Cross-Chapter Paper 6: Polar Regions

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Executive Summary

Observed impacts and future risks

Climate change impacts and cascading impacts in polar regions, particularly the Arctic, are already occurring at a magnitude and pace unprecedented in recent history (*very high confidence*), and much faster than projected for other world regions (*high confidence*[1]).

The polar regions, notably the Arctic and maritime Antarctic, are experiencing impacts from climate change at magnitudes and rates that are among the highest in the world, and will become profoundly different in the near-term future (by 2050) under all warming scenarios (*high confidence*). In the Arctic, accelerated sea-ice loss (particularly during summer), increased permafrost thaw and extreme high temperatures have substantially impacted marine, freshwater and terrestrial sociological-ecological systems (*very high confidence*). Multiple physical, ecological and societal elements of polar regions are approaching a level of change potentially irreversible for hundreds of years, if not millennia (*high confidence*). Evidence of borealization of terrestrial and marine systems is emerging (*high confidence*), and cascading impacts are on-going and widespread yet challenging to quantify fully due to complexity and lags in ecological expression of change. Loss of multi-year sea-ice and the occurrence of a seasonally ice-free Arctic Ocean by the middle of this century will result in substantial range contraction, if not the disappearance of several Arctic fish, crab, bird and marine mammal species, including possible extinction of seals and polar bears in certain regions (*high confidence*). In the Arctic, permafrost thaw and snowfall decrease lead to profound hydrological changes, an overall greening of the tundra and regional browning of tundra and boreal forests (*high confidence*). (CCP6.1; Table CCP6.1; Table CCP6.2; CCP6.2.1; CCP6.2.2; Table CCP6.5)

Contractions of the polar climate zones lead to distribution shifts and changes in food webs, induce declines in many species (*medium confidence*) with impacts on subsistence harvests and commercial fisheries, and threaten global dependence on polar regions for substantial marine food production (*high confidence*). Climate change has induced food web changes resulting in population declines in polar seabirds, including penguins, and marine and terrestrial mammals (*high confidence*). Globally and regionally important harvested fish and invertebrate species are also contracting ranges and declining productivity, including Pacific cod, salmon, snow and king crab in the Arctic and krill in the Antarctic (*medium confidence*), with implications for global food systems (*high confidence*). (Table CCP6.2; CCP6.2.1; CCP6.2.3; Table CCP6.3; Table CCP6.4)

Loss of sea-ice is rapidly expanding opportunities, but also increasing risks for shipping and other economic industries in polar regions (*very high confidence*). Reduced sea-ice enables greater access to high-latitudinal seas for industries, such as fisheries, shipping, tourism (*very high confidence*) and Arctic maritime trade and resource extraction (*medium confidence*). Navigational risks have grown due to increasingly mobile multi-year ice, poor hydrographic charting in newly open areas, and limited weather, water, ice, and climate data and services (*high confidence*). Cascading risks from polar shipping growth include increased air emissions, underwater noise pollution, disruption to subsistence hunting and cultural activities in the Arctic (*high confidence*) and potential for invasive marine species and geopolitical tensions (*medium confidence*). (Table CCP6.3; CCP6.2.4; Box CCP6.1; Table CCP6.5; Table CCP6.6)

Increased permafrost thaw and flooding will disrupt economically important transportation and supply-chain infrastructure to remote Arctic settlements (*high confidence*), increasing risks to economies, Arctic tourism and tourism to cultural heritage sites (*medium confidence*). Arctic permafrost thaw is projected to impact most infrastructure by the middle of this century, impacting millions of people and their economies, and costing billions in damages (*high confidence*). (CCP6.2.3; CCP6.2.4; Box CCP6.1; CCP6.2.5; CCP6.3.1; Table CCP6.5; Table CCP6.6)

[1] 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.

