), 1853–1861, doi:10.1038/s41559-017-0368-3.
- Miège, C. et al., 2016: Spatial extent and temporal variability of Greenland firn aquifers detected by ground and airborne radars. *Journal of Geophysical Research: Earth Surface*, **121** (12), 2381–2398, doi:10.1002/2016JF003869.
- Milaković, A.-S. et al., 2018: Current status and future operational models for transit shipping along the Northern Sea Route. *Marine Policy*, **94**, 53–60, doi:10.1016/j.marpol.2018.04.027.
- Miles, V.V., M.W. Miles and O.M. Johannessen, 2016: Satellite archives reveal abrupt changes in behavior of Helheim Glacier, southeast Greenland. *Journal of Glaciology*, **62** (231), 137–146, doi:10.1017/jog.2016.24.
- Millan, R., J. Mougnot and E. Rignot, 2017: Mass budget of the glaciers and ice caps of the Queen Elizabeth Islands, Canada, from 1991 to 2015. *Environmental Research Letters*, **12** (2), 024016.
- Miller, C.A. and C. Wyborn, 2018: Co-production in global sustainability: Histories and theories. *Environmental Science & Policy*, doi:10.1016/j.envsci.2018.01.016.
- Milner, A.M. et al., 2017: Glacier shrinkage driving global changes in downstream systems. *Proceedings of the National Academy of Sciences*, **114** (37), 9770–9778.
- Minchew, B.M. et al., 2018: Modeling the dynamic response of outlet glaciers to observed ice-shelf thinning in the Bellingshausen Sea Sector, West Antarctica. *Journal of Glaciology*, **64** (244), 333–342, doi:10.1017/jog.2018.24.
- Mintzenbeck, K., 2017: Impacts of Climate Change on the Southern Ocean. In: *Climate Change Impacts on Fisheries and Aquaculture* [Phillips, B.F. and M. Pérez-Ramírez (eds.)]. John Wiley & Sons New Jersey, 663–701.
- Mintzenbeck, K. et al., 2012: Impact of Climate Change on Fishes in Complex Antarctic Ecosystems. *Advances in Ecological Research*, Vol 46: *Global Change in Multispecies Systems, Pt 1*, **46**, 351–426, doi:10.1016/B978-0-12-396992-7.00006-X.
- Mintzenbeck, K. and J.J. Torres, 2017: Impact of Climate Change on the Antarctic Silverfish and Its Consequences for the Antarctic Ecosystem. In: *The Antarctic Silverfish: a Keystone Species in a Changing Ecosystem* [Vacchi, M., E. Pisano and L. Ghigliotti (eds.)]. Springer Nature, New York, 253–286.
- Mioduszewski, J.R. et al., 2016: Atmospheric drivers of Greenland surface melt revealed by self-organizing maps. *Journal of Geophysical Research: Atmospheres*, **121** (10), 5095–5114, doi:10.1002/2015JD024550.
- Möller, M. and R. Möller, 2017: Modeling glacier-surface albedo across Svalbard for the 1979–2015 period: The HiRSvAC500- data set. *Journal of Advances in Modeling Earth Systems*, **9** (1), 404–422, doi:10.1002/2016MS000752.
- Mongwe, N.P., M. Vichi and P.M.S. Monteiro, 2018: The seasonal cycle of pCO₂ and CO₂ fluxes in the Southern Ocean: diagnosing anomalies in CMIP5 Earth system models. *Biogeosciences*, **15** (9), 2851–2872, doi:10.5194/bg-15-2851-2018.
- Monien, D. et al., 2017: Meltwater as a source of potentially bioavailable iron to Antarctica waters. *Antarctic Science*, **29** (3), 277–291, doi:10.1017/S095410201600064X.
- Moon, H.W., W.M.R.W. Hussin, H.C. Kim and I.Y. Ahn, 2015: The impacts of climate change on Antarctic nearshore mega-epifaunal benthic assemblages in a glacial fjord on King George Island: Responses and implications. *Ecological Indicators*, **57**, 280–292, doi:10.1016/j.ecolind.2015.04.031.
- Moon, T., I. Joughin, B. Smith and I. Howat, 2012: 21st-Century Evolution of Greenland Outlet Glacier Velocities. *Science*, **336** (6081), 576, doi:10.1126/science.1219985.
- Moore, S.E. and P.J. Stabeno, 2015: Synthesis of Arctic Research (SOAR) in marine ecosystems of the Pacific Arctic. *Progress in Oceanography*, **136**, 1–11, doi:10.1016/j.pocean.2015.05.017.
- Moore, S.E., P.J. Stabeno, J.M. Grebmeier and S.R. Okkonen, 2018: The Arctic Marine Pulses Model: linking annual oceanographic processes to contiguous ecological domains in the Pacific Arctic. *Deep Sea Research Part II: Topical Studies in Oceanography*, **152**, 8–21, doi:10.1016/j.dsr2.2016.10.011.
- Morgera, E. and K. Kulovesi, 2016: Research Handbook on International Law and Natural Resources. [Morgera, E. and K. Kulovesi (eds.)]. Research Handbooks in International Law, 349–365.
- Morlighem, M. et al., 2016: Modeling of Store Gletscher's calving dynamics, West Greenland, in response to ocean thermal forcing. *Geophysical Research Letters*, **43** (6), 2659–2666, doi:10.1002/2016gl067695.
- Morlighem, M. et al., 2017: BedMachine v3: Complete Bed Topography and Ocean Bathymetry Mapping of Greenland From Multibeam Echo Sounding Combined With Mass Conservation. *Geophysical Research Letters*, **44** (21), 11,051–11,061, doi:10.1002/2017GL074954.
- Morrison, A.K. and A. McC. Hogg, 2013: On the Relationship between Southern Ocean Overturning and ACC Transport. *Journal of Physical Oceanography*, **43** (1), 140–148, doi:10.1175/jpo-d-12-057.1.
- Morrison, A.L. et al., 2018: Isolating the Liquid Cloud Response to Recent Arctic Sea Ice Variability Using Spaceborne Lidar Observations. *Journal of Geophysical Research: Atmospheres*, **123** (1), 473–490, doi:10.1002/2017jd027248.
- Mortin, J. et al., 2016: Melt onset over Arctic sea ice controlled by atmospheric moisture transport. *Geophysical Research Letters*, **43** (12), 6636–6642, doi:10.1002/2016gl069330.
- Mougnot, J., E. Rignot and B. Scheuchl, 2014: Sustained increase in ice discharge from the Amundsen Sea Embayment, West Antarctica, from

- 1973 to 2013. *Geophysical Research Letters*, **41** (5), 1576–1584, doi:10.1002/2013gl059069.
- Mouginot, J. et al., 2015: Fast retreat of Zachariæ Isstrøm, northeast Greenland. *Science*, **350** (6266), 1357–1361, doi:10.1126/science.aac7111.
- Mudryk, L., P. Kushner, C. Derksen and C. Thackeray, 2017: Snow cover response to temperature in observational and climate model ensembles. *Geophysical Research Letters*, **44** (2), 919–926, doi:10.1002/2016GL071789.
- Mueller, I.A. et al., 2012: Exposure to critical thermal maxima increases oxidative stress in hearts of white- but not red-blooded Antarctic notothenioid fishes. *The Journal of Experimental Biology*, **215** (20), 3655, doi:10.1242/jeb.071811.
- Mueter, F.J., J. Weems, E.V. Farley and M.F. Sigler, 2017: Arctic Ecosystem Integrated Survey (Arctic Eis): Marine ecosystem dynamics in the rapidly changing Pacific Arctic Gateway. *Deep Sea Research Part II: Topical Studies in Oceanography*, **135** (Supplement C), 1–6, doi:10.1016/j.dsr2.2016.11.005.
- Mullan, D. et al., 2017: Climate change and the long-term viability of the World's busiest heavy haul ice road. *Theoretical and Applied Climatology*, **129** (3), 1089–1108, doi:10.1007/s00704-016-1830-x.
- Mullowney, D.R.J., E.G. Dawe, E.B. Colbourne and G.A. Rose, 2014: A review of factors contributing to the decline of Newfoundland and Labrador snow crab (*Chionoecetes opilio*). *Reviews in Fish Biology and Fisheries*, **24** (2), 639–657, doi:10.1007/s11160-014-9349-7.
- Mulvaney, R. et al., 2012: Recent Antarctic Peninsula warming relative to Holocene climate and ice-shelf history. *Nature*, **489** (7414), 141–4, doi:10.1038/nature11391.
- Munday, D.R., H.L. Johnson and D.P. Marshall, 2013: Eddy Saturation of Equilibrated Circumpolar Currents. *Journal of Physical Oceanography*, **43** (3), 507–532, doi:10.1175/JPO-D-12-095.1.
- Mundy, C.J., J.K. Ehn, D.G. Barber and C. Michel, 2007: Influence of snow cover and algae on the spectral dependence of transmitted irradiance through Arctic landfast first-year sea ice. *Journal of Geophysical Research: Oceans*, **112** (C3), C03007, doi:10.1029/2006jc003683.
- Munneke, P.K. et al., 2014: Explaining the presence of perennial liquid water bodies in the firm of the Greenland Ice Sheet. *Geophysical Research Letters*, **41** (2), 476–483, doi:10.1002/2013gl058389.
- Munro, D.R. et al., 2015: Recent evidence for a strengthening CO₂ sink in the Southern Ocean from carbonate system measurements in the Drake Passage (2002–2015). *Geophysical Research Letters*, **42** (18), 7623–7630, doi:10.1002/2015GL065194.
- Murphy, E.J., A. Clarke, N.J. Abram and J. Turner, 2014: Variability of sea-ice in the northern Weddell Sea during the 20th century. *Journal of Geophysical Research: Oceans*, **119** (7), 4549–4572, doi:10.1002/2013jc009511.
- Murphy, E.J. et al., 2013: Comparison of the structure and function of Southern Ocean regional ecosystems: The Antarctic Peninsula and South Georgia. *Journal of Marine Systems*, **109**, 22–42, doi:10.1016/j.jmarsys.2012.03.011.
- Murphy, E.J. et al., 2017: Restricted regions of enhanced growth of Antarctic krill in the circumpolar Southern Ocean. *Sci Rep*, **7** (1), 6963, doi:10.1038/s41598-017-07205-9.
- Murray, T. et al., 2015: Extensive retreat of Greenland tidewater glaciers, 2000–2010. *Arctic Antarctic and Alpine Research*, **47** (3), 427–447, doi:10.1657/Aaar0014-049.
- Muster, S. et al., 2017: PeRL: a circum-Arctic Permafrost Region Pond and Lake database. *Earth System Science Data*, **9** (1), 317–348, doi:10.5194/essd-9-317-2017.
- Myers-Smith, I. and D. Hik, 2013: Shrub canopies influence soil temperatures but not nutrient dynamics: An experimental test of tundra snow-shrub interactions. *Ecology and Evolution*, **3** (11), 3683–3700, doi:10.1002/ece3.710.
- Myers-Smith, I. and D. Hik, 2018: Climate warming as a driver of tundra shrubline advance. *Journal of Ecology*, **106** (2), 547–560, doi:10.1111/1365-2745.12817.
- Myers-Smith, I.H. et al., 2015: Climate sensitivity of shrub growth across the tundra biome. *Nature Clim. Change*, **5** (9), 887–891, doi:10.1038/nclimate2697.
- Myers-Smith, I.H. et al., 2019: Eighteen years of ecological monitoring reveals multiple lines of evidence for tundra vegetation change. *Ecological Monographs*, **89** (2), e01351, doi:10.1002/ecm.1351.
- Nahrgang, J. et al., 2014: Gender Specific Reproductive Strategies of an Arctic Key Species (*Boreogadus saida*) and Implications of Climate Change. *Plos One*, **9** (5), e98452, doi:10.1371/journal.pone.0098452.
- Najafi, M.R., F.W. Zwiers and N.P. Gillett, 2015: Attribution of Arctic temperature change to greenhouse-gas and aerosol influences. *Nature Climate Change*, **5** (3), 246–249, doi:10.1038/nclimate2524.
- Nakamura, T. et al., 2016: The stratospheric pathway for Arctic impacts on midlatitude climate. *Geophysical Research Letters*, **43** (7), 3494–3501, doi:10.1002/2016gl068330.
- National Research Council, 2014: *Linkages Between Arctic Warming and Mid-Latitude Weather Patterns: Summary of a Workshop*. The National Academies Press, Washington, DC, 85 pp.
- National Research Council, 2015: *Enhancing the Effectiveness of Team Science*. The National Academies Press, Washington, DC, 280 pp.
- Nauta, A.L. et al., 2014: Permafrost collapse after shrub removal shifts tundra ecosystem to a methane source. *Nature Climate Change*, **5**, 67, doi:10.1038/nclimate2446.
- Navarro, F.J., U.Y. Jonsell, M.I. Corcuera and A. Martín-Español, 2017: Decelerated mass loss of Hurd and Johnsons Glaciers, Livingston Island, Antarctic Peninsula. *Journal of Glaciology*, **59** (213), 115–128, doi:10.3189/2013JoG12J144.
- Neff, T., 2009: Connecting Science and Policy to Combat Climate Change. *Scientific American*; www.scientificamerican.com/article/connecting-science-and-pol.
- Nengye, L., A.K. Elizabeth and H. Tore, 2017: *The European Union and the Arctic*. Brill, Leiden, The Netherlands.
- Nghiem, S.V. et al., 2012: The extreme melt across the Greenland ice sheet in 2012. *Geophysical Research Letters*, **39** (20), 6–11, doi:10.1029/2012GL053611.
- Nicholls, K.W., L. Boehme, M. Biuw and M.A. Fedak, 2008: Wintertime ocean conditions over the southern Weddell Sea continental shelf, Antarctica. *Geophysical Research Letters*, **35** (21), L21605, doi:10.1029/2008gl035742.
- Nicol, S. and J. Foster, 2016: The Fishery for Antarctic Krill: Its Current Status and Management Regime. In: *Biology and Ecology of Antarctic Krill* [Siegel, V. (ed.)]. Springer, New York, 387–421.
- Nicolas, J.P. and D.H. Bromwich, 2014: New reconstruction of antarctic near-surface temperatures: Multidecadal trends and reliability of global reanalyses. *Journal of Climate*, **27** (21), 8070–8093, doi:10.1175/JCLI-D-13-00733.1.
- Nicolaus, M., C. Katlein, J. Maslanik and S. Hendricks, 2012: Changes in Arctic sea ice result in increasing light transmittance and absorption. *Geophysical Research Letters*, **39** (24), L24501, doi:10.1029/2012gl053738.
- Niederrenk, A.L. and D. Notz, 2018: Arctic Sea Ice in a 1.5°C Warmer World. *Geophysical Research Letters*, **45** (4), 1963–1971, doi:10.1002/2017gl076159.
- Nienow, P.W., A.J. Sole, D.A. Slater and T.R. Cowton, 2017: Recent Advances in Our Understanding of the Role of Meltwater in the Greenland Ice Sheet System. *Current Climate Change Reports*, **3** (4), 330–344, doi:10.1007/s40641-017-0083-9.
- Nihashi, S. and K.I. Ohshima, 2015: Circumpolar mapping of Antarctic coastal polynyas and landfast sea ice: relationship and variability. *Journal of Climate*, **28**, 3650–3670, doi:10.1175/JCLI-D-14-00369.1.
- Nilsson, A.E. et al., 2017: Towards extended shared socioeconomic pathways: A combined participatory bottom-up and top-down methodology with results from the Barents region. *Global Environmental Change-Human and Policy Dimensions*, **45**, 124–132, doi:10.1016/j.gloenvcha.2017.06.001.