Climate change increasingly threatens many facets of Arctic livelihoods, culture, identity, health and security, particularly for Indigenous Peoples (*very high confidence*). It has negatively impacted mental health and increased risks of injury, food insecurity and foodborne and waterborne disease, with risks amplified for those reliant on the environment for subsistence, livelihoods and identity (*high confidence*). Permafrost thaw, sea-level rise and reduced sea-ice protection have already damaged or destroyed many cultural heritage sites in some Arctic regions (*very high confidence*) and are projected to continue across all Arctic regions (*very high confidence*). (CCP6.2.3; Table CCP6.3; CCP6.2.4; CCP6.2.5; CCP6.2.6; Figure CCP6.3; Box CCP6.2; CCP6.3.1; Table CCP6.5; Table CCP6.6)

Adaptation

Adaptations to manage climate change impacts and risks in polar regions are urgently needed (*very high confidence*), but implementation is uneven (*high confidence*), limits to adaptation are high and maladaptation is probable (*high confidence*).

Polar zones will continue to contract and diminish in extent under climate change, and local adaptations will be insufficient to achieve long-term resilience of polar systems (*medium confidence*). The pace and extent of change in polar regions is challenging the ability of social and natural systems to adapt (*medium confidence*). Management of different sectors with specific measures to reduce the potential for compounding risks and the development of climate-sensitive strategies would support the resilience of polar systems. Resilience of natural systems can be enhanced through strategies that maintain ecological connectivity over large spatial scales and reduce the particular impact of local extreme events on biodiversity (*medium confidence*). (CCP6.2; Box CCP6.1; CCP6.3; Table CCP6.5; Table CCP6.6; Figure CCP6.6; CCP6.4)

Timing, direction and scale of polar climate change impacts differ sub-regionally and will require adaptation strategies that are flexible, equitable, inclusive and integrated across sectors and governance arrangements to effectively reduce risks (*high confidence*). Governance around climate change planning, preparation and response has been limited in scope, and has often not considered interacting effects of climate change with other risks (*high confidence*). Reactive management strategies will not succeed in reducing risks in polar regions given the rapid change and increasing potential for extreme events (*high confidence*). Greater inclusivity of stakeholders and communities, along with using diverse sources of information, including Indigenous knowledge and local knowledge, can benefit robust planning and decision-making, and uptake of adaptations (*high confidence*). Effectiveness in preparing for and adapting to climate risks can benefit from improved climate, weather and ice forecasting services, tools for integrating climate change data and different types of knowledge into management processes and enhanced polar search, rescue, and emergency response capabilities (*high confidence*). (CCP6.2.3.1; CCP6.3; Table CCP6.6; CCP6.4; Box CCP6.2; Box CCP6.3; Figure CCP6.8)

Climate resilient development

Climate resilience for Arctic Indigenous Peoples and local communities is dependent on Indigenous self-determination in climate-adaptation action (*very high confidence*), inclusive, coordinated, and transboundary governance (*high confidence*) and ecosystem-based policies (*high confidence*) to effectively address climate change impacts and risks across scales and sectors, and to achieve a resilient, secure and equitable future.

Development of robust pathways for climate resilience in the Arctic can be accelerated by adaptation strategies and governance that reflect local conditions, cultures and adaptive capacities of communities and sectors (*high confidence*). Effectiveness of adaptation strategies will be enhanced by accounting for the geographic, climatic, ecological and cultural uniqueness of the polar regions (*medium confidence*). Colonialism can inhibit the development of robust climate adaptation strategies, and exacerbate climate risks (*very high confidence*). Inclusive decision-making in establishing climate adaptations can foster resilience, reflect the unique environmental, cultural, and economic imperatives of the region and support both market-based and sharing economies (*high confidence*). (Box CCP6.2; Table CCP6.6; CCP6.3.2; CCP6.4)