- Nilsson, A.E. and M. Christensen, 2019: *Arctic Geopolitics, Media and Power*. Taylor & Francis Group, London.
- Nitze, I. et al., 2018: Remote sensing quantifies widespread abundance of permafrost region disturbances across the Arctic and Subarctic. *Nat Commun*, **9** (1), 5423, doi:10.1038/s41467-018-07663-3.
- Nitze, I. et al., 2017: Landsat-Based Trend Analysis of Lake Dynamics across Northern Permafrost Regions. *Remote Sensing*, **9** (7), 640, doi:10.3390/rs9070640.
- Noël, B. et al., 2017: A tipping point in refreezing accelerates mass loss of Greenland's glaciers and ice caps. *Nature Communications*, **8**, 14730, doi:10.1038/ncomms14730.
- Noël, B. et al., 2018: Six Decades of Glacial Mass Loss in the Canadian Arctic Archipelago. *Journal of Geophysical Research: Earth Surface*, **123** (6), 1430–1449, doi:10.1029/2017jf004304.
- Noetzli, J. et al., 2017: *Permafrost thermal state* [Blunden, J. and D.S. Arndt (eds.)]. State of the Climate in 2017, **99**, Bull. Amer. Meteor. Soc., Si–S332.
- Nøttestad, L. et al., 2016: Quantifying changes in abundance, biomass, and spatial distribution of Northeast Atlantic mackerel (*Scomber scombrus*) in the Nordic seas from 2007 to 2014. *ICES Journal of Marine Science*, **73** (2), 359–373, doi:10.1093/icesjms/fsv218.
- Notz, D., 2015: How well must climate models agree with observations? *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **373** (2052), 20140164, doi:10.1098/rsta.2014.0164.
- Notz, D. and J. Marotzke, 2012: Observations reveal external driver for Arctic sea-ice retreat. *Geophysical Research Letters*, **39** (8), L08502, doi:10.1029/2012gl01051094.
- Notz, D. and J. Stroeve, 2016: Observed Arctic sea-ice loss directly follows anthropogenic CO₂ emission. *Science*, **354** (6313), 747–750, doi:10.1126/science.aag2345.
- NPFMC, 2018: Draft Bering Sea Fishery Ecosystem Plan. North Pacific Fishery Management Council, 605 West 4th, Site 306, Anchorage, Alaska.
- NPFMC, 2019: Bering Sea Fishery Ecosystem Plan. North Pacific Fishery Management Council, 605 West 4th, Suite 306, Anchorage, Alaska 99501.
- Nummelin, A., M. Illicak, C. Li and L.H. Smedsrud, 2016: Consequences of future increased Arctic runoff on Arctic Ocean stratification, circulation, and sea ice cover. *Journal of Geophysical Research: Oceans*, **121** (1), 617–637, doi:10.1002/2015JC011156.
- Nummelin, A., C. Li and P.J. Hezel, 2017: Connecting ocean heat transport changes from the midlatitudes to the Arctic Ocean. *Geophysical Research Letters*, **44** (4), 1899–1908, doi:10.1002/2016GL071333.
- Nyman, L.J. and G. Fondahl, 2014: Major Findings and Emerging Trends in Arctic Human Development. In: Arctic Human Development Report: Regional Processes and Global Linkages [Nyman Larsen, J. and G. Fondahl (eds.)]. Nordic Council of Ministers, Copenhagen, 479–502.
- Nyström, M. and C. Folke, 2001: Spatial Resilience of Coral Reefs. *Ecosystems*, **4** (5), 406–417, doi:10.1007/s10021-001-0019-y.
- O'Leary, M. and P. Christoffersen, 2013: Calving on tidewater glaciers amplified by submarine frontal melting. *Cryosphere*, **7** (1), 119–128, doi:10.5194/tc-7-119-2013.
- Ó Cofaigh, C. et al., 2014: Reconstruction of ice-sheet changes in the Antarctic Peninsula since the Last Glacial Maximum. *Quaternary Science Reviews*, **100**, 87–110, doi:10.1016/j.quascirev.2014.06.023.
- Odland, J.O., S. Donaldson, A. Dudarev and A. Carlsen, 2016: AMAP assessment 2015: human health in the Arctic. *Int J Circumpolar Health*, **75**, 33949, doi:10.3402/ijch.v75.33949.
- Ohshima, K.I. et al., 2013: Antarctic Bottom Water production by intense sea-ice formation in the Cape Darnley polynya. *Nature Geoscience*, **6**, 235, doi:10.1038/ngeo1738.
- Øigård, T.A., T. Haug and K.T. Nilssen, 2014: Current status of hooded seals in the Greenland Sea. Victims of climate change and predation? *Biological Conservation*, **172**, 29–36, doi:10.1016/j.biocon.2014.02.007.
- Øigård, T.A. et al., 2013: Functional relationship between harp seal body condition and available prey in the Barents Sea. *Marine Ecology Progress Series*, **484**, 287–301, doi:10.3354/meps10272.
- Olafsdottir, A.H. et al., 2019: Geographical expansion of Northeast Atlantic mackerel (*Scomber scombrus*) in the Nordic Seas from 2007 to 2016 was primarily driven by stock size and constrained by low temperatures. *Deep Sea Research Part II: Topical Studies in Oceanography*, **159**, 152–168, doi:10.1016/j.dsr2.2018.05.023.
- Olason, E. and D. Notz, 2014: Drivers of variability in Arctic sea-ice drift speed. *Journal of Geophysical Research: Oceans*, **119** (9), 5755–5775, doi:10.1002/2014jc009897.
- Olefeldt, D. et al., 2016: Circumpolar distribution and carbon storage of thermokarst landscapes. *Nature Communications*, **7**, 13043, doi:10.1038/ncomms13043.
- Oliva, M. et al., 2017: Recent regional climate cooling on the Antarctic Peninsula and associated impacts on the cryosphere. *Sci Total Environ*, **580**, 210–223, doi:10.1016/j.scitotenv.2016.12.030.
- Olsen, J., N.A. Carter, J. Dawson and W. Coetzee, 2019: Community perspectives on the environmental impacts of Arctic shipping: Case studies from Russia, Norway and Canada. *Cogent Social Sciences*, **5** (1), 1609189, doi:10.1080/23311886.2019.1609189.
- Olsen, L.M. et al., 2017: The seeding of ice algal blooms in Arctic pack ice: The multiyear ice seed repository hypothesis. *Journal of Geophysical Research: Biogeosciences*, **122** (7), 1529–1548, doi:10.1002/2016jg003668.
- Onarheim, I.H. and M. Årthun, 2017: Toward an ice-free Barents Sea. *Geophysical Research Letters*, **44** (16), 8387–8395, doi:10.1002/2017GL074304.
- Onarheim, I.H., T. Eldevik, L.H. Smedsrud and J.C. Stroeve, 2018: Seasonal and regional manifestation of Arctic sea ice loss. *Journal of Climate*, **31** (12), 4917–4932, doi:10.1175/jcli-d-17-0427.1.
- Ono, K. et al., 2017: Management strategy analysis for multispecies fisheries including technical interactions and human behavior in modeling management decisions and fishing. *Canadian Journal of Fisheries and Aquatic Sciences*, **75** (8), 1185–1202, doi:10.1139/cjfas-2017-0135.
- Orr, J.C. et al., 2005: Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms. *Nature*, **437** (7059), 681–6, doi:10.1038/nature04095.
- Orsi, A.H. and C.L. Wiederwohl, 2009: A recount of Ross Sea waters. *Deep-Sea Research Part II-Topical Studies in Oceanography*, **56** (13–14), 778–795, doi:10.1016/j.dsr2.2008.10.033.
- Orsi, A.J. et al., 2017: The recent warming trend in North Greenland. *Geophysical Research Letters*, **44** (12), 6235–6243, doi:10.1002/2016gl072212.
- Osokin, N.I. and A.V. Sosnovsky, 2014: Spatial and temporal variability of depth and density of the snow cover in Russia. *Ice and Snow*, **4**, 72–80, doi:10.15356/2076-6734-2014-4-72-80.
- Ostapchuk, J. et al., 2015: Exploring Elders' and Seniors' Perceptions of How Climate Change is Impacting Health and Well-being in Rigolet, Nunatsiavut. *Journal of Aboriginal Health*, **9**, 6–24, doi:10.18357/ijh92201214358.
- Overland, J. et al., 2018a: The urgency of Arctic change. *Polar Science*, doi:10.1016/j.polar.2018.11.008.
- Overland, J. et al., 2017: *Synthesis: summary and implications of findings*. Snow, Water, Ice and Permafrost in the Arctic (SWIPA), Arctic Monitoring and Assessment Programme, Oslo, Norway, 269p.
- Overland, J.E., 2018: Sea ice Index. Boulder, Colorado USA. NASA National Snow and Ice Data Center Distributed Active Archive Center.
- Overland, J.E. et al., 2018b: *Surface air temperature*. [in Arctic Report Card 2018] [Available at: <https://arctic.noaa.gov/Report-Card/Report-Card-2018/ArtMID/7878/ArticleID/783/Surface-Air-Temperature>].
- Overland, J.E. and M.Y. Wang, 2013: When will the summer Arctic be nearly sea ice free? *Geophysical Research Letters*, **40** (10), 2097–2101, doi:10.1002/grl.50316.
- Overland, J.E. and M.Y. Wang, 2016: Recent Extreme Arctic Temperatures are due to a Split Polar Vortex. *Journal of Climate*, **29** (15), 5609–5616, doi:10.1175/jcli-d-16-0320.1.

- Overland, J.E. and M.Y. Wang, 2018a: Arctic-midlatitude weather linkages in North America. *Polar Science*, (16), 1–9, doi:10.1016/j.polar.2018.02.001.
- Overland, J.E. and M.Y. Wang, 2018b: Resolving Future Arctic/Midlatitude Weather Connections. *Earth's Future*, 6 (8), 1146–1152, doi:10.1029/2018ef000901.
- Paar, M. et al., 2016: Temporal shift in biomass and production of macrozoobenthos in the macroalgal belt at Hansneset, Kongsfjorden, after 15 years. *Polar Biology*, 39 (11), 2065–2076, doi:10.1007/s00300-015-1760-6.
- PAME, 2013: Large Marine Ecosystems (LMEs) of the Arctic area. Revision of the Arctic LME map. PAME Secretariat, Akureyri, Iceland.
- Panic, M. and J.D. Ford, 2013: A review of national-level adaptation planning with regards to the risks posed by climate change on infectious diseases in 14 OECD nations. *International Journal of Environmental Research and Public Health*, 10 (12), 7083–7109, doi:10.3390/ijerph10127083.
- Paolo, F.S., H.A. Fricker and L. Padman, 2015: Volume loss from Antarctic ice shelves is accelerating. *Science*, 348 (6232), 327–331, doi:10.1126/science.aaa0940.
- Paolo, F.S. et al., 2018: Response of Pacific-sector Antarctic ice shelves to the El Niño/Southern Oscillation. *Nature Geoscience*, 11 (2), 121–126, doi:10.1038/s41561-017-0033-0.
- Pardo, D., S. Jenouvrier, H. Weimerskirch and C. Barbraud, 2017: Effect of extreme sea surface temperature events on the demography of an age-structured albatross population. *Philos Trans R Soc Lond B Biol Sci*, 372 (1723), 1–10, doi:10.1098/rstb.2016.0143.
- Parizek, B.R. et al., 2019: Ice-cliff failure via retrogressive slumping. *Geology*, 47 (5), 449–452, doi:10.1130/g45880.1.
- Park, H., H. Yabuki and T. Ohata, 2012: Analysis of satellite and model datasets for variability and trends in Arctic snow extent and depth, 1948–2006. *Polar Science*, 6, 23–37, doi:10.1016/j.polar.2011.11.002.
- Park, H. et al., 2015: Quantification of Warming Climate-Induced Changes in Terrestrial Arctic River Ice Thickness and Phenology. *Journal of Climate*, 29 (5), 1733–1754, doi:10.1175/jcli-d-15-0569.1.
- Park, J. et al., 2017: Light availability rather than Fe controls the magnitude of massive phytoplankton bloom in the Amundsen Sea polynyas, Antarctica. *Limnology and Oceanography*, 62 (5), 2260–2276, doi:10.1002/lno.10565.
- Parker, M.L. et al., 2015: Assemblages of micronektonic fishes and invertebrates in a gradient of regional warming along the Western Antarctic Peninsula. *Journal of Marine Systems*, 152, 18–41, doi:10.1016/j.jmarsys.2015.07.005.
- Parkinson, A.J. and J. Berner, 2009: Climate change and impacts on human health in the Arctic: an international workshop on emerging threats and the response of Arctic communities to climate change. *International Journal of Circumpolar Health*, 68 (1), 84–91, doi:10.3402/ijch.v68i1.18295.
- Parkinson, A.J. et al., 2014: Climate change and infectious diseases in the Arctic: establishment of a circumpolar working group. *International Journal of Circumpolar Health*, 73 (1), 25163, doi:10.3402/ijch.v73.25163.
- Parlee, B. and C. Furgal, 2012: Well-being and environmental change in the arctic: a synthesis of selected research from Canada's International Polar Year program. *Climatic Change*, 115 (1), 13–34, doi:10.1007/s10584-012-0588-0.
- Pashkevich, A., J. Dawson and E.J. Stewart, 2015: Governance of expedition cruise ship tourism in the Arctic: A comparison of the Canadian and Russian Arctic. *Tourism in Marine Environments*, 10 (3/4), 225–240, doi:10.1016/j.ocecoaman.2013.12.005.
- Pastick, N.J. et al., 2017: Historical and projected trends in landscape drivers affecting carbon dynamics in Alaska. *Ecol Appl*, 27 (5), 1383–1402, doi:10.1002/eap.1538.
- Pastick, N.J. et al., 2019: Spatiotemporal remote sensing of ecosystem change and causation across Alaska. *Glob Chang Biol*, 25 (3), 1171–1189, doi:10.1111/gcb.14279.
- Patara, L. and C.W. Böning, 2014: Abyssal ocean warming around Antarctica strengthens the Atlantic overturning circulation. *Geophysical Research Letters*, 41 (11), 3972–3978, doi:10.1002/2014GL059923.
- Patara, L., C.W. Böning and A. Biastoch, 2016: Variability and trends in Southern Ocean eddy activity in 1/12 ocean model simulations. *Geophysical Research Letters*, 43 (9), 4517–4523, doi:10.1002/2016GL069026.
- Pattyn, F., 2010: Antarctic subglacial conditions inferred from a hybrid ice sheet/ice stream model. *Earth Planet. Sci. Lett.*, 295, 451–461, doi:10.1016/j.epsl.2010.04.025.
- Pattyn, F., 2018: The paradigm shift in Antarctic ice sheet modelling. *Nature Communications*, 9 (2728), 1–3, doi:10.1038/s41467-018-05003-z.
- Paul, S. et al., 2018: Empirical parametrization of Envisat freeboard retrieval of Arctic and Antarctic sea ice based on CryoSat-2: progress in the ESA Climate Change Initiative. *The Cryosphere*, 12 (7), 2437–2460, doi:10.5194/tc-12-2437-2018.
- Pauling, A.G., C.M. Bitz, I.J. Smith and P.J. Langhorne, 2016: The Response of the Southern Ocean and Antarctic Sea Ice to Freshwater from Ice Shelves in an Earth System Model. *Journal of Climate*, 29 (5), 1655–1672, doi:10.1175/jcli-d-15-0501.1.
- Pauling, A.G., I.J. Smith, P.J. Langhorne and C.M. Bitz, 2017: Time-dependent freshwater input from ice shelves: Impacts on Antarctic sea ice and the Southern Ocean in an Earth System Model. *Geophysical Research Letters*, 44 (20), 10454–10461, doi:10.1002/2017GL075017.
- Pearce, T., J. Ford, A.C. Willox and B. Smit, 2015: Inuit Traditional Ecological Knowledge (TEK), Subsistence Hunting and Adaptation to Climate Change in the Canadian Arctic. *Arctic*, 68 (2), 233–245, doi:10.14430/arctic4475.
- Pearce, T. et al., 2011: Advancing adaptation planning for climate change in the Inuvialuit Settlement Region (ISR): a review and critique. *Regional Environmental Change*, 11 (1), 1–17, doi:10.1007/s10113-010-0126-4.
- Pearce, T. et al., 2010: Inuit vulnerability and adaptive capacity to climate change in Ulukhaktok, Northwest Territories, Canada. *Polar Record*, 46 (2), 157–177, doi:10.1017/S0032247409008602.
- Pearson, R.G. et al., 2013: Shifts in Arctic vegetation and associated feedbacks under climate change. *Nature Climate Change*, 3 (7), 673–677, doi:10.1038/nclimate1858.
- Peck, M. and J.K. Pinnegar, 2018: Chapter 5: Climate change impacts, vulnerabilities and adaptations: North Atlantic and Atlantic Arctic marine fisheries. In: Impacts of climate change on fisheries and aquaculture: synthesis of current knowledge, adaptation and mitigation options. FAO Fisheries and Aquaculture Technical Paper No. 627. [Barange, M., T. Bahri, M.C.M. Beveridge, K.L. Cochrane, S. Funge-Smith and F. Poulain (eds.)], Rome.
- Peck, V.L. et al., 2018: Pteropods counter mechanical damage and dissolution through extensive shell repair. *Nature Communications*, 9 (1), 1–7, doi:10.1038/s41467-017-02692-w.
- Peck, V.L. et al., 2016: Outer organic layer and internal repair mechanism protects pteropod *Limacina helicina* from ocean acidification. *Deep Sea Research Part II: Topical Studies in Oceanography*, 127, 41–52, doi:10.1016/j.dsr2.2015.12.005.
- Pecl, G.T. et al., 2017: Biodiversity redistribution under climate change: Impacts on ecosystems and human well-being. *Science*, 355 (6332), eaai9214, doi:10.1126/science.aai9214
- Pellichero, V., J.-B. Sallée, C.C. Chapman and S.M. Downes, 2018: The southern ocean meridional overturning in the sea-ice sector is driven by freshwater fluxes. *Nature Communications*, 9 (1), 1789, doi:10.1038/s41467-018-04101-2.
- Pendakur, K., 2017: Northern Territories. In: Climate risks and adaptation practices for the Canadian transportation sector 2016 [Palko, K. and D.S. Lemmen (eds.)]. Government of Canada, Ottawa, 27–64.
- Penn, H.J.F., S.C. Gerlach and P.A. Loring, 2016: Seasons of Stress: Understanding the Dynamic Nature of People's Ability to Respond to Change and Surprise. *Weather, Climate, and Society*, 8 (4), 435–446, doi:10.1175/WCAS-D-15-0061.1.

- Perovich, D.K., 2016: Sea ice and sunlight. In: Sea Ice [Thomas, D.N. (ed.)]. Wiley Online Library, 110–137.
- Perovich, D.K. and C. Polashenski, 2012: Albedo evolution of seasonal Arctic sea ice. *Geophysical Research Letters*, **39** (8), L08501, doi:10.1029/2012gl051432.
- Perreault, N. et al., 2017: Remote sensing evaluation of High Arctic wetland depletion following permafrost disturbance by thermo-erosion gully processes. *Arctic Science*, **3** (2), 237–253, doi:10.1139/as-2016-0047.
- Pertierra, L.R., K.A. Hughes, G.C. Vega and M.A. Olalla-Tarraga, 2017: High Resolution Spatial Mapping of Human Footprint across Antarctica and Its Implications for the Strategic Conservation of Avifauna. *Plos One*, **12** (1), e0168280, doi:10.1371/journal.pone.0168280.
- Petrasek-MacDonald, J., J.D. Ford, A.C. Willox and N.A. Ross, 2013: A review of protective factors and causal mechanisms that enhance the mental health of Indigenous Circumpolar youth. *International Journal of Circumpolar Health*, **72** (1), 21775, doi:10.3402/ijch.v72i0.21775.
- Petrack, S. et al., 2017: Climate change, future Arctic Sea ice, and the competitiveness of European Arctic offshore oil and gas production on world markets. *AMBIO*, **46** (Suppl 3), 410–422, doi:10.1007/s13280-017-0957-z.
- Petrov, A.N. et al., 2016: Arctic sustainability research: toward a new agenda. *Polar Geography*, **39** (3), 165–178, doi:10.1080/1088937x.2016.1217095.
- PEW Charitable Trust, 2016: *The integrated arctic corridors framework: planning for responsible shipping in Canadian arctic waters*. [Available at: www.pewtrusts.org/en/research-and-analysis/reports/2016/04/the-integrated-arctic-corridors-framework].
- Phoenix, G.K. and J.W. Bjerke, 2016: Arctic browning: extreme events and trends reversing Arctic greening. *Global Change Biology*, **22** (9), 2960–2962, doi:10.1111/gcb.13261.
- Pilfold, N., W. et al., 2017: Migratory response of polar bears to sea ice loss: to swim or not to swim. *Ecography*, **40** (1), 189–199, doi:10.1111/ecog.02109.
- Pincus, R. and S.H. Ali, 2016: Have you been to 'The Arctic'? Frame theory and the role of media coverage in shaping Arctic discourse. *Polar Geography*, **39** (2), 83–97, doi:10.1080/1088937x.2016.1184722.
- Pincus, R. and J.G. Speth, 2015: Security in the Arctic
A Receding Wall. In: Diplomacy on Ice [Pincus, R. and S.H. Ali (eds.)]. Yale University Press, 161–168.
- Piñones, A. and A.V. Fedorov, 2016: Projected changes of Antarctic krill habitat by the end of the 21st century. *Geophysical Research Letters*, **43** (16), 8580–8589, doi:10.1002/2016gl069656.
- Pistone, K., I. Eisenman and V. Ramanathan, 2014: Observational determination of albedo decrease caused by vanishing Arctic sea ice. *Proceedings of the National Academy of Sciences*, **111** (9), 3322–3326.
- Pithan, F. and T. Mauritsen, 2014: Arctic amplification dominated by temperature feedbacks in contemporary climate models. *Nature Geoscience*, **7**, 181, doi:10.1038/ngeo2071.
- Pizzolato, L. et al., 2016: The influence of declining sea ice on shipping activity in the Canadian Arctic. *Geophysical Research Letters*, **43** (23), 12,146–12,154, doi:10.1002/2016gl071489.
- Pizzolato, L. et al., 2014: Changing sea ice conditions and marine transportation activity in Canadian Arctic waters between 1990 and 2012. *Climatic Change*, **123** (2), 161–173, doi:10.1007/s10584-013-1038-3.
- Planque, B. et al., 2019: A participatory scenario method to explore the future of marine social-ecological systems. *Fish and Fisheries*, **20** (3), 434–451, doi:10.1111/faf.12356.
- Poesch, M., S. et al., 2016: Climate Change Impacts on Freshwater Fishes: A Canadian Perspective. *Fisheries*, **41** (7), 385–391, doi:10.1080/03632415.2016.1180285.
- Poinar, K. et al., 2017: Drainage of Southeast Greenland Firn Aquifer Water through Crevasses to the Bed. *Frontiers in Earth Science*, **5**, 1–15, doi:10.3389/feart.2017.00005.
- Polashenski, C. et al., 2014: Observations of pronounced Greenland ice sheet firn warming and implications for runoff production. *Geophysical Research Letters*, **41** (12), 4238–4246, doi:10.1002/2014GL059806.
- Polishchuk, Y.M., N.A. Bryksina and V.Y. Polishchuk, 2015: Remote analysis of changes in the number of small thermokarst lakes and their distribution with respect to their sizes in the cryolithozone of Western Siberia, 2015. *Izvestiya, Atmospheric and Oceanic Physics*, **51** (9), 999–1006, doi:10.1134/s0001433815090145.
- Pollard, D., R.M. DeConto and R.B. Alley, 2015: Potential Antarctic Ice Sheet retreat driven by hydrofracturing and ice cliff failure. *Earth and Planetary Science Letters*, **412**, 112–121, doi:10.1016/j.epsl.2014.12.035.
- Polvani, L.M. and K.L. Smith, 2013: Can natural variability explain observed Antarctic sea ice trends? New modeling evidence from CMIP5. *Geophysical Research Letters*, **40** (12), 3195–3199, doi:10.1002/grl.50578.
- Polyak, L. et al., 2010: History of sea ice in the Arctic. *Quaternary Science Reviews*, **29** (15–16), 1757–1778, doi:10.1016/j.quascirev.2010.02.010.
- Polyakov, I.V. et al., 2017: Greater role for Atlantic inflows on sea-ice loss in the Eurasian Basin of the Arctic Ocean. *Science*, **356** (6335), 285–291, doi:10.1126/science.aai8204.
- Polyakov, I.V. et al., 2010: Arctic Ocean Warming Contributes to Reduced Polar Ice Cap. *Journal of Physical Oceanography*, **40** (12), 2743–2756, doi:10.1175/2010jpo4339.1.
- Poole, K.G., A. Gunn, B.R. Patterson and M. Dumond, 2010: Sea Ice and Migration of the Dolphin and Union Caribou Herd in the Canadian Arctic: An Uncertain Future. *Arctic*, **63** (4), 414–428, doi:10.14430/arctic3331.
- Pope, S., L. Copland and B. Alt, 2017: Recent changes in sea ice plugs along the northern Canadian Arctic Archipelago. In: Arctic Ice Shelves and Ice Islands [Copland, L. and D. Mueller (eds.)]. Springer Nature, Dordrecht, 317–342.
- Popov, S.V. and V.N. Masolov, 2007: Forty-seven new subglacial lakes in the 0–110°E sector of East Antarctica. *J. Glaciol.*, **53** (181), 289–297, doi:10.3189/172756507782202856.
- Popova, E.E. et al., 2014: Regional variability of acidification in the Arctic: a sea of contrasts. *Biogeosciences*, **11** (2), 293–308, doi:10.5194/bg-11-293-2014.
- Pörtner, H.-O. et al., 2014: *Ocean systems* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea and L.L. White (eds.)]. Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Press, C.U., Cambridge, United Kingdom and New York, NY, USA, 411–484.
- Portnov, A. et al., 2013: Offshore permafrost decay and massive seabed methane escape in water depths >20 m at the South Kara Sea shelf. *Geophysical Research Letters*, **40** (15), 3962–3967, doi:10.1002/grl.50735.
- Post, E. et al., 2013: Ecological Consequences of Sea-Ice Decline. *Science*, **341** (6145), 519–524, doi:10.1126/science.1235225.
- Poulter, B. et al., 2017: Global wetland contribution to 2000–2012 atmospheric methane growth rate dynamics. *Environmental Research Letters*, **12** (9), 094013, doi:10.1088/1748-9326/aa8391.
- Powlledge, F., 2012: Scientists, Policymakers, and a Climate of Uncertainty Can research gain a foothold in the politics of climate change? *Bioscience*, **62** (1), 8–13, doi:10.1525/bio.2012.62.1.3.
- Prior, T.L., 2013: Breaking the Wall of Monocentric Governance: Polycentricity in the Governance of Persistent Organic Pollutants in the Arctic. *The Yearbook of Polar Law Online*, **5** (1), 185–232, doi:10.1163/22116427-91000123.
- Pristupa, A.O., M. Lamers, M. Tysiachniouk and B. Amelung, 2018: Reindeer Herders Without Reindeer. The Challenges of Joint Knowledge Production on Kolguev Island in the Russian Arctic. *Society & Natural Resources*, **32** (3), 338–356, doi:10.1080/08941920.2018.1505012.
- Pritchard, H.D. et al., 2012: Antarctic ice-sheet loss driven by basal melting of ice shelves. *Nature*, **484** (7395), 502, doi:10.1038/nature10968.

- Proshutinsky, A. et al., 2015: Arctic circulation regimes. *Phil. Trans. R. Soc. A*, **373** (2052), 20140160, doi:10.1098/rsta.2014.0160.
- Provencher, J.F., A.J. Gaston, P.D. O'Hara and H.G. Gilchrist, 2012: Seabird diet indicates changing Arctic marine communities in eastern Canada. *Marine Ecology Progress Series*, **454**, 171–182, doi:10.3354/meps09299.
- Prowse, T. et al., 2011: Effects of Changes in Arctic Lake and River Ice. *AMBIO*, **40** (1), 63–74, doi:10.1007/s13280-011-0217-6.
- Prowse, T. et al., 2015: Arctic Freshwater Synthesis: Summary of key emerging issues. *Journal of Geophysical Research: Biogeosciences*, **120** (10), 1887–1893, doi:10.1002/2015JG003128.
- Prowse, T., R. Shrestha, B. Bonsal and Y. Dibike, 2010: Changing spring air-temperature gradients along large northern rivers: Implications for severity of river-ice floods. *Geophysical Research Letters*, **37** (19), L19706, doi:10.1029/2010gl044878.
- Pulsifer, P. et al., 2012: The role of data management in engaging communities in Arctic research: overview of the Exchange for Local Observations and Knowledge of the Arctic (ELOKA). *Polar Geography*, **35** (3–4), 271–290, doi:10.1080/1088937X.2012.708364.
- Punt, A.E. et al., 2016: Effects of long-term exposure to ocean acidification conditions on future southern Tanner crab (*Chionoecetes bairdi*) fisheries management. *ICES Journal of Marine Science: Journal du Conseil*, **73** (3), 849–864, doi:10.1093/icesjms/fsv205.
- Purich, A., W.J. Cai, M.H. England and T. Cowan, 2016a: Evidence for link between modelled trends in Antarctic sea ice and underestimated westerly wind changes. *Nature Communications*, **7**, 10409, doi:10.1038/ncomms10409.
- Purich, A. et al., 2016b: Tropical Pacific SST Drivers of Recent Antarctic Sea Ice Trends. *Journal of Climate*, **29** (24), 8931–8948, doi:10.1175/jcli-d-16-0440.1.
- Purich, A. et al., 2018: Impacts of Broad-Scale Surface Freshening of the Southern Ocean in a Coupled Climate Model. *Journal of Climate*, **31** (7), 2613–2632, doi:10.1175/jcli-d-17-0092.1.
- Purkey, S.G. and G.C. Johnson, 2012: Global Contraction of Antarctic Bottom Water between the 1980s and 2000s*. *Journal of Climate*, **25** (17), 5830–5844, doi:10.1175/jcli-d-11-00612.1.
- Purkey, S.G. and G.C. Johnson, 2013: Antarctic Bottom Water warming and freshening: Contributions to sea level rise, ocean freshwater budgets, and global heat gain. *Journal of Climate*, **26** (16), 6105–6122, doi:10.1175/JCLI-D-12-00834.1.
- Qi, D. et al., 2017: Increase in acidifying water in the western Arctic Ocean. *Nature Climate Change*, **7** (3), 195, doi:10.1038/nclimate3228.
- Qu, X. and A. Hall, 2014: On the persistent spread in snow-albedo feedback. *Climate Dynamics*, **42** (1), 69–81, doi:10.1007/s00382-013-1774-0.
- Quinlan, A.E. et al., 2016: Measuring and assessing resilience: Broadening understanding through multiple disciplinary perspectives. *Journal of Applied Ecology*, **53** (3), 677–687, doi:10.1111/1365-2664.12550.
- Rabe, B. et al., 2014: Arctic Ocean basin liquid freshwater storage trend 1992–2012. *Geophysical Research Letters*, **41** (3), 961–968, doi:10.1002/2013GL058121.
- Radosavljevic, B. et al., 2015: Erosion and Flooding – Threats to Coastal Infrastructure in the Arctic: A Case Study from Herschel Island, Yukon Territory, Canada. *Estuaries and Coasts*, **39** (4), 900–915, doi:10.1007/s12237-015-0046-0.
- Raiswell, R. et al., 2016: Potentially Bioavailable Iron Delivery by Iceberg hosted Sediments and Atmospheric Dust to the Polar Oceans. *Biogeosciences Discussions*, **13** (13), 3887–3900, doi:10.5194/bg-2016-20.
- Rampal, P., J. Weiss, C. Dubois and J.-M. Campin, 2011: IPCC climate models do not capture Arctic sea ice drift acceleration: Consequences in terms of projected sea ice thinning and decline. *Journal of Geophysical Research: Oceans*, **116** (C8), C00D07, doi:10.1029/2011JC007110.
- Rampal, P., J. Weiss and D. Marsan, 2009: Positive trend in the mean speed and deformation rate of Arctic sea ice, 1979–2007. *Journal of Geophysical Research: Oceans*, **114** (C5), C05013, doi:10.1029/2008jc005066.
- Randelhoff, A. and J.D. Guthrie, 2016: Regional patterns in current and future export production in the central Arctic Ocean quantified from nitrate fluxes. *Geophysical Research Letters*, **43** (16), 8600–8608, doi:10.1002/2016GL070252.
- Randerson, J.T. et al., 2012: Global burned area and biomass burning emissions from small fires. *Journal of Geophysical Research: Biogeosciences*, **117** (G4), G04012, doi:10.1029/2012JG002128.
- Raphael, M.N., W. Hobbs and I. Wainer, 2011: The effect of Antarctic sea ice on the Southern Hemisphere atmosphere during the southern summer. *Climate Dynamics*, **36** (7–8), 1403–1417, doi:10.1007/s00382-010-0892-1.
- Raphael, M.N. et al., 2016: The Amundsen Sea Low Variability, Change, and Impact on Antarctic Climate. *Bulletin of the American Meteorological Society*, **97** (1), 111–121, doi:10.1175/bams-d-14-00018.1.
- Rathmann, N.M. et al., 2017: Highly temporally resolved response to seasonal surface melt of the Zachariae and 79N outlet glaciers in northeast Greenland. *Geophysical Research Letters*, **44** (19), 9805–9814, doi:10.1002/2017gl074368.
- Rautio, A., B. Poppel and K. Young, 2014: Human Health and Well-Being. In: Arctic Human Development Report [Nymand Larson, J. and G. Fondahl (eds.)]. Nordic Council of Ministers, Copenhagen, 299–348.
- Rawlins, M.A. et al., 2010: Analysis of the Arctic System for Freshwater Cycle Intensification: Observations and Expectations. *Journal of Climate*, **23** (21), 5715–5737, doi:10.1175/2010jcli3421.1.
- Raymond, B. et al., 2014: Important marine habitat off east Antarctica revealed by two decades of multi-species predator tracking. *Ecography*, **38** (2), 121–129, doi:10.1111/ecog.01021.
- Rayner, N.A., 2003: Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. *Journal of Geophysical Research*, **108** (D14), 4407, doi:10.1029/2002jd002670.
- Raynolds, M.K. et al., 2014: Cumulative geocological effects of 62 years of infrastructure and climate change in ice-rich permafrost landscapes, Prudhoe Bay Oilfield, Alaska. *Global Change Biology*, **20** (4), 1211–1224, doi:10.1111/gcb.12500.
- Reese, R., G.H. Gudmundsson, A. Levermann and R. Winkelmann, 2018: The far reach of ice-shelf thinning in Antarctica. *Nature Climate Change*, **8** (1), 53–57, doi:10.1038/s41558-017-0020-x.
- Regan, H.C., C. Lique and T.W.K. Armitage, 2019: The Beaufort Gyre Extent, Shape, and Location Between 2003 and 2014 From Satellite Observations. *Journal of Geophysical Research: Oceans*, **124** (2), 844–862, doi:10.1029/2018jc014379.
- Régnière, J., J. Powell, B. Bentz and V. Nealis, 2012: Effects of temperature on development, survival and reproduction of insects: Experimental design, data analysis and modeling. *Journal of Insect Physiology*, **58** (5), 634–647, doi:10.1016/j.jinsphys.2012.01.010.
- Reid, K., J. Croxall, D. Briggs and E. Murphy, 2005: Antarctic ecosystem monitoring: quantifying the response of ecosystem indicators to variability in Antarctic krill. *ICES Journal of Marine Science*, **62** (3), 366–373, doi:10.1016/j.icesjms.2004.11.003.
- Reintges, A., T. Martin, M. Latif and N.S. Keenlyside, 2017: Uncertainty in twenty-first century projections of the Atlantic Meridional Overturning Circulation in CMIP3 and CMIP5 models. *Climate Dynamics*, **49** (5–6), 1495–1511, doi:10.1007/s00382-016-3180-x.
- Reist, J., 2018: Fisheries. In: Marine Fisheries of Arctic Canada [Coad, B.W. and J. Reist (eds.)]. Canadian Museum of Nature and University of Toronto Press, Toronto, 618p.
- Reist, J.D., C.D. Sawatzky and L. Johnson, 2016: The Arctic 'Great' Lakes of Canada and their fish faunas – An overview in the context of Arctic change. *Journal of Great Lakes Research*, **42** (2), 173–192, doi:10.1016/j.jglr.2015.10.008.
- Renaud, P.E. et al., 2018: Pelagic food-webs in a changing Arctic: a trait-based perspective suggests a mode of resilience. *ICES Journal of Marine Science*, **75** (6), 1871–1881, doi:10.1093/icesjms/fsy063.

- Renaud, P.E. et al., 2015: The future of Arctic benthos: Expansion, invasion, and biodiversity. *Progress in Oceanography*, **139**, 244–257, doi:10.1016/j.pcean.2015.07.007.
- Renner, A.H.H. et al., 2014: Evidence of Arctic sea ice thinning from direct observations. *Geophysical Research Letters*, **41** (14), 5029–5036, doi:10.1002/2014gl060369.
- Renner, M. et al., 2016: Timing of ice retreat alters seabird abundances and distributions in the southeast Bering Sea. *Biology Letters*, **12** (9), 20160276, doi:10.1098/rsbl.2016.0276.
- Retter, G.-B. et al., 2004: *Community-based Monitoring Discussion paper*. Supporting publication to the CAFF Circumpolar Biodiversity Monitoring Program – Framework Document, CAFF CBMP Report No. 9, CAFF International Secretariat, Council, A., Akureyri, Iceland, 21 pp [Available at: <https://oaarchive.arctic-council.org/handle/11374/178>].
- Rey, D.M. et al., 2019: Investigating lake-area dynamics across a permafrost-thaw spectrum using airborne electromagnetic surveys and remote sensing time-series data in Yukon Flats, Alaska. *Environmental Research Letters*, **14** (2), 025001, doi:10.1088/1748-9326/aaf06f.
- Reynolds, R.W. et al., 2002: An Improved In Situ and Satellite SST Analysis for Climate. *Journal of Climate*, **15** (13), 1609–1625, doi:10.1175/1520-0442.
- RGI Consortium, 2017: Randolph Glacier Inventory – A Dataset of Global Glacier Outlines: Version 6.0: Technical Report, Global Land Ice Measurements from Space. Digital Media, Colorado, USA, doi: <https://doi.org/10.7265/N5-RGI-60>.
- Richter-Menge, J., J.E. Overland, J.T. Mathis and E.E. Osborne, 2017: *Arctic Report Card 2017*. [Available at: www.arctic.noaa.gov/Report-Card].
- Rickard, G. and E. Behrens, 2016: CMIP5 Earth System Models with biogeochemistry: a Ross Sea assessment. *Antarctic Science*, **28** (5), 327–346, doi:10.1017/s0954102016000122.
- Ricker, R., F. Girard-Ardhuin, T. Krumpen and C. Lique, 2018: Satellite-derived sea ice export and its impact on Arctic ice mass balance. *The Cryosphere*, **12** (9), 3017–3032, doi:10.5194/tc-12-3017-2018.
- Ricker, R. et al., 2017: A weekly Arctic sea-ice thickness data record from merged CryoSat-2 and SMOS satellite data. *The Cryosphere*, **11** (4), 1607–1623, doi:10.5194/tc-11-1607-2017.
- Ridley, J.K., J.A. Lowe and H.T. Hewitt, 2012: How reversible is sea ice loss? *The Cryosphere*, **6** (1), 193–198, doi:10.5194/tc-6-193-2012.
- Rignot, E., S. Jacobs, J. Mouginot and B. Scheuchl, 2013: Ice-shelf melting around Antarctica. *Science*, **341** (6143), 266–70, doi:10.1126/science.1235798.
- Rignot, E., M. Koppes and I. Velicogna, 2010: Rapid submarine melting of the calving faces of West Greenland glaciers. *Nature Geoscience*, **3** (3), 187–191, doi:10.1038/Ngeo765.
- Rignot, E. et al., 2014: Widespread, rapid grounding line retreat of Pine Island, Thwaites, Smith, and Kohler glaciers, West Antarctica, from 1992 to 2011. *Geophysical Research Letters*, **41** (10), 3502–3509, doi:10.1002/2014gl060140.
- Rignot, E. et al., 2019: Four decades of Antarctic Ice Sheet mass balance from 1979–2017. *Proc Natl Acad Sci U S A*, **116** (4), 1095–1103, doi:10.1073/pnas.1812883116.
- Riley, W.J. et al., 2011: Barriers to predicting changes in global terrestrial methane fluxes: analyses using CLM4Me, a methane biogeochemistry model integrated in CESM. *Biogeosciences*, **8** (7), 1925–1953, doi:10.5194/bg-8-1925-2011.
- Rintoul, S.R. et al., 2016: Ocean heat drives rapid basal melt of the Totten Ice Shelf. *Science Advances*, **2** (12), doi:10.1126/sciadv.1601610.
- Ristoph, E.B., 2017: Presenting a Picture of Alaska Native Village Adaptation: A Method of Analysis. *Sociology and Anthropology*, **5** (9), 762–775, doi:10.13189/sa.2017.050908.
- Ritter, R. et al., 2017: Observation-Based Trends of the Southern Ocean Carbon Sink. *Geophysical Research Letters*, **44** (24), 12,339–12,348, doi:papers2://publication/doi/10.1175/JTECH-D-13-00137.1.
- Robards, M.D. et al., 2018: Understanding and adapting to observed changes in the Alaskan Arctic: Actionable knowledge co-production with Alaska Native communities. *Deep Sea Research Part II: Topical Studies in Oceanography*, doi:10.1016/j.dsr2.2018.02.008.
- Robbins, L.L. et al., 2013: Baseline Monitoring of the Western Arctic Ocean Estimates 20% of Canadian Basin Surface Waters Are Undersaturated with Respect to Aragonite. *Plos One*, **8** (9), 15, doi:10.1371/journal.pone.0073796.
- Roberts, J. et al., 2018: Ocean forced variability of Totten Glacier mass loss. *Geological Society, London, Special Publications*, **461** (1), 175–186, doi:10.1144/sp461.6.
- Robinson, H., W. Gardiner, R.J. Wenning and M.A. Rempel-Hester, 2017: Spill Impact Mitigation Assessment Framework for Oil Spill Response Planning in the Arctic Environment. *International Oil Spill Conference Proceedings*, **2017** (1), 1325–1344, doi:10.7901/2169-3358-2017.1.1325.
- Rocha, J.C., G. Peterson, O. Bodin and S. Levin, 2018: Cascading regime shifts within and across scales. *Science*, **362** (6421), 1379–1383, doi:10.1126/science.aat7850.
- Roemmich, D. et al., 2015: Unabated planetary warming and its ocean structure since 2006. *Nature Climate Change*, **5** (3), 240, doi:10.1038/nclimate2513.
- Romanovsky, V. et al., 2017: Changing permafrost and its impacts. In: Snow, Water, Ice and Permafrost in the Arctic (SWIPA). Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway, 65–102.
- Romanovsky, V.E., S.L. Smith and H.H. Christiansen, 2010: Permafrost thermal state in the polar Northern Hemisphere during the international polar year 2007–2009: a synthesis. *Permafrost and Periglacial Processes*, **21** (2), 106–116, doi:10.1002/ppp.689.
- Romero Manrique, D., S. Corral and Â. Guimarães Pereira, 2018: Climate-related displacements of coastal communities in the Arctic: Engaging traditional knowledge in adaptation strategies and policies. *Environmental Science & Policy*, **85**, 90–100, doi:10.1016/j.envsci.2018.04.007.
- Rosales, J. and L.J. Chapman, 2015: Perceptions of Obvious and Disruptive Climate Change: Community-Based Risk Assessment for Two Native Villages in Alaska. *Climate*, **3** (4), 812–832, doi:10.3390/cli3040812.
- Rösel, A. et al., 2018: Thin Sea Ice, Thick Snow, and Widespread Negative Freeboard Observed During N-ICE2015 North of Svalbard. *Journal of Geophysical Research: Oceans*, **123** (2), 1156–1176, doi:10.1002/2017jc012865.
- Rosenblum, E. and I. Eisenman, 2017: Sea Ice Trends in Climate Models Only Accurate in Runs with Biased Global Warming. *Journal of Climate*, **30** (16), 6265–6278, doi:10.1175/jcli-d-16-0455.1.
- Rosol, R., S. Powell-Hellyer and L.H.M. Chan, 2016: Impacts of decline harvest of country food on nutrient intake among Inuit in Arctic Canada: Impact of climate change and possible adaptation plan. *International Journal of Circumpolar Health*, **75**, 31127, doi:10.3402/ijch.v75.31127.
- Rott, H. et al., 2018: Changing pattern of ice flow and mass balance for glaciers discharging into the Larsen A and B embayments, Antarctic Peninsula, 2011 to 2016. *The Cryosphere*, **12** (4), 1273–1291, doi:10.5194/tc-12-1273-2018.
- Routson, C.C. et al., 2019: Mid-latitude net precipitation decreased with Arctic warming during the Holocene. *Nature*, **568** (7750), 83–87, doi:10.1038/s41586-019-1060-3.
- Rover, J., L. Ji, B.K. Wylie and L.L. Tieszen, 2012: Establishing water body areal extent trends in interior Alaska from multi-temporal Landsat data. *Remote Sensing Letters*, **3** (7), 595–604, doi:10.1080/01431161.2011.643507.
- Rowland, J.C. et al., 2011: Arctic Landscapes in Transition: Responses to Thawing Permafrost. *Eos, Transactions American Geophysical Union*, **91** (26), 229–230, doi:10.1029/2010eo260001.
- Rupp, T.S. et al., 2016: Climate Scenarios, Land Cover, and Wildland Fire. In: *Baseline and Projected Future Carbon Storage and Greenhouse-Gas Fluxes in Ecosystems of Alaska* [Zhu, Z. and A.D. McGuire (eds.)], USGS Professional Paper 1826, 196.