Indigenous self-determination in managing climate change impacts, adaptations, and solutions can accelerate effective robust climate-resilient development pathways in the Arctic (*very high confidence*). Arctic Indigenous self-determination in decision-making can establish robust climate resilience, especially in Indigenous communities, incorporating locally-derived definitions of social and economic success, culturally legitimate institutions of government, strategic visioning and thinking and public-spirited, nation-building leadership (*very high confidence*). (Box CCP6.2; CCP6.3; CCP6.4)

CCP6.1 The Global Importance of Climate Change in Polar Regions

Polar regions (Figure CCP6.1) are considered flagship areas for climate change, since some of the most extreme climate change impacts that are projected to occur by 2050 elsewhere in the world have already been observed in the Arctic and Antarctic and have resulted in transformative and unprecedented change. Polar regions are not only home to cultural keystone species such as polar bears (Arctic) and penguins (Antarctic), they also play fundamental roles in regulating the global climate system and in the provision of ecosystem services for the global community and for Arctic Indigenous Peoples and local communities in the region.

These changes are causing a suite of direct and cascading risks for all polar ecosystems with larger effects to date in the Arctic than the Antarctic (*high confidence*), due to larger and regionally more consistent physical changes (Figure CCP6.2, Table CCP6.1; Chapter 3) (Meredith et al., 2019; Ranasinghe et al., 2021). In the Arctic, these changes affect every sector of society, impacting its 4,000,000 inhabitants, including 400,000 Indigenous People. The Antarctic has no permanent human settlements; however, many nations conduct field research, operate seasonal and permanent stations and have an interest in the management of the region (Hughes et al., 2018; Grant et al., 2021). During summer, when Antarctic science, tourism and fishery activities are greatest, 4,400 people live there, whereas only 1,100 people live there over winter (Meredith et al., 2019). Although adaptation is occurring in polar regions, it is uneven and sporadic and does not meet the risks posed by future climate change. Indigenous knowledge-based solutions, inclusive ecosystem-based policies and integrated technologies demonstrate the potential to effectively address climate change impacts across scales and sectors; yet implementation barriers remain (CCP6.4.1).

This Cross Chapter Paper (CCP) assesses the impacts, risks and adaptation implications resulting from the physical and chemical changes in the polar regions that were detailed in the WGI contribution to the AR6 (IPCC, 2021). Several key WGI AR6 findings have important implications for natural and human systems in polar regions. Warming and wetting have persisted as key climatic impact drivers in polar regions (*very high confidence*) and will *very likely*[2] continue to 2100 (Fox-Kemper et al., 2021; Gulev et al., 2021) with cascading climate effects regarding heatwaves, fire, weather, floods and heavy precipitation, river runoff, snowfall, glaciers and ice sheets, permafrost, lake, river and sea-ice, relative sea level and coastal flooding and erosion (Gutiérrez et al., 2021; Ranasinghe et al., 2021) (Table CCP6.1). They represent major climate hazards in all key risks for polar regions (Table CCP6.5). Key points of departure for this CCP also include AR5 (IPCC, 2014) and the Polar Regions chapter in the Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC) (Meredith et al., 2019). SROCC assessed physical, biological and social systems concerning the Arctic and Antarctic Oceans and cryosphere, and how they are affected by current and future climate change. This CCP assesses the rapidly increasing evidence that has been published since AR5 and SROCC, and advances previous IPCC assessments. First, results from the Coupled Model Intercomparison Projects (CMIP6) are an important advance since SROCC, which improve the certainty and resolution of projections of the main climate impact drivers and the risks they have for polar systems (Fox-Kemper et al., 2021; Ranasinghe et al., 2021). Second, building from the framework outlined in SROCC (Crate et al., 2019), scientific, Indigenous knowledge (IK) and local knowledge (LK) systems are included in this assessment. Importantly, Indigenous authors led the assessment of the impacts, adaptation and governance of climate change for Indigenous Peoples, which is an important advance since AR5 and represents an important step towards Indigenous self-determination in international assessment processes (Ford et al., 2012; Ford et al., 2016; Hill et al., 2020).