- Ruppel, C.D., B.M. Herman, L.L. Brothers and P.E. Hart, 2016: Subsea ice-bearing permafrost on the U.S. Beaufort Margin: 2. Borehole constraints. *Geochemistry, Geophysics, Geosystems*, **17** (11), 4333–4353, doi:10.1002/2016GC006582.
- Ruppel, C.D. and J.D. Kessler, 2016: The interaction of climate change and methane hydrates. *Reviews of Geophysics*, **55** (1), 126–168, doi:10.1002/2016RG000534.
- Ruscio, B.A. et al., 2015: One Health – a strategy for resilience in a changing arctic. *International Journal of Circumpolar Health*, **74** (1), 27913, doi:10.3402/ijch.v74.27913.
- Russell, D., 2014a: *Energy-protein modeling of North Baffin Island caribou in relation to the Mary River Project: a reassessment from Russell (2012)*. Prepared for EDI Environmental Dynamics Inc., Whitehorse YT and Baffinland Iron Mines Corporation, Oakville Ontario.
- Russell, D., 2014b: *Kiggavik Project Effects: Energy-Protein and Population Modeling of the Qamanirjuaq Caribou Herd*. Prepared for EDI Environmental Dynamics Inc., Whitehorse YT and AREVA Resources Canada.
- Russell, J.L. et al., 2018: Metrics for the Evaluation of the Southern Ocean in Coupled Climate Models and Earth System Models. *Journal of Geophysical Research: Oceans*, **123** (5), 3120–3143, doi:10.1002/2017JC013461.
- Rutzen, I. and R.R. Hopcroft, 2018: Abundance, biomass and community structure of epipelagic zooplankton in the Canada Basin. *Journal of Plankton Research*, **40** (4), 486–499, doi:10.1093/plankt/fby028.
- Ryan, J.C. et al., 2018: Dark zone of the Greenland Ice Sheet controlled by distributed biologically-active impurities. *Nature Communications*, **9** (1), 1065, doi:10.1038/s41467-018-03353-2.
- Ryan, J.C. et al., 2019: Greenland Ice Sheet surface melt amplified by snowline migration and bare ice exposure. *Sci Adv*, **5** (3), eaav3738, doi:10.1126/sciadv.aav3738.
- Ryer, C.H. et al., 2016: Temperature-Dependent Growth of Early Juvenile Southern Tanner Crab *Chionoecetes bairdi*: Implications for Cold Pool Effects and Climate Change in the Southeastern Bering Sea. *Journal of Shellfish Research*, **35** (1), 259–267, doi:10.2983/035.035.0128.
- Rysgaard, S. et al., 2013: Ikaite crystal distribution in winter sea ice and implications for CO₂ system dynamics. *Cryosphere*, **7** (2), 707–718, doi:10.5194/tc-7-707-2013.
- Safronov, V.M., 2016: Climate change and mammals of Yakutia. *Biology Bulletin*, **43** (9), 1256–1270, doi:10.1134/S1062359016110121.
- Sahade, R. et al., 2015: Climate change and glacier retreat drive shifts in an Antarctic benthic ecosystem. *Science Advances*, **1**, doi:10.1126/sciadv.1500050
- Sakhujia, V., 2014: The Polar Code and Arctic Navigation. *Strategic Analysis*, **38** (6), 803–811, doi:10.1080/09700161.2014.952943.
- Sallée, J.-B. et al., 2013a: Assessment of Southern Ocean mixed-layer depths in CMIP5 models: Historical bias and forcing response. *Journal of Geophysical Research: Oceans*, **118** (4), 1845–1862, doi:10.1002/jgrc.20157.
- Sallée, J.-B. et al., 2013b: Assessment of Southern Ocean water mass circulation and characteristics in CMIP5 models: Historical bias and forcing response. *Journal of Geophysical Research: Oceans*, **118** (4), 1830–1844, doi:10.1002/jgrc.20135.
- Salmon, V.G. et al., 2016: Nitrogen availability increases in a tundra ecosystem during five years of experimental permafrost thaw. *Global Change Biology*, **22** (5), 1927–1941, doi:10.1111/gcb.13204.
- Sand, M., T.K. Berntsen, Ø. Seland and J.E. Kristjánsson, 2013: Arctic surface temperature change to emissions of black carbon within Arctic or midlatitudes. *Journal of Geophysical Research: Atmospheres*, **118** (14), 7788–7798, doi:10.1002/jgrd.50613.
- Sandberg Sørensen, L. et al., 2018: 25 years of elevation changes of the Greenland Ice Sheet from ERS, Envisat, and CryoSat-2 radar altimetry. *Earth and Planetary Science Letters*, **495**, 234–241, doi:10.1016/j.epsl.2018.05.015.
- Sanderson, B.M. et al., 2017: Community climate simulations to assess avoided impacts in 1.5 and 2°C futures. *Earth Syst. Dynam.*, **8** (3), 827–847, doi:10.5194/esd-8-827-2017.
- Santora, J.A. et al., 2017: Impacts of ocean climate variability on biodiversity of pelagic forage species in an upwelling ecosystem. *Marine Ecology Progress Series*, **580**, 205–220, doi:10.3354/meps12278.
- Sarkki, S. and N. Acosta García, 2019: Merging social equity and conservation goals in IPBES. *Conservation Biology*, **33** (5), 1214–1218, doi:10.1111/cobi.13297.
- Sasse, T.P., B.I. McNeil, R.J. Matear and A. Lenton, 2015: Quantifying the influence of CO₂ seasonality on future aragonite undersaturation onset. *Biogeosciences*, **12** (20), 6017–6031, doi:10.5194/bg-12-6017-2015.
- Saunio, M. et al., 2016: The global methane budget 2000–2012. *Earth System Science Data*, **8** (2), 697–751, doi:10.5194/essd-8-697-2016.
- Schädel, C. et al., 2014: Circumpolar assessment of permafrost C quality and its vulnerability over time using long-term incubation data. *Global Change Biology*, **20** (2), 641–652, doi:10.1111/gcb.12417.
- Schaefer, J.M. et al., 2016: Greenland was nearly ice-free for extended periods during the Pleistocene. *Nature*, **540** (7632), 252–255, doi:10.1038/nature20146.
- Schaefer, K. et al., 2014: The impact of the permafrost carbon feedback on global climate. *Environmental Research Letters*, **9** (8), 085003, doi:10.1088/1748-9326/9/8/085003.
- Schaefer, K., T. Zhang, L. Bruhwiler and A.P. Barrett, 2011: Amount and timing of permafrost carbon release in response to climate warming. *Tellus B: Chemical and Physical Meteorology*, **63** (2), 165–180, doi:10.1111/j.1600-0889.2011.00527.x.
- Schaphoff, S. et al., 2013: Contribution of permafrost soils to the global carbon budget. *Environmental Research Letters*, **8** (1), 014026, doi:10.1088/1748-9326/8/1/014026.
- Schartmüller, B., A.-S. Milaković, M. Bergström and S. Ehlers, 2015: A Simulation-Based Decision Support Tool for Arctic Transit Transport. (56567), V008T07A006, doi:10.1115/OMAE2015-41375.
- Schirrmeister, L. et al., 2011: Fossil organic matter characteristics in permafrost deposits of the northeast Siberian Arctic. *Journal of Geophysical Research: Biogeosciences*, **116** (G2), G00M02, doi:10.1029/2011jg001647.
- Schmidt, K. and A. Atkinson, 2016: Feeding and Food Processing in Antarctic Krill (*Euphausia superba* Dana). In: *Biology and Ecology of Antarctic Krill* [Siegel, V. (ed.)]. Springer, New York, 175–224.
- Schmidt, N.M. et al., 2017: Interaction webs in arctic ecosystems: Determinants of arctic change? *AMBIO*, **46** (1), 12–25, doi:10.1007/s13280-016-0862-x.
- Schmidt, N.M., S.H. Pedersen, J.B. Mosbacher and L.H. Hansen, 2015: Long-term patterns of muskox (*Ovibos moschatus*) demographics in high arctic Greenland. *Polar Biology*, **38** (10), 1667–1675, doi:10.1007/s00300-015-1733-9.
- Schmidtke, S., K.J. Heywood, A.F. Thompson and S. Aoki, 2014: Multidecadal warming of Antarctic waters. *Science*, **346** (6214), 1227–1231.
- Schneider, D.P., C. Deser and T. Fan, 2015: Comparing the Impacts of Tropical SST Variability and Polar Stratospheric Ozone Loss on the Southern Ocean Westerly Winds. *Journal of Climate*, **28** (23), 9350–9372, doi:10.1175/jcli-d-15-0090.1.
- Schneider, D.P. and D.B. Reusch, 2015: Antarctic and Southern Ocean Surface Temperatures in CMIP5 Models in the Context of the Surface Energy Budget. *Journal of Climate*, **29** (5), 1689–1716, doi:10.1175/JCLI-D-15-0429.1.
- Schneider von Deimling, T. et al., 2015: Observation-based modelling of permafrost carbon fluxes with accounting for deep carbon deposits and thermokarst activity. *Biogeosciences*, **12** (11), 3469–3488, doi:10.5194/bg-12-3469-2015.
- Schofield, O. et al., 2018: Changes in the upper ocean mixed layer and phytoplankton productivity along the West Antarctic Peninsula. *Philos Trans A Math Phys Eng Sci*, **376** (2122), doi:10.1098/rsta.2017.0173.
- Schofield, O. et al., 2017: Decadal variability in coastal phytoplankton community composition in a changing West Antarctic Peninsula. *Deep*

- Sea Research Part I: Oceanographic Research Papers, **124**, 42–54, doi:10.1016/j.dsr.2017.04.014.
- Schrama, E.J.O., B. Wouters and R. Rietbroek, 2014: A mascon approach to assess ice sheet and glacier mass balances and their uncertainties from GRACE data. *Journal of Geophysical Research: Solid Earth*, **119** (7), 6048–6066, doi:10.1002/2013jb010923.
- Schroeter, S., W. Hobbs and N.L. Bindoff, 2017: Interactions between Antarctic sea ice and large-scale atmospheric modes in CMIP5 models. *Cryosphere*, **11** (2), 789–803, doi:10.5194/tc-11-789-2017.
- Schulze, L.M. and R.S. Pickart, 2012: Seasonal variation of upwelling in the Alaskan Beaufort Sea: Impact of sea ice cover. *Journal of Geophysical Research: Oceans*, **117** (C6), C06022, doi:10.1029/2012JC007985.
- Schuster, P.F. et al., 2018: Permafrost Stores a Globally Significant Amount of Mercury. *Geophysical Research Letters*, **45** (3), 1463–1471, doi:10.1002/2017GL075571.
- Schuur, E.A.G. et al., 2013: Expert assessment of vulnerability of permafrost carbon to climate change. *Climatic Change*, **119** (2), 359–374, doi:10.1007/s10584-013-0730-7.
- Schuur, E.A.G. et al., 2018: Chapter 11: Arctic and boreal carbon. In: Second State of the Carbon Cycle Report (SOCCR2): A Sustained Assessment Report [Cavallaro, N., G. Shrestha, R. Birdsey, M.A. Mayes, R.G. Najjar, S.C. Reed, P. Romero-Lankao and Z. Zhu (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, 428–468.
- Schuur, E.A.G. et al., 2015: Climate change and the permafrost carbon feedback. *Nature*, **520** (7546), 171–179, doi:10.1038/nature14338.
- Schweiger, A.J., K.R. Wood and J. Zhang, 2019: Arctic sea ice volume variability over 1901–2010: A model-based reconstruction. *Journal of Climate*, **32** (15), 4731–4752, doi:10.1175/jcli-d-19-0008.1.
- Schweitzer, P., P. Sköld and O. Ulturgasheva, 2014: Cultures and Identities. In: Arctic Human Development Report: Regional Processes and Global Linkages [Nyman Larsen, J. and G. Fondhal (eds.)]. Nordic Council of Ministers, Copenhagen, 105–150.
- Screen, J.A., T.J. Bracegirdle and I. Simmonds, 2018: Polar Climate Change as Manifest in Atmospheric Circulation. *Curr Clim Change Rep*, **4** (4), 383–395, doi:10.1007/s40641-018-0111-4.
- Screen, J.A. and C. Deser, 2019: Pacific Ocean Variability Influences the Time of Emergence of a Seasonally Ice-Free Arctic Ocean. *Geophysical Research Letters*, **46** (4), 2222–2231, doi:10.1029/2018gl081393.
- Screen, J.A. and I. Simmonds, 2010: The central role of diminishing sea ice in recent Arctic temperature amplification. *Nature*, **464** (7293), 1334–7, doi:10.1038/nature09051.
- Sedlar, J., 2018: Spring Arctic Atmospheric Preconditioning: Do Not Rule Out Shortwave Radiation Just Yet. *Journal of Climate*, **31** (11), 4225–4240, doi:10.1175/jcli-d-17-0710.1.
- Seehaus, T. et al., 2015: Changes in ice dynamics, elevation and mass discharge of Dinsmoor–Bombardier–Edgeworth glacier system, Antarctic Peninsula. *Earth and Planetary Science Letters*, **427**, 125–135, doi:10.1016/j.epsl.2015.06.047.
- Sejr, M.K. et al., 2017: Evidence of local and regional freshening of Northeast Greenland coastal waters. *Sci Rep*, **7** (1), 13183, doi:10.1038/s41598-017-10610-9.
- Semiletov, I. et al., 2016: Acidification of East Siberian Arctic Shelf waters through addition of freshwater and terrestrial carbon (vol 9, pg 361, 2016). *Nature Geoscience*, **9** (9), 1, doi:10.1038/ngeo2799.
- Serreze, M.C., A.P. Barrett and J. Stroeve, 2012: Recent changes in tropospheric water vapor over the Arctic as assessed from radiosondes and atmospheric reanalyses. *Journal of Geophysical Research: Atmospheres*, **117** (D10), n/a–n/a, doi:10.1029/2011jd017421.
- Serreze, M.C. et al., 2009: The emergence of surface-based Arctic amplification. *The Cryosphere*, **3** (1), 11–19, doi:10.5194/tc-3-11-2009.
- Serreze, M.C. and R.G. Barry, 2011: Processes and impacts of Arctic amplification: A research synthesis. *Global and Planetary Change*, **77** (1–2), 85–96, doi:10.1016/j.gloplacha.2011.03.004.
- Serreze, M.C., J. Stroeve, A.P. Barrett and L.N. Boisvert, 2016: Summer atmospheric circulation anomalies over the Arctic Ocean and their influences on September sea ice extent: A cautionary tale. *Journal of Geophysical Research: Atmospheres*, **121** (19), 11,463–11,485, doi:10.1002/2016jd025161.
- Sevestre, H. et al., 2018: Tidewater Glacier Surges Initiated at the Terminus. *Journal of Geophysical Research: Earth Surface*, **123** (5), 1035–1051, doi:10.1029/2017JF004358.
- Seyboth, E. et al., 2016: Southern Right Whale (*Eubalaena australis*) Reproductive Success is Influenced by Krill (*Euphausia superba*) Density and Climate. *Sci Rep*, **6**, 28205, doi:10.1038/srep28205.
- Sformo, T.L. et al., 2017: Observations and first reports of saprolegniosis in Aanaqliq, broad whitefish (*Coregonus nasus*), from the Colville River near Nuiqsut, Alaska. *Polar Science*, **14**, 78–82, doi:10.1016/j.polar.2017.07.002.
- Shadian, J.M., 2014: *The Politics of Arctic Sovereignty: oil, ice and Inuit governance*. Routledge Press, London.
- Shadwick, E.H. et al., 2013: Glacier tongue calving reduced dense water formation and enhanced carbon uptake. *Geophysical Research Letters*, **40** (5), 904–909, doi:10.1002/grl.50178.
- Shadwick, E.H., B. Tilbrook and K.I. Currie, 2017: Late-summer biogeochemistry in the Mertz Polynya: East Antarctica. *Journal of Geophysical Research: Oceans*, **122** (9), 7380–7394, doi:10.1002/2017jc013015.
- Shakhova, N. et al., 2013: Ebullition and storm-induced methane release from the East Siberian Arctic Shelf. *Nature Geoscience*, **7**, 64, doi:10.1038/ngeo2007.
- Shapovalova, D., 2016: The Effectiveness of the Regulatory Regime for Black Carbon Mitigation in the Arctic. *Arctic Review on Law and Politics*, **7** (2), 136–151, doi:10.17585/arctic.v7.427.
- Sharma, B.M. et al., 2015: Melting Himalayan glaciers contaminated by legacy atmospheric depositions are important sources of PCBs and high-molecular-weight PAHs for the Ganges floodplain during dry periods. *Environmental Pollution*, **206** (Supplement C), 588–596, doi:10.1016/j.envpol.2015.08.012.
- Sharma, S. et al., 2019: Widespread loss of lake ice around the Northern Hemisphere in a warming world. *Nature Climate Change*, **9** (3), 227–231, doi:10.1038/s41558-018-0393-5.
- Sharonov, D.S., N.A. Bryksina, V.Y. Polishuk and Y.M. Polishuk, 2012: Comparative analysis of thermokarst dynamics in permafrost territory of Western Siberia and Gorny Altai on the basis of space images. *Current problems in remote sensing of the earth from space*, **9** (1), 313–319.
- Shepherd, A. et al., 2012: A reconciled estimate of ice-sheet mass balance. *Science*, **338** (6111), 1183–9, doi:10.1126/science.1228102.
- Sheppard, S.R.J. et al., 2011: Future visioning of local climate change: A framework for community engagement and planning with scenarios and visualisation. *Futures*, **43** (4), 400–412, doi:10.1016/j.futures.2011.01.009.
- Shi, J.-R., S.-P. Xie and L.D. Talley, 2018: Evolving Relative Importance of the Southern Ocean and North Atlantic in Anthropogenic Ocean Heat Uptake. *Journal of Climate*, **31** (18), 7459–7479, doi:10.1175/jcli-d-18-0170.1.
- Shibata, A., 2015: Japan and 100 Years of Antarctic Legal Order: Any Lessons for the Arctic? *The Yearbook of Polar Law Online*, **7** (1), 1–54, doi:10.1163/2211-6427_002.
- Shiklomanov, A.I. and R.B. Lammers, 2014: River ice responses to a warming Arctic – recent evidence from Russian rivers. *Environmental Research Letters*, **9** (3), 035008, doi:10.1088/1748-9326/9/3/035008.
- Shiklomanov, N.I., D.A. Streletskiy, V.I. Grebenets and L. Suter, 2017a: Conquering the permafrost: urban infrastructure development in Norilsk, Russia. *Polar Geography*, **40** (4), 273–290, doi:10.1080/1088937X.2017.1329237.
- Shiklomanov, N.I., D.A. Streletskiy and F.E. Nelson, 2012: Northern Hemisphere component of the global Circumpolar Active Layer Monitoring (CALM) program. In: *10th International Conference on Permafrost*, Salekhard, Russia, 377–382.

- Shiklomanov, N.I., D.A. Streletskiy, T.B. Swales and V.A. Kokorev, 2017b: Climate Change and Stability of Urban Infrastructure in Russian Permafrost Regions: Prognostic Assessment based on GCM Climate Projections. *Geographical Review*, **107** (1), 125–142, doi:10.1111/gere.12214.
- Shindell, D.T., 2004: Southern Hemisphere climate response to ozone changes and greenhouse gas increases. *Geophysical Research Letters*, **31** (18), doi:10.1029/2004gl020724.
- Shu, Q., Z. Song and F. Qiao, 2015: Assessment of sea ice simulations in the CMIP5 models. *Cryosphere*, **9** (1), 399–409, doi:10.5194/tc-9-399-2015.
- Shuman, J.K. et al., 2015: Forest forecasting with vegetation models across Russia. *Canadian Journal of Forest Research*, **45** (2), 175–184, doi:10.1139/cjfr-2014-0138.
- Siegel, V., Eds., 2016: *Biology and Ecology of Antarctic Krill*. Springer, 1–458 pp.
- Siegert, M.J., 2017: A 60-year international history of Antarctic subglacial lake exploration. In: *Exploration of subsurface Antarctica: Uncovering past changes and modern processes* [Siegert, M.J., S.S.R. Jamieson and D.A. White (eds.)]. Geological Society, London, **461**, 7–21.
- Siegert, M.J. et al., 2017: Antarctic glacial groundwater: a concept paper on its measurement and potential influence on ice flow. In: *Exploration of subsurface Antarctica: uncovering past changes and modern processes* [Siegert, M.J., S.S.R. Jamieson and D.A. White (eds.)]. The Geological Society, London, **461**, 197–213.
- Siegert, M.J., A.M. Le Brocq and A.J. Payne, 2007: Hydrological connections between Antarctic subglacial lakes, the flow of water beneath the East Antarctic ice sheet and implications for sedimentary processes. In: *Glacial sedimentary processes and products* [Hambrey, M.J., P. Christoffersen, N.F. Glasser and B. Hubbard (eds.)]. International Association of Sedimentologists, 3–22.
- Siegert, M.J., N. Ross and A.M. Le Brocq, 2016: Recent advances in understanding Antarctic subglacial lakes and hydrology. *Phil. Trans. R. Soc. A*, **374** (20140306), doi:10.1098/rsta.2014.0306.
- Sigler, M.F. et al., 2017: Late summer zoogeography of the northern Bering and Chukchi seas. *Deep Sea Research Part II: Topical Studies in Oceanography*, **135** (Supplement C), 168–189, doi:10.1016/j.dsr2.2016.03.005.
- Sigmond, M., J.C. Fyfe and N.C. Swart, 2018: Ice-free Arctic projections under the Paris Agreement. *Nature Climate Change*, **8** (5), 404–408, doi:10.1038/s41558-018-0124-y.
- Sillmann, J. et al., 2013: Climate extremes indices in the CMIP5 multimodel ensemble: Part 2. Future climate projections. *Journal of Geophysical Research: Atmospheres*, **118** (6), 2473–2493, doi:10.1002/jgrd.50188.
- Silvano, A. et al., 2018: Freshening by glacial meltwater enhances melting of ice shelves and reduces formation of Antarctic Bottom Water. *Sci Adv*, **4** (4), eaap9467, doi:10.1126/sciadv.aap9467.
- Singh, D., M.G. Flanner and J. Perket, 2015: The global land shortwave cryosphere radiative effect during the MODIS era. *The Cryosphere*, **9** (6), 2057–2070, doi:10.5194/tc-9-2057-2015.
- Skific, N. and J.A. Francis, 2013: Drivers of projected change in arctic moist static energy transport. *Journal of Geophysical Research: Atmospheres*, **118** (7), 2748–2761, doi:10.1002/jgrd.50292.
- Skiles, S.M. et al., 2018: Radiative forcing by light-absorbing particles in snow. *Nature Climate Change*, **8** (11), 964–971, doi:10.1038/s41558-018-0296-5.
- Skliris, N. et al., 2014: Salinity changes in the World Ocean since 1950 in relation to changing surface freshwater fluxes. *Climate Dynamics*, **43** (3–4), 709–736, doi:10.1007/s00382-014-2131-7.
- Skogen, M.D. et al., 2014: Modelling ocean acidification in the Nordic and Barents Seas in present and future climate. *Journal of Marine Systems*, **131**, 10–20, doi:10.1016/j.jmarsys.2013.10.005.
- Slater, A.G. and D.M. Lawrence, 2013: Diagnosing Present and Future Permafrost from Climate Models. *Journal of Climate*, **26** (15), 5608–5623, doi:10.1175/jcli-d-12-00341.1.
- Slater, D.A. et al., 2015: Effect of near-terminus subglacial hydrology on tidewater glacier submarine melt rates. *Geophysical Research Letters*, **42** (8), 2861–2868, doi:10.1002/2014GL062494.
- Sledd, A. and T. L'Ecuyer, 2019: How much do clouds mask the impacts of Arctic sea ice and snow cover variations? Different perspectives from observations and reanalyses. *Atmosphere*, **10** (1), 12, doi:10.3390/atmos10010012.
- Small, D. et al., 2019: Antarctic ice sheet palaeo-thinning rates from vertical transects of cosmogenic exposure ages. *Quaternary Science Reviews*, **206**, 65–80, doi:10.1016/j.quascirev.2018.12.024.
- Smedsrud, L.H., 2005: Warming of the deep water in the Weddell Sea along the Greenwich meridian: 1977–2001. *Deep-Sea Research Part I-Oceanographic Research Papers*, **52** (2), 241–258, doi:10.1016/j.dsr.2004.10.004.
- Smedsrud, L.H. et al., 2013: The Role of the Barents Sea in the Arctic Climate System. *Reviews of Geophysics*, **51** (3), 415–449, doi:10.1002/rog.20017.
- Smedsrud, L.H. et al., 2017: Fram Strait sea ice export variability and September Arctic sea ice extent over the last 80 years. *The Cryosphere*, **11** (1), 65–79, doi:10.5194/tc-11-65-2017.
- Šmejkalová, T., M.E. Edwards and J. Dash, 2016: Arctic lakes show strong decadal trend in earlier spring ice-out. *Scientific Reports*, **6**, 38449, doi:10.1038/srep38449.
- Smith, A.J. et al., 2017a: Beluga whale summer habitat associations in the Nelson River estuary, western Hudson Bay, Canada. *Plos One*, **12** (8), e0181045, doi:10.1371/journal.pone.0181045.
- Smith, D.M. et al., 2017b: Atmospheric Response to Arctic and Antarctic Sea Ice: The Importance of Ocean–Atmosphere Coupling and the Background State. *Journal of Climate*, **30** (12), 4547–4565, doi:10.1175/JCLI-D-16-0564.1.
- Smith, J.A. et al., 2017c: Sub-ice-shelf sediments record history of twentieth-century retreat of Pine Island Glacier. *Nature*, **541**, 77, doi:10.1038/nature20136.
- Smith, K.E. et al., 2017d: Climate change and the threat of novel marine predators in Antarctica. *Ecosphere*, **8** (11), 1–3, doi:10.1002/ecs2.2017.
- Smith, K.L. and L.M. Polvani, 2017: Spatial patterns of recent Antarctic surface temperature trends and the importance of natural variability: lessons from multiple reconstructions and the CMIP5 models. *Climate Dynamics*, **48** (7–8), 2653–2670, doi:10.1007/s00382-016-3230-4.
- Smith, L.C. et al., 2007: Rising minimum daily flows in northern Eurasian rivers: A growing influence of groundwater in the high-latitude hydrologic cycle. *Journal of Geophysical Research*, **112** (G04547), doi:doi:10.1029/2006JG000327.
- Smith, L.C., Y. Sheng, G.M. MacDonald and L.D. Hinzman, 2005: Disappearing Arctic Lakes. *Science*, **308** (5727), 1429, doi:10.1126/science.1108142.
- Smith, M.D., A.K. Knapp and S.L. Collins, 2009: A framework for assessing ecosystem dynamics in response to chronic resource alterations induced by global change. *Ecology*, **90** (12), 3279–3289, doi:10.1890/08-1815.1.
- Smith, R.W. et al., 2015: High rates of organic carbon burial in fjord sediments globally. *Nature Geosci*, **8** (6), 450–453, doi:10.1038/ngeo2421.
- Smits, C.C.A., J. van Leeuwen and J.P.M. van Tatenhove, 2017: Oil and gas development in Greenland: A social license to operate, trust and legitimacy in environmental governance. *Resources Policy*, **53**, 109–116, doi:10.1016/j.resourpol.2017.06.004.
- Smoot, C.A. and R.R. Hopcroft, 2017: Depth-stratified community structure of Beaufort Sea slope zooplankton and its relations to water masses. *Journal of Plankton Research*, **39** (1), 79–91, doi:10.1093/plankt/fbw087.
- Sole, A. et al., 2013: Winter motion mediates dynamic response of the Greenland Ice Sheet to warmer summers. *Geophysical Research Letters*, **40** (15), 3940–3944, doi:10.1002/ogl.50764.
- Solomina, O.N. et al., 2015: Holocene glacier fluctuations. *Quaternary Science Reviews*, **111**, 9–34, doi:10.1016/j.quascirev.2014.11.018.
- Solovyev, B. et al., 2017: Identifying a network of priority areas for conservation in the Arctic seas: Practical lessons from Russia. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **27** (S1), 30–51, doi:10.1002/aqc.2806.
- Song, H.J. et al., 2016: In-situ measured primary productivity of ice algae in Arctic sea ice floes using a new incubation method. *Ocean Science Journal*, **51** (3), 387–396, doi:10.1007/s12601-016-0035-7.

- Soulen, B.K., K. Cammen, T.F. Schultz and D.W. Johnston, 2013: Factors Affecting Harp Seal (*Pagophilus groenlandicus*) Strandings in the Northwest Atlantic. *Plos One*, **8** (7), e68779, doi:10.1371/journal.pone.0068779.
- Southcott, C. and D. Natcher, 2018: Extractive industries and Indigenous subsistence economies: a complex and unresolved relationship. *Canadian Journal of Development Studies / Revue canadienne d'études du développement*, **39** (1), 137–154, doi:10.1080/02255189.2017.1400955.
- Southwell, C. et al., 2012: A review of data on abundance, trends in abundance, habitat utilisation and diet for Southern Ocean ice-breeding seals. *CCAMLR Science*, **19**, 1–49.
- Southwell, C. et al., 2015: Spatially Extensive Standardized Surveys Reveal Widespread, Multi-Decadal Increase in East Antarctic Adelie Penguin Populations. *Plos One*, **10** (10), 18, doi:10.1371/journal.pone.0139877.
- Spence, P. et al., 2014: Rapid subsurface warming and circulation changes of Antarctic coastal waters by poleward shifting winds. *Geophysical Research Letters*, **41** (13), 4601–4610, doi:10.1002/2014gl060613.
- Spreen, G., R. Kwok and D. Menemenlis, 2011: Trends in Arctic sea ice drift and role of wind forcing: 1992–2009. *Geophysical Research Letters*, **38** (19), L19501, doi:10.1029/2011gl048970.
- St-Laurent, P., J.M. Klinck and M.S. Dinniman, 2015: Impact of local winter cooling on the melt of Pine Island Glacier, Antarctica. *Journal of Geophysical Research: Oceans*, **120** (10), 6718–6732, doi:10.1002/2015JC010709.
- St Pierre, K.A. et al., 2018: Unprecedented Increases in Total and Methyl Mercury Concentrations Downstream of Retrogressive Thaw Slumps in the Western Canadian Arctic. *Environ Sci Technol*, **52** (24), 14099–14109, doi:10.1021/acs.est.8b05348.
- St. Jacques, J.-M. and D.J. Sauchyn, 2009: Increasing winter baseflow and mean annual streamflow from possible permafrost thawing in the Northwest Territories, Canada. *Geophysical Research Letters*, **36** (1), L01401, doi:10.1029/2008gl035822.
- Stammerjohn, S. and T. Maksym, 2016: Gaining (and losing) Antarctic sea ice: variability, trends and mechanisms. In: *Sea Ice*. John Wiley & Sons, Ltd, 261–289.
- Stammerjohn, S., R. Massom, D. Rind and D. Martinson, 2012: Regions of rapid sea ice change: An inter-hemispheric seasonal comparison. *Geophysical Research Letters*, **39** (6), L06501, doi:10.1029/2012GL050874.
- Stanley, R.H.R., Z.O. Sandwith and W.J. Williams, 2015: Rates of summertime biological productivity in the Beaufort Gyre: A comparison between the low and record-low ice conditions of August 2011 and 2012. *Journal of Marine Systems*, **147** (Supplement C), 29–44, doi:10.1016/j.jmarsys.2014.04.006.
- Stapleton, S., E. Peacock and D. Garshelis, 2016: Aerial surveys suggest long-term stability in the seasonally ice-free Foxe Basin (Nunavut) polar bear population. *Marine Mammal Science*, **32** (1), 181–201, doi:10.1111/mms.12251.
- Stasko, A.D. et al., 2018: Benthic-pelagic trophic coupling in an Arctic marine food web along vertical water mass and organic matter gradients. *Marine Ecology Progress Series*, **594**, 1–19, doi:10.3354/meps12582.
- Steele, M. and S. Dickinson, 2016: The phenology of Arctic Ocean surface warming. *J Geophys Res Oceans*, **121** (9), 6847–6861, doi:10.1002/2016JC012089.
- Steger, C.R. et al., 2017: Firn Meltwater Retention on the Greenland Ice Sheet: A Model Comparison. *Frontiers in Earth Science*, **5**, doi:10.3389/feart.2017.00003.
- Steig, E.J., Q. Ding, D.S. Battisti and A. Jenkins, 2017: Tropical forcing of Circumpolar Deep Water Inflow and outlet glacier thinning in the Amundsen Sea Embayment, West Antarctica. *Annals of Glaciology*, **53** (60), 19–28, doi:10.3189/2012AoG60A110.
- Steig, E.J. et al., 2013: Recent climate and ice-sheet changes in West Antarctica compared with the past 2,000 years. *Nature Geoscience*, **6** (5), 372–375, doi:10.1038/ngeo1778.
- Steinberg, D.K. et al., 2015: Long-term (1993–2013) changes in macrozooplankton off the Western Antarctic Peninsula. *Deep Sea Research Part I: Oceanographic Research Papers*, **101**, 54–70, doi:10.1016/j.dsr.2015.02.009.
- Steiner, N.S. et al., 2014: Future ocean acidification in the Canada Basin and surrounding Arctic Ocean from CMIP5 earth system models. *Journal of Geophysical Research-Oceans*, **119** (1), 332–347, doi:10.1002/2013jc009069.
- Stenni, B. et al., 2017: Antarctic climate variability on regional and continental scales over the last 2000 years. *Climate of the Past*, **13** (11), 1609–1634, doi:10.5194/cp-13-1609-2017.
- Stenson, G.B. and M.O. Hammill, 2014: Can ice breeding seals adapt to habitat loss in a time of climate change? *ICES Journal of Marine Science*, **71** (7), 1977–1986, doi:10.1093/icesjms/fsu074.
- Stephenson, S.R., L.C. Smith and J.A. Agnew, 2011: Divergent long-term trajectories of human access to the Arctic. *Nature Climate Change*, **1**, 156, doi:10.1038/nclimate1120.
- Stephenson, S.R., L.C. Smith, L.W. Brigham and J.A. Agnew, 2013: Projected 21st-century changes to Arctic marine access. *Climatic Change*, **118** (3), 885–899, doi:10.1007/s10584-012-0685-0.
- Stevens, L.A. et al., 2016: Greenland Ice Sheet flow response to runoff variability. *Geophysical Research Letters*, **43** (21), 11,295–11,303, doi:10.1002/2016GL070414.
- Stevenson, D.E. and R.R. Lauth, 2018: Bottom trawl surveys in the northern Bering Sea indicate recent shifts in the distribution of marine species. *Polar Biology*, **42** (2), 407–421, doi:10.1007/s00300-018-2431-1.
- Stewart, E., J. Dawson and M. Johnston, 2015: Risks and opportunities associated with change in the cruise tourism sector: community perspectives from Arctic Canada. *The Polar Journal*, **5** (2), 403–427, doi:10.1080/2154896x.2015.1082283.
- Stewart, E.J. et al., 2013: Local-level responses to sea ice change and cruise tourism in Arctic Canada's Northwest Passage. *Polar Geography*, **36** (1–2), 142–162, doi:10.1080/1088937x.2012.705352.
- Stiasny, M.H. et al., 2016: Ocean Acidification Effects on Atlantic Cod Larval Survival and Recruitment to the Fished Population. *Plos One*, **11** (8), e0155448, doi:10.1371/journal.pone.0155448.
- Stibal, M. et al., 2017: Algae Drive Enhanced Darkening of Bare Ice on the Greenland Ice Sheet. *Geophysical Research Letters*, **44** (22), 11, 463–11,471, doi:10.1002/2017GL075958.
- Stirling, I., 1997: The importance of polynyas, ice edges, and leads to marine mammals and birds. *Journal of Marine Systems*, **10** (1), 9–21, doi:10.1016/S0924-7963(96)00054-1.
- Stokke, K.B. and J.V. Haukeland, 2017: Balancing tourism development and nature protection across national park borders – a case study of a coastal protected area in Norway. *Journal of Environmental Planning and Management*, **61** (12), 2151–2165, doi:10.1080/09640568.2017.1388772.
- Stokke, O.S., 2009: Protecting the Arctic Environment: The Interplay of Global and Regional Regimes. *The Yearbook of Polar Law Online*, **1** (1), 349–369, doi:10.1163/22116427-91000018.
- Stokke, O.S., 2013: Political Stability and Multi-level Governance in the Arctic. In: *Environmental Security in the Arctic Ocean*, Dordrecht, [Berkman, P. and A. Vylegzhanin (eds.)], Springer Netherlands, 297–311.
- Storrie, L. et al., 2018: Determining the species assemblage and habitat use of cetaceans in the Svalbard Archipelago, based on observations from 2002 to 2014. *Polar Research*, **37** (1), 1463065, doi:10.1080/17518369.2018.1463065.
- Straneo, F. and C. Cenedese, 2015: The Dynamics of Greenland's Glacial Fjords and Their Role in Climate. *Ann Rev Mar Sci*, **7**, 89–112, doi:10.1146/annurev-marine-010213-135133.
- Straneo, F., G.S. Hamilton, L.A. Stearns and D.A. Sutherland, 2016: Connecting the Greenland Ice Sheet and the ocean: A case study of Helheim Glacier and Semilik Fjord. *Oceanography*, **29** (4), 34–45, doi:10.5670/oceanog.2016.97.
- Straneo, F. et al., 2013: Challenges to understanding the dynamic response of Greenland's marine terminating glaciers to oceanic and atmospheric