Herein, observed impacts and future risks (CCP6.2), key risks and adaptation (CCP6.3) and climate resilient development pathways (CCP6.4) in the polar regions are assessed. The CCP describes how the implications of climate change impacts in the Arctic and Antarctic extend beyond their boundaries, in terms of transregional coupled ecological systems (CCP6.2.1, CCP6.2.2), global nutritional security (CCP6.2.3), global trade and shipping (CCP6.2.4) and cultural value (CCP6.2.5, CCP6.2.6). Given the synthetic and

[2] 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*). This Report also uses the term '*likely* range' to indicate that the assessed likelihood of an outcome lies within the 17-83% probability range.

policy-facing mandate of CCPs and with SROCC as a key point of departure, this CCP is not intended to cover the full breadth of issues for polar regions but rather it highlights select key policy-relevant topics by synthesizing and adding value to the relevant material from AR6 sectoral and regional chapters.

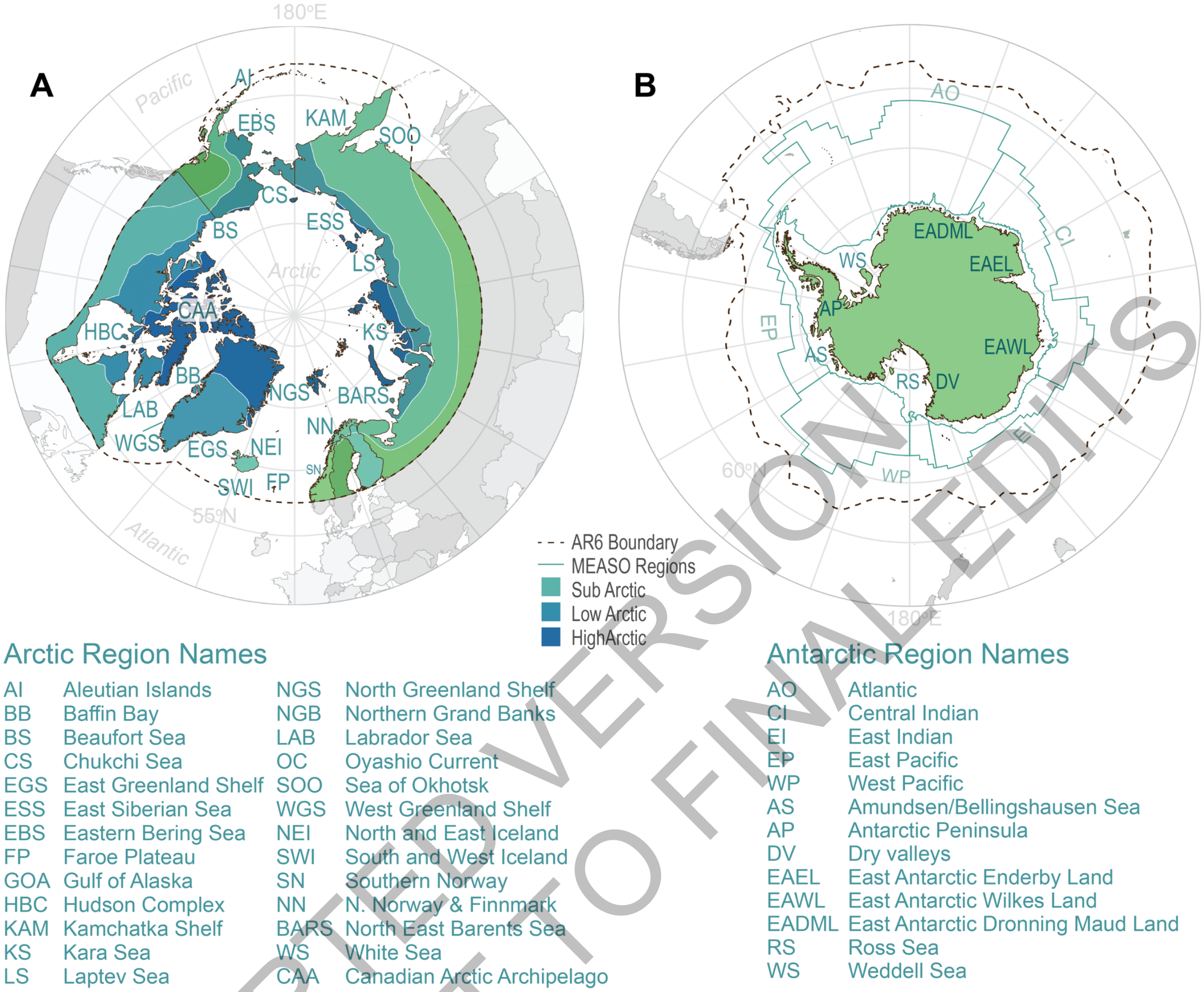

Figure CCP6.1: Polar regions include the Arctic, Antarctica, Iceland, Greenland, Faroe Islands, and some sub-Arctic areas (e.g., Bering Sea and Aleutian Islands as well as the Fennoscandian and Siberian boreal areas), and all sub-Antarctic areas. This CCP augments the geographical