- forcing. *Bulletin of the American Meteorological Society*, **94** (8), 1131–1144, doi:10.1175/BAMS-D-12-00100.1.
- Straneo, F. et al., 2017: Characteristics of ocean waters reaching Greenland's glaciers. *Annals of Glaciology*, **53** (60), 202–210, doi:10.3189/2012AoG60A059.
- Strauss, J. et al., 2017: Deep Yedoma permafrost: A synthesis of depositional characteristics and carbon vulnerability. *Earth-Science Reviews*, **172**, 75–86, doi:10.1016/j.earscirev.2017.07.007.
- Strauss, J. et al., 2013: The Deep Permafrost Carbon Pool of the Yedoma Region in Siberia and Alaska. *Geophysical Research Letters*, **40**, 6165–6170, doi:10.1002/2013gl058088.
- Streletskiy, D., N. Shiklomanov and E. Hatleberg, 2012: Infrastructure and a Changing Climate in the Russian Arctic: A Geographic Impact Assessment. In: *Proceedings of the 10th International Conference on Permafrost*, June 25 – 29, 2012, Salekhard, Russia, **1**, 407–412.
- Streletskiy, D.A. et al., 2017: Thaw Subsidence in Undisturbed Tundra Landscapes, Barrow, Alaska, 1962–2015. *Permafrost and Periglacial Processes*, **28** (3), 566–572, doi:10.1002/ppp.1918.
- Striegl, R.G. et al., 2005: A decrease in discharge-normalized DOC export by the Yukon River during summer through autumn. *Geophysical Research Letters*, **32** (21), doi:10.1029/2005gl024413.
- Stroeve, J., A. Barrett, M. Serreze and A. Schweiger, 2014a: Using records from submarine, aircraft and satellites to evaluate climate model simulations of Arctic sea ice thickness. *The Cryosphere*, **8** (5), 1839–1854, doi:10.5194/tc-8-1839-2014.
- Stroeve, J. and D. Notz, 2015: Insights on past and future sea-ice evolution from combining observations and models. *Global and Planetary Change*, **135** (Supplement C), 119–132, doi:10.1016/j.gloplacha.2015.10.011.
- Stroeve, J. and D. Notz, 2018: Changing state of Arctic sea ice across all seasons. *Environmental Research Letters*, **13** (10), 103001, doi:10.1088/1748-9326/13/10/103001.
- Stroeve, J.C. et al., 2012a: Trends in Arctic sea ice extent from CMIP5, CMIP3 and observations. *Geophysical Research Letters*, **39** (16), L16502, doi:10.1029/2012gl052676.
- Stroeve, J.C. et al., 2014b: Changes in Arctic melt season and implications for sea ice loss. *Geophysical Research Letters*, **41** (4), 1216–1225, doi:10.1002/2013gl058951.
- Stroeve, J.C. et al., 2012b: The Arctic's rapidly shrinking sea ice cover: a research synthesis. *Climatic Change*, **110** (3), 1005–1027, doi:10.1007/s10584-011-0101-1.
- Strozzi, T. et al., 2017: Circum-Arctic Changes in the Flow of Glaciers and Ice Caps from Satellite SAR Data between the 1990s and 2017. *Remote Sensing*, **9** (9), 947, doi:10.3390/rs9090947.
- Stuecker, M.F. et al., 2018: Polar amplification dominated by local forcing and feedbacks. *Nature Climate Change*, **8** (12), 1076–1081, doi:10.1038/s41558-018-0339-y.
- Stuefer, S.L., C.D. Arp, D.L. Kane and A.K. Liljedahl, 2017: Recent Extreme Runoff Observations From Coastal Arctic Watersheds in Alaska. *Water Resources Research*, **53** (11), 9145–9163, doi:10.1002/2017WR020567.
- Sturm, M., M.A. Goldstein, H. Huntington and T.A. Douglas, 2017: Using an option pricing approach to evaluate strategic decisions in a rapidly changing climate: Black-Scholes and climate change. *Climatic Change*, **140** (3), 437–449, doi:10.1007/s10584-016-1860-5.
- Sturm, M. and R.A. Massom, 2016: Snow in the sea ice system: friend or foe? In: *Sea Ice* [Thomas, D.N. (ed.)]. Wiley-Blackwell, 652.
- Sturm, M. and S. Stuefer, 2013: Wind-blown flux rates derived from drifts at arctic snow fences. *Journal of Glaciology*, **59** (213), 21–34, doi:10.3189/2013JoG12J110.
- Sundby, S., K.F. Drinkwater and O.S. Kjesbu, 2016: The North Atlantic Spring-Bloom System – Where the Changing Climate Meets the Winter Dark. *Frontiers in Marine Science*, **3**, doi:10.3389/fmars.2016.00028.
- Suprenand, P.M. and C.H. Ainsworth, 2017: Trophodynamic effects of climate change-induced alterations to primary production along the western Antarctic Peninsula. *Marine Ecology Progress Series*, **569**, 37–54, doi:10.3354/meps12100.
- Surdu, C.M., C.R. Duguay, L.C. Brown and D. Fernández Prieto, 2014: Response of ice cover on shallow lakes of the North Slope of Alaska to contemporary climate conditions (1950–2011): radar remote-sensing and numerical modeling data analysis. *The Cryosphere*, **8** (1), 167–180, doi:10.5194/tc-8-167-2014.
- Surdu, C.M., C.R. Duguay and D. Fernández Prieto, 2016: Evidence of recent changes in the ice regime of lakes in the Canadian High Arctic from spaceborne satellite observations. *The Cryosphere*, **10** (3), 941–960, doi:10.5194/tc-10-941-2016.
- Sutterley, T.C. et al., 2014: Mass loss of the Amundsen Sea Embayment of West Antarctica from four independent techniques. *Geophysical Research Letters*, **41** (23), 8421–8428, doi:10.1002/2014GL061940.
- Suzuki, K. et al., 2018: Hydrological Variability and Changes in the Arctic Circumpolar Tundra and the Three Largest Pan-Arctic River Basins from 2002 to 2016. *Remote Sensing*, **10** (3), doi:10.3390/rs10030402.
- Swart, N.C. and J.C. Fyfe, 2013: The influence of recent Antarctic ice sheet retreat on simulated sea ice area trends. *Geophysical Research Letters*, **40**, 4328–4332, doi:10.1002/grl.50820.
- Swart, N.C., J.C. Fyfe, N. Gillett and G.J. Marshall, 2015a: Comparing Trends in the Southern Annular Mode and Surface Westerly Jet. *Journal of Climate*, **28** (22), 8840–8859, doi:10.1175/JCLI-D-14-00716.s1.
- Swart, N.C. et al., 2015b: Influence of internal variability on Arctic sea-ice trends. *Nature Climate Change*, **5**, 86, doi:10.1038/nclimate2483.
- Swart, N.C., J.C. Fyfe, O.A. Saenko and M. Eby, 2014: Wind-driven changes in the ocean carbon sink. *Biogeosciences*, **11** (21), 6107–6117, doi:10.5194/bg-11-6107-2014.
- Swart, N.C., S.T. Gille, J.C. Fyfe and N.P. Gillett, 2018: Recent Southern Ocean warming and freshening driven by greenhouse gas emissions and ozone depletion. *Nature Geoscience*, **11** (11), 836–841, doi:10.1038/s41561-018-0226-1.
- Sweeney, C. et al., 2016: No significant increase in long-term CH₄ emissions on North Slope of Alaska despite significant increase in air temperature. *Geophysical Research Letters*, **43** (12), 6604–6611, doi:10.1002/2016GL069292.
- Swiney, K.M., W.C. Long and R.J. Foy, 2017: Decreased pH and increased temperatures affect young-of-the-year red king crab (*Paralithodes camtschaticus*). *ICES Journal of Marine Science*, **74** (4), 1191–1200, doi:10.1093/icesjms/fsw251.
- Sydeman, W.J., E. Poloczanska, T.E. Reed and S.A. Thompson, 2015: Climate change and marine vertebrates. *Science*, **350** (6262), 772–777, doi:10.1126/science.aac9874.
- Szpak, P., M. Buckley, C.M. Darwent and M.P. Richards, 2018: Long-term ecological changes in marine mammals driven by recent warming in northwestern Alaska. *Global Change Biology*, **24** (1), 490–503, doi:10.1111/gcb.13880.
- Takakura, H., 2018: Local Perception of River Thaw and Spring Flooding of the Lena River. In: *Global Warming and Human-Nature Dimension in Northern Eurasia* [Hiyama, T. and H. Takakura (eds.)]. Springer, Singapore, 29–51.
- Talley, L.D. et al., 2016: Changes in Ocean Heat, Carbon Content, and Ventilation: A Review of the First Decade of GO-SHIP Global Repeat Hydrography. *Ann Rev Mar Sci*, **8**, 185–215, doi:10.1146/annurev-marine-052915-100829.
- Tamura, T., K.I. Ohshima, A.D. Fraser and G.D. Williams, 2016: Sea ice production variability in Antarctic coastal polynyas. *Journal of Geophysical Research: Oceans*, **121** (5), 2967–2979, doi:10.1002/2015jc011537.
- Tan, Z. and Q. Zhuang, 2015: Arctic lakes are continuous methane sources to the atmosphere under warming conditions. *Environmental Research Letters*, **10** (5), 054016, doi:10.1088/1748-9326/10/5/054016.
- Tandon, N.F. et al., 2018: Reassessing Sea Ice Drift and Its Relationship to Long-Term Arctic Sea Ice Loss in Coupled Climate Models. *Journal of Geophysical Research: Oceans*, **123** (6), 4338–4359, doi:10.1029/2017jc013697.

- Tanhua, T. et al., 2017: Temporal changes in ventilation and the carbonate system in the Atlantic sector of the Southern Ocean. *Deep-Sea Research Part II*, **138**, 26–38, doi:10.1016/j.dsr2.2016.10.004.
- Tank, S.E. et al., 2012: A land-to-ocean perspective on the magnitude, source and implication of DIC flux from major Arctic rivers to the Arctic Ocean. *Global Biogeochemical Cycles*, **26** (4), GB4018, doi:10.1029/2011gb004192.
- Tape, K.D. et al., 2016: Range Expansion of Moose in Arctic Alaska Linked to Warming and Increased Shrub Habitat. *Plos One*, **11** (4), e0152636, doi:10.1371/journal.pone.0152636.
- Tape, K.D. et al., 2018: Tundra be dammed: Beaver colonization of the Arctic. *Global Change Biology*, **24** (10), 4478–4488, doi:10.1111/gcb.14332.
- Tarling, G.A., P. Ward and S.E. Thorpe, 2018: Spatial distributions of Southern Ocean mesozooplankton communities have been resilient to long-term surface warming. *Glob Chang Biol*, **24** (1), 132–142, doi:10.1111/gcb.13834.
- Tarnocai, C. et al., 2009: Soil organic carbon pools in the northern circumpolar permafrost region. *Global Biogeochemical Cycles*, **23**, GB2023, doi:10.1029/2008gb003327.
- Taylor, D.J., M.J. Ballinger, A.S. Medeiros and A.A. Kotov, 2015: Climate-associated tundra thaw pond formation and range expansion of boreal zooplankton predators. *Ecography*, **39** (1), 43–53, doi:10.1111/ecog.01514.
- Taylor, P., B. Hegyi, R. Boeke and L. Boisvert, 2018: On the Increasing Importance of Air-Sea Exchanges in a Thawing Arctic: A Review. *Atmosphere*, **9** (2), doi:10.3390/atmos9020041.
- Taylor, S.G., 2007: Climate warming causes phenological shift in Pink Salmon, *Oncorhynchus gorbuscha*, behavior at Auke Creek, Alaska. *Global Change Biology*, **14** (2), 229–235, doi:10.1111/j.1365-2486.2007.01494.x.
- Tedesco, M. et al., 2016a: The darkening of the Greenland ice sheet: trends, drivers, and projections (1981–2100). *The Cryosphere*, **10** (2), 477–496, doi:10.5194/tc-10-477-2016.
- Tedesco, M. et al., 2013: Evidence and analysis of 2012 Greenland records from spaceborne observations, a regional climate model and reanalysis data. *The Cryosphere*, **7** (2), 615–630, doi:10.5194/tc-7-615-2013.
- Tedesco, M. et al., 2016b: Arctic cut-off high drives the poleward shift of a new Greenland melting record. *Nat Commun*, **7**, 11723, doi:10.1038/ncomms11723.
- Tedstone, A.J. et al., 2015: Decadal slowdown of a land-terminating sector of the Greenland Ice Sheet despite warming. *Nature*, **526**, 692, doi:10.1038/nature15722.
- Tesar, C., M.-A. Dubois, M. Sommerkorn and A. Shestakov, 2016a: Warming to the subject: the Arctic Council and climate change. *The Polar Journal*, **6** (2), 417–429, doi:10.1080/2154896X.2016.1247025.
- Tesar, C., M.A. Dubois and A. Shestakov, 2016b: Toward strategic, coherent, policy-relevant arctic science. *Science*, **353** (6306), 1368–1370, doi:10.1126/science.aai8198.
- Têtu, P.-L., J.-F. Pelletier and F. Lasserre, 2015: The mining industry in Canada north of the 55th parallel: a maritime traffic generator? *Polar Geography*, **38** (2), 107–122, doi:10.1080/1088937x.2015.1028576.
- Thackeray, C.W. and C.G. Fletcher, 2016: Snow albedo feedback: Current knowledge, importance, outstanding issues and future directions. *Progress in Physical Geography*, **40** (3), 392–408, doi:10.1177/0309133315620999.
- Thackeray, C.W., C.G. Fletcher and C. Derksen, 2014: The influence of canopy snow parameterizations on snow albedo feedback in boreal forest regions. *Journal of Geophysical Research: Atmospheres*, **119** (16), 9810–9821, doi:10.1002/2014jd021858.
- Thackeray, C.W., C.G. Fletcher, L.R. Mudryk and C. Derksen, 2016: Quantifying the Uncertainty in Historical and Future Simulations of Northern Hemisphere Spring Snow Cover. *Journal of Climate*, **29** (23), 8647–8663, doi:10.1175/jcli-d-16-0341.1.
- The IMBIE Team, 2018: Mass balance of the Antarctic Ice Sheet from 1992 to 2017. *Nature*, **558** (7709), 219–222, doi:10.1038/s41586-018-0179-y.
- The World Factbook, 2016: *The World Factbook 2016–17*. Central Intelligence Agency, Washington, DC [Available at: www.cia.gov/library/publications/the-world-factbook/index.html].
- Thomas, C.D. and P.K. Gillingham, 2015: The performance of protected areas for biodiversity under climate change. *Biological Journal of the Linnean Society*, **115** (3), 718–730, doi:10.1111/bij.12510.
- Thomas, E.R. et al., 2015: Twentieth century increase in snowfall in coastal West Antarctica. *Geophysical Research Letters*, **42** (21), 9387–9393, doi:10.1002/2015GL065750.
- Thomas, E.R. et al., 2017a: Regional Antarctic snow accumulation over the past 1000 years. *Climate of the Past*, **13** (11), 1491–1513, doi:10.5194/cp-13-1491-2017.
- Thomas, E.R. et al., 2017b: Review of regional Antarctic snow accumulation over the past 1000 years. *Climate of the Past Discussions*, 1–42, doi:10.5194/cp-2017-18.
- Thompson, A.F. and A.C. Naveira Garabato, 2014: Equilibration of the Antarctic Circumpolar Current by Standing Meanders. *Journal of Physical Oceanography*, **44** (7), 1811–1828, doi:10.1175/JPO-D-13-0163.1.
- Thomson, J. and W.E. Rogers, 2014: Swell and sea in the emerging Arctic Ocean. *Geophysical Research Letters*, **41** (9), 3136–3140, doi:10.1002/2014gl059983.
- Thor, P. et al., 2018: Contrasting physiological responses to future ocean acidification among Arctic copepod populations. *Glob Chang Biol*, **24** (1), e365–e377, doi:10.1111/gcb.13870.
- Thornalley, D.J.R. et al., 2018: Anomalously weak Labrador Sea convection and Atlantic overturning during the past 150 years. *Nature*, **556** (7700), 227–230, doi:10.1038/s41586-018-0007-4.
- Thornton, B.F. et al., 2016: Methane fluxes from the sea to the atmosphere across the Siberian shelf seas. *Geophysical Research Letters*, **43** (11), 5869–5877, doi:10.1002/2016GL068977.
- Timmermans, M.-L., C. Ladd and K. Wood, 2017: *Sea surface temperature* [NOAA (ed.)]. Arctic Report Card, NOAA, <https://arctic.noaa.gov/Report-Card/Report-Card-2017/ArtMID/7798/ArticleID/698/Sea-Surface-Temperature>.
- Timmermans, M.-L., J. Toole and R. Krishfield, 2018: Warming of the interior Arctic Ocean linked to sea ice losses at the basin margins. *Science Advances*, **4** (8), doi:10.1126/sciadv.aat6773.
- Timmermans, M.L., 2015: The impact of stored solar heat on Arctic sea ice growth. *Geophysical Research Letters*, **42** (15), 6399–6406, doi:10.1002/2015GL064541.
- Timmermans, M.L. et al., 2014: Mechanisms of Pacific summer water variability in the Arctic's Central Canada basin. *Journal of Geophysical Research: Oceans*, **119** (11), 7523–7548, doi:10.1002/2014JC010273.
- Ting, Y.-H. and M. Holzer, 2017: Decadal changes in Southern Ocean ventilation inferred from deconvolutions of repeat hydrographies. *Geophysical Research Letters*, **44** (11), 5655–5664, doi:10.1002/2017gl073788.
- Todd, J. and P. Christoffersen, 2014: Are seasonal calving dynamics forced by buttressing from ice mélange or undercutting by melting? Outcomes from full-Stokes simulations of Store Glacier, West Greenland. *Cryosphere*, **8** (6), 2353–2365, doi:10.5194/tc-8-2353-2014.
- Trathan, P.N., S.M. Grant, V. Siegel and K.H. Kock, 2013: Precautionary spatial protection to facilitate the scientific study of habitats and communities under ice shelves in the context of recent, rapid, regional climate change. *CCAMLR Science*, **20**, 139–151.
- Trathan, P.N. and S.L. Hill, 2016: The Importance of Krill Predation in the Southern Ocean. In: *Biology and Ecology of Antarctic Krill* [Siegel, V. (ed.)]. Springer, 321–350.
- Trenary, L., T. DeSole, M.K. Tippett and B. Doty, 2016: Extreme eastern U.S. winter of 2015 not symptomatic of climate change [in “Explaining Extreme Events of 2015 from a Climate Perspective”]. **97**, S31–S35, doi:10.1175/BAMS-D-16-0156.1.
- Trimborn, S. et al., 2017: Two Southern Ocean diatoms are more sensitive to ocean acidification and changes in irradiance than the prymnesiophyte

- Phaeocystis antarctica. *Physiol Plant*, **160** (2), 155–170, doi:10.1111/ppl.12539.
- Trivelpiece, W.Z. et al., 2011: Variability in krill biomass links harvesting and climate warming to penguin population changes in Antarctica. *Proc Natl Acad Sci U S A*, **108** (18), 7625–8, doi:10.1073/pnas.1016560108.
- Troy, T.J., J. Sheffield and E.F. Wood, 2012: The role of winter precipitation and temperature on northern Eurasian streamflow trends. *Journal of Geophysical Research: Atmospheres*, **117** (D5), D05131, doi:10.1029/2011jd016208.
- Trump, B.D., M. Kadenic and I. Linkov, 2018: A sustainable Arctic: Making hard decisions. *Arctic, Antarctic, and Alpine Research*, **50** (1), doi:10.1080/15230430.2018.1438345.
- Trusel, L.D. et al., 2018: Nonlinear rise in Greenland runoff in response to post-industrial Arctic warming. *Nature*, **564** (7734), 104–108, doi:10.1038/s41586-018-0752-4.
- Tulloch, V.J.D. et al., 2019: Future recovery of baleen whales is imperiled by climate change. *Glob Chang Biol*, doi:10.1111/gcb.14573.
- Tuori, K., 2011: The Disputed Roots of Legal Pluralism. *Law, Culture and the Humanities*, **9** (2), 330–351, doi:10.1177/1743872111412718.
- Turetsky, M.R. et al., 2011: Recent acceleration of biomass burning and carbon losses in Alaskan forests and peatlands. *Nature Geoscience*, **4** (1), 27–31, doi:https://doi.org/10.1038/ngeo1027.
- Turner, D.R., I.-M. Hasselöv, E. Ytreberg and A. Rutgersson, 2017a: Shipping and the environment: Smokestack emissions, scrubbers and unregulated oceanic consequences. *Elem Sci Anth*, **5**, 45, doi:http://doi.org/10.1525/elementa.167.
- Turner, J. et al., 2009: *Antarctic Climate Change and the Environment*. Scientific Committee on Antarctic Research Scott Polar Research Institute, Cambridge, UK.
- Turner, J. et al., 2013: An Initial Assessment of Antarctic Sea Ice Extent in the CMIP5 Models. *Journal of Climate*, **26** (5), 1473–1484, doi:10.1175/jcli-d-12-00068.1.
- Turner, J. et al., 2016: Absence of 21st century warming on Antarctic Peninsula consistent with natural variability. *Nature*, **535** (7612), 411–415, doi:10.1038/nature18645.
- Turner, J. et al., 2017b: Unprecedented springtime retreat of Antarctic sea ice in 2016. *Geophysical Research Letters*, **44** (13), 6868–6875, doi:10.1002/2017gl073656.
- Turney, C.S.M. et al., 2017: Tropical forcing of increased Southern Ocean climate variability revealed by a 140-year subantarctic temperature reconstruction. *Clim. Past*, **13** (3), 231–248, doi:10.5194/cp-13-231-2017.
- Turunen, M.T. et al., 2016: Coping with difficult weather and snow conditions: Reindeer herders' views on climate change impacts and coping strategies. *Climate Risk Management*, **11**, 15–36, doi:10.1016/j.crm.2016.01.002.
- Uboni, A. et al., 2016: Long-term trends and role of climate in the population dynamics of eurAsian reindeer. *Plos One*, **11** (6), 1–20, doi:10.1371/journal.pone.0158359.
- Udevitz, M.S. et al., 2017: Forecasting consequences of changing sea ice availability for Pacific walrus. *Ecosphere*, **8** (11), e02014, doi:10.1002/ecs2.2014.
- Ueyama, M. et al., 2013: Growing season and spatial variations of carbon fluxes of Arctic and boreal ecosystems in Alaska (USA). *Ecological Applications*, **23** (8), 1798–1816, doi:10.1890/11-0875.1.
- Ulrich, M. et al., 2017: Differences in behavior and distribution of permafrost-related lakes in Central Yakutia and their response to climatic drivers. *Water Resources Research*, **53** (2), 1167–1188, doi:10.1002/2016wr019267.
- Uotila, P., T. Vihma and M. Tsukernik, 2013: Close interactions between the Antarctic cyclone budget and large-scale atmospheric circulation. *Geophysical Research Letters*, **40** (12), 3237–3241, doi:10.1002/grl.50560.
- Utvik, T.I.R. and C. Jahre-Nilsen, 2016: The Importance of Early Identification of Safety and Sustainability Related Risks in Arctic Oil and Gas Operations. In: *SPE International Conference and Exhibition on Health, Safety, Security, Environment, and Social Responsibility*, 2016/4/11, Stavanger, Norway, Society of Petroleum Engineers, SPE, doi:10.2118/179325-MS.
- Vacchi, M. et al., 2012: A nursery area for the Antarctic silverfish *Pleuragramma antarcticum* at Terra Nova Bay (Ross Sea): first estimate of distribution and abundance of eggs and larvae under the seasonal sea-ice. *Polar Biology*, **35** (10), 1573–1585, doi:10.1007/s00300-012-1199-y.
- Vallot, D. et al., 2018: Effects of undercutting and sliding on calving: a global approach applied to Kronebreen, Svalbard. *The Cryosphere*, **12** (2), 609–625, doi:10.5194/tc-12-609-2018.
- van den Broeke, M. et al., 2017: Greenland Ice Sheet Surface Mass Loss: Recent Developments in Observation and Modeling. *Current Climate Change Reports*, **3** (4), 345–356, doi:10.1007/s40641-017-0084-8.
- van den Broeke, M.R. et al., 2016: On the recent contribution of the Greenland ice sheet to sea level change. *The Cryosphere*, **10** (5), 1933–1946, doi:10.5194/tc-10-1933-2016.
- van der Hel, S., 2016: New science for global sustainability? The institutionalisation of knowledge co-production in Future Earth. *Environmental Science & Policy*, **61**, 165–175, doi:10.1016/j.envsci.2016.03.012.
- van der Linden, S., E. Maibach and A. Leiserowitz, 2015: Improving Public Engagement With Climate Change: Five “Best Practice” Insights From Psychological Science. *Perspectives on Psychological Science*, **10** (6), 758–763, doi:10.1177/1745691615598516.
- van der Werf, G.R. et al., 2010: Global fire emissions and the contribution of deforestation, savanna, forest, agricultural, and peat fires (1997–2009). *Atmospheric Chemistry and Physics*, **10** (23), 11707–11735, doi:10.5194/acp-10-11707-2010.
- van Oort, B., M. Bjørkan and E.M. Klyuchnikova, 2015: *Future narratives for two locations in the Barents region*. CICERO Report. CICERO Report, Research, C.C. f. I.C. a. E., Oslo [Available at: http://hdl.handle.net/11250/2367371].
- van Vliet, M.T.H. et al., 2013: Global river discharge and water temperature under climate change. *Global Environmental Change*, **23** (2), 450–464, doi:10.1016/j.gloenvcha.2012.11.002.
- Van Wychen, W. et al., 2014: Glacier velocities and dynamic ice discharge from the Queen Elizabeth Islands, Nunavut, Canada. *Geophysical Research Letters*, **41** (2), 484–490, doi:10.1002/2013gl058558.
- Van Wychen, W. et al., 2016: Characterizing interannual variability of glacier dynamics and dynamic discharge (1999–2015) for the ice masses of Ellesmere and Axel Heiberg Islands, Nunavut, Canada. *Journal of Geophysical Research: Earth Surface*, **121** (1), 39–63, doi:10.1002/2015jf003708.
- Vancoppenolle, M. et al., 2013: Future arctic ocean primary productivity from CMIP5 simulations: Uncertain outcome, but consistent mechanisms. *Global Biogeochemical Cycles*, **27** (3), 605–619, doi:10.1002/gbc.20055.
- Vargas-Moreno, J.C., B. Fradkin, S. Emperador and O.L. (eds), 2016: *Project Summary: Prioritizing Science Needs Through Participatory Scenarios for Energy and Resource Development on the North Slope and Adjacent Seas*. GeoAdaptive, LLC, Boston, Massachusetts. [Available at: http://northslope.org/scenarios/].
- Vavrus, S.J. et al., 2012: Twenty-First-Century Arctic Climate Change in CCSM4. *Journal of Climate*, **25** (8), 2696–2710, doi:10.1175/jcli-d-11-00220.1.
- Velicogna, I., T.C. Sutterley and M.R. Van Den Broeke, 2014: Regional acceleration in ice mass loss from Greenland and Antarctica using GRACE time-variable gravity data. *Geophysical Research Letters*, **41** (22), 8130–8137, doi:10.1002/2014GL061052.
- Venables, H.J., A. Clarke and M.P. Meredith, 2013: Wintertime controls on summer stratification and productivity at the western Antarctic Peninsula. *Limnology and Oceanography*, **58** (3), 1035–1047, doi:10.4319/lo.2013.58.3.1035.
- Veraverbeke, S. et al., 2017: Lightning as a major driver of recent large fire years in North American boreal forests. *Nature Climate Change*, **7** (7), 529–534, doi:10.1038/nclimate3329.
- Verfaillie, D. et al., 2015: Recent glacier decline in the Kerguelen Islands (49°S, 69°E) derived from modeling, field observations, and satellite

- data. *Journal of Geophysical Research: Earth Surface*, **120** (3), 637–654, doi:10.1002/2014JF003329.
- Verschuuren, J., 2013: Legal Aspects of Climate Change Adaptation In: Climate Change and the Law Part III: Comparative Perspectives on Law and Justice. [Hollo, E., K. Kulovesi and M. Mehling (eds.)]. Springer, Dordrecht, 21.
- Vickers, H. et al., 2016: Changes in greening in the high Arctic: insights from a 30 year AVHRR max NDVI dataset for Svalbard. *Environmental Research Letters*, **11** (10), doi:10.1088/1748-9326/11/10/105004.
- Vihma, T. et al., 2016: The atmospheric role in the Arctic water cycle: A review on processes, past and future changes, and their impacts. *Journal of Geophysical Research: Biogeosciences*, **121** (3), 586–620, doi:10.1002/2015jg003132.
- Vihma, T., P. Tisler and P. Uotila, 2012: Atmospheric forcing on the drift of Arctic sea ice in 1989–2009. *Geophysical Research Letters*, **39** (2), doi:10.1029/2011gl050118.
- Vihtakari, M. et al., 2018: Black-legged kittiwakes as messengers of Atlantification in the Arctic. *Scientific Reports*, **8** (1), 1178, doi:10.1038/s41598-017-19118-8.
- Vincent et al., 2015: Observed trends in Canada's climate and influence of low-frequency variability modes. *Journal of Climate*, **28**, 4545–4560, doi:10.1175/jcli-d-14-00697.1.
- Vincent, W.F. et al., 2011: Ecological Implications of Changes in the Arctic Cryosphere. *AMBIO*, **40** (1), 87–99, doi:10.1007/s13280-011-0218-5.
- Vincent, W.F., M. Lemay and M. Allard, 2017: Arctic permafrost landscapes in transition: towards an integrated Earth system approach. *Arctic Science*, **3** (2), 39–64, doi:10.1139/as-2016-0027.
- Vinther, B.M. et al., 2009: Holocene thinning of the Greenland ice sheet. *Nature*, **461** (7262), 385–8, doi:10.1038/nature08355.
- Vlasova, T. and S. Volkov, 2016: Towards transdisciplinarity in Arctic sustainability knowledge co-production: Socially-Oriented Observations as a participatory integrated activity. *Polar Science*, **10** (3), 425–432, doi:10.1016/j.polar.2016.06.002.
- Vonk, J.E. et al., 2015: Reviews and syntheses: Effects of permafrost thaw on Arctic aquatic ecosystems. *Biogeosciences*, **12** (23), 7129–7167, doi:10.5194/bg-12-7129-2015.
- Voorhees, H., R. Sparks, H.P. Huntington and K.D. Rode, 2014: Traditional Knowledge about Polar Bears (*Ursus maritimus*) in Northwestern Alaska. *Arctic*, **67** (4), 523–536.
- Wadham, J.L. et al., 2013: The potential role of the Antarctic Ice Sheet in global biogeochemical cycles. *Earth and Environmental Science Transactions of the Royal Society of Edinburgh*, **104** (1), 55–67, doi:10.1017/S1755691013000108.
- Wadham, J.L. et al., 2016: Sources, cycling and export of nitrogen on the Greenland Ice Sheet. *Biogeosciences*, **13** (22), 6339–6352, doi:10.5194/bg-13-6339-2016.
- Walker, C.C. and A.S. Gardner, 2017: Rapid drawdown of Antarctica's Wordie Ice Shelf glaciers in response to ENSO/Southern Annular Mode-driven warming in the Southern Ocean. *Earth and Planetary Science Letters*, **476**, 100–110, doi:10.1016/j.epsl.2017.08.005.
- Walker, D.A. et al., 2015: A hierarchic approach for examining panarctic vegetation with a focus on the linkages between remote-sensing and plot-based studies: A prototype example from Toolik Lake, Alaska. In: *AGU Fall meeting 14–19 Dec 2015*, San Francisco, USA, AGU Fall Meeting.
- Walker, D.A. et al., 2016: Circumpolar Arctic vegetation: a hierarchic review and roadmap toward an internationally consistent approach to survey, archive and classify tundra plot data. *Environmental Research Letters*, **11** (5), 055005, doi:10.1088/1748-9326/11/5/055005.
- Walker, D.P. et al., 2013: Oceanographic observations at the shelf break of the Amundsen Sea, Antarctica. *Journal of Geophysical Research: Oceans*, **118** (6), 2906–2918, doi:10.1002/jgrc.20212.
- Wallhead, P.J. et al., 2017: Bottom Water Acidification and Warming on the Western Eurasian Arctic Shelves: Dynamical Downscaling Projections. *Journal of Geophysical Research: Oceans*, **122** (10), 8126–8144, doi:10.1002/2017jc013231.
- Walsh, J.E., F. Fetterer, J. Scott Stewart and W.L. Chapman, 2017: A database for depicting Arctic sea ice variations back to 1850. *Geographical Review*, **107** (1), 89–107, doi:10.1111/j.1931-0846.2016.12195.x.
- Walsh, M.G., A.W. de Smalen and S.M. Mor, 2018: Climatic influence on anthrax suitability in warming northern latitudes. *Sci Rep*, **8** (1), 9269, doi:10.1038/s41598-018-27604-w.
- Walter Anthony, K. et al., 2018: 21st-century modeled permafrost carbon emissions accelerated by abrupt thaw beneath lakes. *Nat Commun*, **9** (1), 3262, doi:10.1038/s41467-018-05738-9.
- Walter Anthony, K.M., P. Anthony, G. Grosse and J. Chanton, 2012: Geologic methane seeps along boundaries of Arctic permafrost thaw and melting glaciers. *Nature Geoscience*, **5** (6), 419–426, doi:10.1038/ngeo1480.
- Walter Anthony, K.M. et al., 2014: A shift of thermokarst lakes from carbon sources to sinks during the Holocene epoch. *Nature*, **511** (7510), 452–456, doi:10.1038/nature13560.
- Walter, K.M. et al., 2007: Thermokarst Lakes as a Source of Atmospheric CH₄ During the Last Deglaciation. *Science*, **318** (5850), 633–636, doi:10.1126/science.1142924.
- Walvoord, M.A. and B.L. Kurylyk, 2016: Hydrologic Impacts of Thawing Permafrost – A Review. *Vadose Zone Journal*, **15** (6), doi:10.2136/vzj2016.01.0010.
- Walvoord, M.A. and R.G. Striegl, 2007: Increased groundwater to stream discharge from permafrost thawing in the Yukon River basin: Potential impacts on lateral export of carbon and nitrogen. *Geophysical Research Letters*, **34** (L12402), doi:10.1029/2007GL030216.
- Walvoord, M.A., C.I. Voss, B.A. Ebel and B.J. Minsley, 2019: Development of perennial thaw zones in boreal hillslopes enhances potential mobilization of permafrost carbon. *Environmental Research Letters*, **14** (1), doi:10.1088/1748-9326/aaf0cc.
- Wang, C. et al., 2014: A global perspective on CMIP5 climate model biases. *Nature Climate Change*, **4** (3), 201, doi:10.1038/nclimate2118.
- Wang, G. et al., 2019: Compounding tropical and stratospheric forcing of the record low Antarctic sea-ice in 2016. *Nat Commun*, **10** (1), 13, doi:10.1038/s41467-018-07689-7.
- Wang, L., C. Derksen and R. Brown, 2013: Recent changes in pan-Arctic melt onset from satellite passive microwave measurements. *Geophysical Research Letters*, **40**, 522–528, doi:10.1002/grl.50098.
- Wang, Q. et al., 2016a: Sea ice leads in the Arctic Ocean: Model assessment, interannual variability and trends. *Geophysical Research Letters*, **43** (13), 7019–7027, doi:10.1002/2016GL068696.
- Wang, S.W. et al., 2015: Importance of sympagic production to Bering Sea zooplankton as revealed from fatty acid-carbon stable isotope analyses. *Marine Ecology Progress Series*, **518**, 31–50, doi:10.3354/meps11076.
- Wang, Y. et al., 2016b: A Comparison of Antarctic Ice Sheet Surface Mass Balance from Atmospheric Climate Models and In Situ Observations. *Journal of Climate*, **29** (14), 5317–5337, doi:10.1175/JCLI-D-15-0642.1.
- Ward, E.J. et al., 2017: Effects of increased specialization on revenue of Alaskan salmon fishers over four decades. *Journal of Applied Ecology*, **55** (3), 1082–1091, doi:10.1111/1365-2664.13058.
- Warren, S.G. et al., 1999: Snow Depth on Arctic Sea Ice. *Journal of Climate*, **12** (6), 1814–1829, doi:10.1175/1520-0442(1999)012<1814:sdoasi>2.0.co;2.
- Wassmann, P. et al., 2015: The contiguous domains of Arctic Ocean advection: Trails of life and death. *Progress in Oceanography*, **139**, 42–65, doi:10.1016/j.pocean.2015.06.011.
- Wassmann, P. and T.M. Lenton, 2012: Arctic Tipping Points in an Earth System Perspective. *AMBIO*, **41** (1), 1–9, doi:10.1007/s13280-011-0230-9.
- Watts, P., K. Koutouki, S. Booth and S. Blum, 2017: Inuit food security in Canada: arctic marine ethnoecology. *Food Security*, **9** (3), 421–440, doi:10.1007/s12571-017-0668-0.
- Waugh, D.W., 2014: Changes in the ventilation of the southern oceans. *Phil. Trans. R. Soc. A*, **372** (2019), 20130269, doi:10.1126/science.1225411.