boundaries for the Arctic (Meredith et al., 2019) to also include the subarctic boundary (as defined by the Arctic Biodiversity Assessment), northern boreal areas, parts of the Siberian taiga and southern Labrador. The Antarctic region is delineated along the sub-Antarctic Front (Orsi et al., 1995). Geographic boundaries of the polar regions and important sub-regional locations are displayed including five marine sectors as defined in the Marine Ecosystem Assessment for the Southern Ocean (MEASO), e.g., Grant et al., (2021).

Table CCP6.1: Climatic impact drivers in the Arctic and Antarctic derived from WGI-AR6 chapters (indicated as WG1-9 (Fox-Kemper et al., 2021) and WG1-12 (Ranasinghe et al., 2021)) and Meredith et al (2019) (indicated as SROCC-3). Supplementary Material (SMCCP6.1) contains supplemental data for these drivers of projected changes (2021-2040, 2041-2060, 2081-2100) derived from the WGI-AR6 Interactive Atlas (indicated as Atlas)(Gutiérrez et al., 2021)(https://interactive-atlas.ipcc.ch).

Driver	Region	Observed Changes	Projected Changes
Marine and sea-ice			
Sea level (relative)	Arctic	No consistent trend (increase in NW America, decrease in NE America, stable in Greenland and Arctic Russia) (WG1-12)	Rise in all polar regions (except areas of substantial land uplift in NE Canada, the west coast of Greenland) (*high confidence*);