- Waugh, D.W., C.I. Garfinkel and L.M. Polvani, 2015: Drivers of the Recent Tropical Expansion in the Southern Hemisphere: Changing SSTs or Ozone Depletion? *Journal of Climate*, **28** (16), 6581–6586, doi:10.1175/jcli-d-15-0138.1.
- Waugh, D.W., F. Primeau, T. DeVries and M. Holzer, 2013: Recent Changes in the Ventilation of the Southern Oceans. *Science*, **339** (6119), 568–570, doi:10.1029/2008JC004864.
- WCRP, 2018: Global sea-level budget 1993–present. *Earth System Science Data*, **10** (3), 1551–1590, doi:10.5194/essd-10-1551-2018.
- Webb, B.W. et al., 2008: Recent advances in stream and river temperature research. *Hydrological Processes*, **22** (7), 902–918, doi:10.1002/hyp.6994.
- Webb, E.E. et al., 2016: Increased wintertime CO₂ loss as a result of sustained tundra warming. *Journal of Geophysical Research: Biogeosciences*, **121** (2), 249–265, doi:10.1002/2014jg002795.
- Webber, B.G.M. et al., 2017: Mechanisms driving variability in the ocean forcing of Pine Island Glacier. *Nature Communications*, **8**, 14507, doi:10.1038/ncomms14507.
- Weber, M.E. et al., 2014: Millennial-scale variability in Antarctic ice-sheet discharge during the last deglaciation. *Nature*, **510**, 134, doi:10.1038/nature13397.
- Webster, M. et al., 2018: Snow in the changing sea-ice systems. *Nature Climate Change*, **8** (11), 946–953, doi:10.1038/s41558-018-0286-7.
- Webster, M.A. et al., 2014: Interdecadal changes in snow depth on Arctic sea ice. *Journal of Geophysical Research: Oceans*, **119** (8), 5395–5406, doi:10.1002/2014jc009985.
- Wedekind, C. et al., 2010: Elevated resource availability sufficient to turn opportunistic into virulent fish pathogens. *Ecology*, **91** (5), 1251–1256, doi:10.1890/09-1067.1.
- Wehrmann, D., 2016: The Polar Regions as “barometers” in the Anthropocene: towards a new significance of non-state actors in international cooperation? *The Polar Journal*, **6** (2), 379–397, doi:10.1080/2154896X.2016.1241483.
- Wehrmann, L.M. et al., 2013: The evolution of early diagenetic signals in Bering Sea subsurface sediments in response to varying organic carbon deposition over the last 4.3Ma. *Geochimica et Cosmochimica Acta*, **109**, 175–196, doi:10.1016/j.gca.2013.01.025.
- Wehrmann, L.M. et al., 2014: Iron and manganese speciation and cycling in glacially influenced high-latitude fjord sediments (West Spitsbergen, Svalbard): Evidence for a benthic recycling-transport mechanism. *Geochimica et Cosmochimica Acta*, **141**, 628–655, doi:10.1016/j.gca.2014.06.007.
- Weimerskirch, H., M. Louzao, S. de Grissac and K. Delord, 2012: Changes in wind pattern alter albatross distribution and life-history traits. *Science*, **335** (6065), 211–4, doi:10.1126/science.1210270.
- Wellman, T.P., C.I. Voss and M.A. Walvoord, 2013: Impacts of climate, lake size, and supra- and sub-permafrost groundwater flow on lake-talik evolution, Yukon Flats, Alaska (USA). *Hydrogeology Journal*, **21** (1), 281–298, doi:10.1007/s10040-012-0941-4.
- Wenzel, L. et al., 2016: Polar opposites? Marine conservation tools and experiences in the changing Arctic and Antarctic. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **26**, 61–84, doi:10.1002/aqc.2649.
- Westergaard-Nielsen, A. et al., 2017: Transitions in high-Arctic vegetation growth patterns and ecosystem productivity tracked with automated cameras from 2000 to 2013. *AMBIO*, **46** (1), 39–52, doi:10.1007/s13280-016-0864-8.
- Westwood, K.J. et al., 2018: Ocean acidification impacts primary and bacterial production in Antarctic coastal waters during austral summer. *Journal of Experimental Marine Biology and Ecology*, **498**, 46–60, doi:10.1016/j.jembe.2017.11.003.
- Wheeler, H.C. et al., 2018: Identifying key needs for the integration of social-ecological outcomes in arctic wildlife monitoring. *Conserv Biol*, doi:10.1111/cobi.13257.
- Whitehead, A.L. et al., 2015: Factors driving Adélie penguin chick size, mass and condition at colonies of different sizes in the Southern Ross Sea. *Marine Ecology Progress Series*, **523**, 199–213, doi:10.3354/meps11130.
- Wickland, K.P. et al., 2018: Dissolved organic carbon and nitrogen release from boreal Holocene permafrost and seasonally frozen soils of Alaska. *Environmental Research Letters*, **13** (6), 065011, doi:10.1088/1748-9326/aac4ad.
- Williams, N.L. et al., 2017: Calculating surface ocean pCO₂ from biogeochemical Argo floats equipped with pH: An uncertainty analysis. *Global Biogeochemical Cycles*, **31** (3), 591–604, doi:10.1002/2016GB005541.
- Williams, P. et al., 2018: Community-based observing networks and systems in the Arctic: Human perceptions of environmental change and instrument-derived data. *Regional Environmental Change*, **18** (2), 547–559, doi:10.1007/s10113-017-1220-7.
- Williams, W.J. and E.C. Carmack, 2015: The ‘interior’ shelves of the Arctic Ocean: Physical oceanographic setting, climatology and effects of sea-ice retreat on cross-shelf exchange. *Progress in Oceanography*, **139**, 24–41, doi:10.1016/j.pocean.2015.07.008.
- Willis, M.J., A.K. Melkonian and M.E. Pritchard, 2015: Outlet glacier response to the 2012 collapse of the Matusevich Ice Shelf, Severnaya Zemlya, Russian Arctic. *Journal of Geophysical Research: Earth Surface*, **120** (10), 2040–2055, doi:10.1002/2015JF003544.
- Willis, M.J. et al., 2018: Massive destabilization of an Arctic ice cap. *Earth and Planetary Science Letters*, **502**, 146–155, doi:10.1016/j.epsl.2018.08.049.
- Wilson, D.J. et al., 2018: Ice loss from the East Antarctic Ice Sheet during late Pleistocene interglacials. *Nature*, **561** (7723), 383–386, doi:10.1038/s41586-018-0501-8.
- Wilson, E.A., S.C. Riser, E.C. Campbell and A.P.S. Wong, 2019: Winter Upper-Ocean Stability and Ice–Ocean Feedbacks in the Sea Ice–Covered Southern Ocean. *Journal of Physical Oceanography*, **49** (4), 1099–1117, doi:10.1175/jpo-d-18-0184.1.
- Wilson, W.J. and O.A. Ormseth, 2009: A new management plan for Arctic waters of the United States. *Fisheries*, **34** (11), 555–558.
- Winfield, I.J. et al., 2010: Population trends of Arctic charr (*Salvelinus alpinus*) in the UK: assessing the evidence for a widespread decline in response to climate change. *Hydrobiologia*, **650** (1), 55–65, doi:10.1007/s10750-009-0078-1.
- Wise, M.G., J.A. Dowdeswell, M. Jakobsson and R.D. Larter, 2017: Evidence of marine ice-cliff instability in Pine Island Bay from iceberg-keel plough marks. *Nature*, **550** (7677), 506–510, doi:10.1038/nature24458.
- Woodgate, R.A., 2018: Increases in the Pacific inflow to the Arctic from 1990 to 2015, and insights into seasonal trends and driving mechanisms from year-round Bering Strait mooring data. *Progress in Oceanography*, **160**, 124–154, doi:10.1016/j.pocean.2017.12.007.
- Woodgate, R.A., K.M. Stafford and F.G. Prah, 2015: A synthesis of year-round interdisciplinary mooring measurements in the Bering Strait (1990–2014) and the RUSALCA years (2004–2011). *Oceanography*, **28** (3), 46–67, doi:10.5670/oceanog.2015.57.
- Worby, A.P. et al., 2008: Thickness distribution of Antarctic sea ice. *Journal of Geophysical Research-Oceans*, **113** (C5), C05s92, doi:10.1029/2007jc004254.
- Wotton, B.M., M.D. Flannigan and G.A. Marshall, 2017: Potential climate change impacts on fire intensity and key wildfire suppression thresholds in Canada. *Environmental Research Letters*, **12** (9), 095003, doi:10.1088/1748-9326/aa7e6e.
- Wouters, B., A.S. Gardner and G. Moholdt, 2019: Global Glacier Mass Loss During the GRACE Satellite Mission (2002–2016). *Frontiers in Earth Science*, **7**, doi:10.3389/feart.2019.00096.
- Wouters, B. et al., 2015: Dynamic thinning of glaciers on the Southern Antarctic Peninsula. *Science*, **348** (6237), 899–903, doi:10.1126/science.aaa5727.

- Wright, C.J. et al., 2018: Water quality and health in northern Canada: stored drinking water and acute gastrointestinal illness in Labrador Inuit. *Environ Sci Pollut Res Int*, **25** (33), 32975–32987, doi:10.1007/s11356-017-9695-9.
- Wrona, F.J. et al., 2016: Transitions in Arctic ecosystems: Ecological implications of a changing hydrological regime. *Journal of Geophysical Research: Biogeosciences*, **121** (3), 650–674, doi:10.1002/2015jg003133.
- Wu, C. et al., 2017: Present-day and future contribution of climate and fires to vegetation composition in the boreal forest of China. *Ecosphere*, **8** (8), e01917, doi:10.1002/ecs2.1917.
- Wu, S.-Y. and S. Hou, 2017: Impact of icebergs on net primary productivity in the Southern Ocean. *The Cryosphere*, **11** (2), 707–722, doi:10.5194/tc-11-707-2017.
- Wuite, J. et al., 2015: Evolution of surface velocities and ice discharge of Larsen B outlet glaciers from 1995 to 2013. *The Cryosphere*, **9** (3), 957–969, doi:10.5194/tc-9-957-2015.
- Xu, L. et al., 2013a: Temperature and vegetation seasonality diminishment over northern lands. *Nature Climate Change*, **3**, 581, doi:10.1038/nclimate1836
- Xu, Y. et al., 2013b: Subaqueous melting of Store Glacier, west Greenland from three-dimensional, high-resolution numerical modeling and ocean observations. *Geophysical Research Letters*, **40** (17), 4648–4653, doi:10.1002/grl.50825.
- Yager, P.L. et al., 2016: A carbon budget for the Amundsen Sea Polynya, Antarctica: Estimating net community production and export in a highly productive polar ecosystem. *Elementa-Science of the Anthropocene*, **4**, 000140, doi:http://doi.org/10.12952/journal.elementa.000140.
- Yamamoto-Kawai, M., T. Mifune, T. Kikuchi and S. Nishino, 2016: Seasonal variation of CaCO₃ saturation state in bottom water of a biological hotspot in the Chukchi Sea, Arctic Ocean. *Biogeosciences*, **13** (22), 6155–6169, doi:10.5194/bg-13-6155-2016.
- Yang, D., 2014: Double Fence Intercomparison Reference (DFIR) vs. Bush Gauge for “true” snowfall measurement. *Journal of Hydrology*, **509** (Supplement C), 94–100, doi:10.1016/j.jhydrol.2013.08.052.
- Yang, D., P. Marsh and S. Ge, 2014: Heat flux calculations for Mackenzie and Yukon Rivers. *Polar Science*, **8** (3), 232–241, doi:10.1016/j.polar.2014.05.001.
- Yang, D. and A. Peterson, 2017: River Water Temperature in Relation to Local Air Temperature in the Mackenzie and Yukon Basins. *Arctic*, **70** (1), 47–58, doi:10.14430/arctic4627.
- Yang, D., B. Ye and D.L. Kane, 2004a: Streamflow changes over Siberian Yenisei River Basin. *Journal of Hydrology*, **296** (1), 59–80, doi:10.1016/j.jhydrol.2004.03.017.
- Yang, D., B. Ye and A. Shiklomanov, 2004b: Discharge Characteristics and Changes over the Ob River Watershed in Siberia. *Journal of Hydrometeorology*, **5** (4), 595–610, doi:10.1175/1525-7541.
- Ye, B., D. Yang and D.L. Kane, 2003: Changes in Lena River streamflow hydrology: Human impacts versus natural variations. *Water Resources Research*, **39** (7), 1200, doi:10.1029/2003wr001991.
- Young, A.M., P.E. Higuera, P.A. Duffy and F.S. Hu, 2017: Climatic thresholds shape northern high-latitude fire regimes and imply vulnerability to future climate change. *Ecography*, **40** (5), 606–617, doi:10.1111/ecog.02205.
- Young, E.F. et al., 2018: Stepping stones to isolation: Impacts of a changing climate on the connectivity of fragmented fish populations. *Evol Appl*, **11** (6), 978–994, doi:10.1111/eva.12613.
- Young, I., K. Gropp, A. Fazil and B.A. Smith, 2015: Knowledge synthesis to support risk assessment of climate change impacts on food and water safety: A case study of the effects of water temperature and salinity on *Vibrio parahaemolyticus* in raw oysters and harvest waters. *Food Research International*, **68**, 86–93, doi:10.1016/j.foodres.2014.06.035.
- Young, O.R., 2011: If an Arctic Ocean treaty is not the solution, what is the alternative? *Polar Record*, **47** (4), 327–334, doi:10.1017/S0032247410000677.
- Young, O.R., 2016: The shifting landscape of Arctic politics: implications for international cooperation. *The Polar Journal*, **6** (2), 209–223, doi:10.1080/2154896X.2016.1253823.
- Younger, J.L. et al., 2015: Too much of a good thing: sea ice extent may have forced emperor penguins into refugia during the last glacial maximum. *Glob Chang Biol*, **21** (6), 2215–26, doi:10.1111/gcb.12882.
- Youngflesh, C. et al., 2017: Circumpolar analysis of the Adelie Penguin reveals the importance of environmental variability in phenological mismatch. *Ecology*, **98** (4), 940–951, doi:10.1002/ecs.1749.
- Yu, Q., H. Epstein, R. Engstrom and D. Walker, 2017: Circumpolar arctic tundra biomass and productivity dynamics in response to projected climate change and herbivory. *Global Change Biology*, **23** (9), 3895–3907, doi:10.1111/gcb.13632.
- Yu, Y. et al., 2013: Interannual Variability of Arctic Landfast Ice between 1976 and 2007. *Journal of Climate*, **27** (1), 227–243, doi:10.1175/jcli-d-13-00178.1.
- Yuan, X., M.R. Kaplan and M.A. Cane, 2018: The Interconnected Global Climate System – A Review of Tropical–Polar Teleconnections. *Journal of Climate*, **31** (15), 5765–5792, doi:10.1175/jcli-d-16-0637.1.
- Yun, M.S. et al., 2015: Regional productivity of phytoplankton in the Western Arctic Ocean during summer in 2010. *Deep Sea Research Part II: Topical Studies in Oceanography*, **120** (Supplement C), 61–71, doi:10.1016/j.dsr2.2014.11.023.
- Zador, S.G. et al., 2017: Ecosystem considerations in Alaska: the value of qualitative assessments. *ICES Journal of Marine Science*, **74** (1), 421–430, doi:10.1093/icesjms/fsw144.
- Zamani, B., T. Krumpfen, L.H. Smedsrud and R. Gerdes, 2019: Fram Strait sea ice export affected by thinning: comparing high-resolution simulations and observations. *Climate Dynamics*, **53** (5–6), 3257–3270, doi:10.1007/s00382-019-04699-z.
- Zdanowicz, C. et al., 2012: Summer melt rates on Penny Ice Cap, Baffin Island: Past and recent trends and implications for regional climate. *Journal of Geophysical Research: Earth Surface*, **117** (F2), doi:10.1029/2011JF002248.
- Zekollari, H., B.S. Lecavalier and P. Huybrechts, 2017: Holocene evolution of Hans Tausen Iskappe (Greenland) and implications for the palaeoclimatic evolution of the high Arctic. *Quaternary Science Reviews*, **168**, 182–193, doi:10.1016/j.quascirev.2017.05.010.
- Zemp, M. et al., 2019: Global glacier mass changes and their contributions to sea-level rise from 1961 to 2016. *Nature*, **568** (7752), 382–386, doi:10.1038/s41586-019-1071-0.
- Zhang, J. et al., 2015: The influence of sea ice and snow cover and nutrient availability on the formation of massive under-ice phytoplankton blooms in the Chukchi Sea. *Deep Sea Research Part II: Topical Studies in Oceanography*, **118** (Part A), 122–135, doi:10.1016/j.dsr2.2015.02.008.
- Zhang, J., R. Lindsay, A. Schweiger and M. Steele, 2013: The impact of an intense summer cyclone on 2012 Arctic sea ice retreat. *Geophysical Research Letters*, **40** (4), 720–726, doi:10.1002/grl.50190.
- Zhang, L., T.L. Delworth, W. Cooke and X. Yang, 2018a: Natural variability of Southern Ocean convection as a driver of observed climate trends. *Nature Climate Change*, **9** (1), 59–65, doi:10.1038/s41558-018-0350-3.
- Zhang, P. et al., 2018b: A stratospheric pathway linking a colder Siberia to Barents-Kara Sea sea ice loss. *Sci Adv*, **4** (7), eaat6025, doi:10.1126/sciadv.aat6025.
- Zhang, T. et al., 2008: Statistics and characteristics of permafrost and ground-ice distribution in the Northern Hemisphere. *Polar Geography*, **31** (1–2), 47–68, doi:10.1080/10889370802175895.
- Zhang, X. et al., 2012: Enhanced poleward moisture transport and amplified northern high-latitude wetting trend. *Nature Climate Change*, **3** (1), 47–51, doi:10.1038/nclimate1631.
- Zhang, Y., Q. Meng and S.H. Ng, 2016: Shipping efficiency comparison between Northern Sea Route and the conventional Asia-Europe shipping route via Suez Canal. *Journal of Transport Geography*, **57**, 241–249, doi:10.1016/j.jtrangeo.2016.09.008.

- Zhang, Z. et al., 2017: Emerging role of wetland methane emissions in driving 21st century climate change. *Proceedings of the National Academy of Sciences*, **114** (36), 9647.
- Zhao, M. et al., 2014: Characterizing the eddy field in the Arctic Ocean halocline. *Journal of Geophysical Research: Oceans*, **119** (12), 8800–8817.
- Zhao, M. et al., 2016: Evolution of the eddy field in the Arctic Ocean's Canada Basin, 2005–2015. *Geophysical Research Letters*, **43** (15), 8106–8114, doi:10.1002/2016GL069671.
- Zhuang, Q. et al., 2006: CO₂ and CH₄ exchanges between land ecosystems and the atmosphere in northern high latitudes over the 21st century. *Geophysical Research Letters*, **33** (17), L17403, doi:10.1029/2006gl026972.
- Zisserson, B. and A. Cook, 2017: Impact of bottom water temperature change on the southernmost snow crab fishery in the Atlantic Ocean. *Fisheries Research*, **195** (Supplement C), 12–18, doi:10.1016/j.fishres.2017.06.009.
- Zolkos, S., S.E. Tank and S.V. Kokelj, 2018: Mineral Weathering and the Permafrost Carbon-Climate Feedback. *Geophysical Research Letters*, **45** (18), 9623–9632, doi:10.1029/2018gl078748.
- Zona, D. et al., 2016: Cold season emissions dominate the Arctic tundra methane budget. *Proceedings of the National Academy of Sciences USA*, **113** (1), 40–45, doi:10.1073/pnas.1516017113.
- Zunz, V., H. Goosse and F. Massonnet, 2013: How does internal variability influence the ability of CMIP5 models to reproduce the recent trend in Southern Ocean sea ice extent? *The Cryosphere*, **7** (2), 451–468, doi:10.5194/tc-7-451-2013.
- Zwally, H.J. et al., 2017: Mass gains of the Antarctic ice sheet exceed losses. *Journal of Glaciology*, **61** (230), 1019–1036, doi:10.3189/2015JoG15J071.