			Increase of extreme sea levels in Russian Arctic and NW America (*high confidence*) Greenland/Iceland and NE America (given glacial isostatic adjustment) (*medium confidence,* WG1-12)
	Antarctic		Rise in all polar regions (except areas of substantial land uplift in W Antarctica) (*high confidence*, WG1-12)
Sea-surface temperature	Arctic	Increase of ~0.5°C per decade during 1982-2017 in ice-free regions in summer (*high confidence*, SROCC-3)	Further increases (*high confidence*, WG1-12)
	Antarctic	Warmed in northern areas of Southern Ocean but cooled in its southernmost regions since the 1980s (*high confidence*, SROCC-3)	Circumpolar increases (*high confidence*, WG1-12)
Sea-ice cover	Arctic	Loss (particularly of multi-year sea-ice) accelerated since 2001 (*very likely*, WG1-9)	Will become sea-ice free (< 1 x 10^6 km^2) during summer before 2050, irrespective of global warming level (*likely*, WG1-9)
	Antarctic	No significant circumpolar trend from 1979–2018 (*very high confidence*), but decrease off the Antarctic Peninsula (*high confidence*) and increases and decreases in other regions (*medium confidence*, WG1-9)	Circumpolar decrease (*low confidence* due to limited understanding of driving processes, WG1-9)
Ocean surface pH	Both Poles	Decrease since 1980 at rates of 0.003–0.026 pH units per decade in open polar zones (*very likely*, WG1-12)	Further acidification by 0.1–0.6 pH by 2100 (Atlas), characterized by year-around conditions corrosive for aragonite minerals by 2100 (*very likely*, SROCC-3)
Terrestrial, freshwater and ice			
Atmospheric Temperature	Arctic	Increase of means higher than twice global mean, most pronounced in cold season (*high confidence*, WG1-12)	Further increase (Table SMCCP6.1)
	Antarctic	Warmed from 1957–2016 at 0.2–0.3°C per decade in W. Antarctica (*very likely*); No consistent change in E. Antarctica (*limited evidence*, WG1-12)	Region: Future warming across continent (*high confidence*, WG1-12)
Extreme Heat Events	Arctic	Increase since 1979 (WG1-12)	Polar amplification will drive further increases (*high confidence*, WG1-12)
	Antarctic	Heatwave across Antarctica (2020) (WG1-12, (Robinson et al., 2020).	Further increase, with > 50 additional days above freezing by 2100 (under RCP8.5, vs. 2014) over the Antarctic Peninsula but smaller changes over mainland Antarctica (*medium confidence,* WG1-12)
Fire Weather (FW)	Arctic	Over 4 decades, fire season lengthened and number of fires increased in N America (WG1-12)	FW index increases and more frequent fires in tundra regions (*high confidence*, WG1-12)
Precipitation	Arctic	Increase, highest during the cold season (*likely*, Atlas)	

	Antarctic	Increasing trend over the 20th century, while large interannual variability masks any existing trend since the end of 1970 (*medium confidence*, Atlas)	
Floods	Arctic	Increasing river runoff, increasing heavy precipitation (*high confidence*, WG1-12)	Further increases in all variables (*high confidence*, WG1-12)
Snowfall	Arctic	Recent overall declines in snow extent and seasonal duration (*high confidence*, WG1-12)	Higher % of precipitation as rain (fall and spring) (*high confidence*, WG1-12)
	Antarctic	Increases in the 20th century (*medium confidence*, WG1-12)	Further increases (over land) (*likely*, WG1-12)
Glaciers and Ice Sheets (IS)	Arctic	Losses in glacier mass since 2000 (*high confidence*, WG1-12); Losses in Greenland IS mass since 1980 at increasing rates (*high confidence*, WG1-9)	Further mass loss until 2100 under all warming scenarios (*virtually certain*, WG1-9 and -12)
	Antarctic	Losses in glacier mass since 2000 (*high confidence*, WG1-12); Losses in Antarctic IS mass since 1992 (in W Antarctica but also parts of E Antarctica since 2000) (*high confidence*, WG1-9)	Further mass loss until 2100 under all warming scenarios (*likely*, WG1-9 and -12)
Permafrost	Arctic	Rising permafrost temperatures over past 3-4 decades (*high confidence*, WG1-9); Decreases in permafrost active layer thickness (*very high confidence*) (Biskaborn et al., 2019). Submarine permafrost warming (*medium confidence*, WG1-9)	Increases in temperature and active layer thickness (WG1-9); Near-surface terrestrial permafrost extent will reduce under all scenarios by 2100 (*virtually certain*, WG1-9)
	Antarctic	Rising permafrost temperatures over past 3-4 decades (high confidence, WG1-9).	
Lake, River Ice	Arctic	Declines in seasonal lake ice cover thickness and duration over most Arctic lakes; Declines in cold-season river ice extent (*high confidence,* WG1-12)	Many lakes will lose > 1 month lake ice cover by 2050 (*medium confidence*), Reductions in average Northern Hemisphere seasonal river ice duration of 6.10 days per 1°C GWL (WG1-12)
Coastal floods / erosion	Arctic	Increase (*medium confidence*, WG1-12)	Further increase (*high agreement-limited evidence,* WG1-12)
	Antarctic	(Lack of studies, WG1-12)	

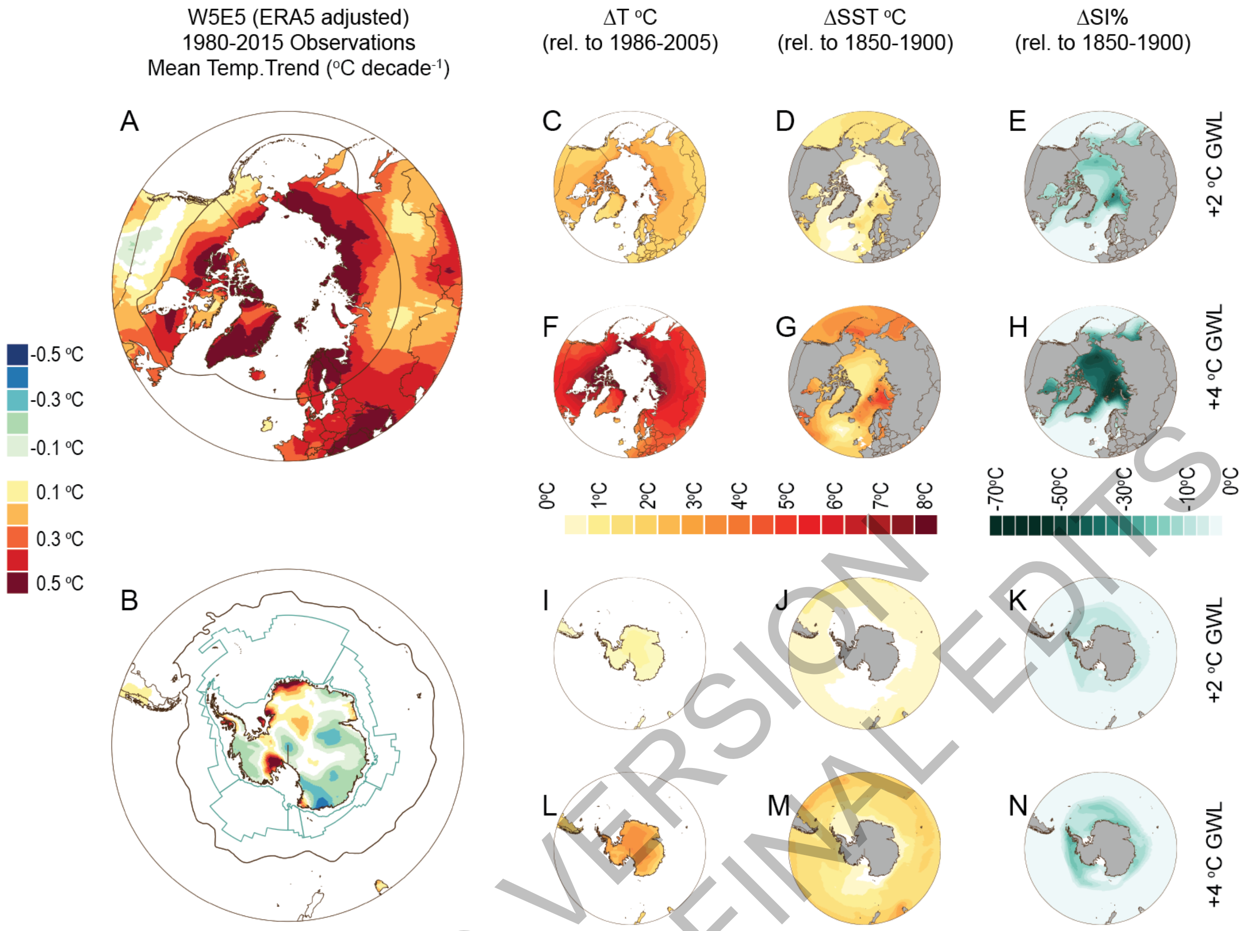

Figure CCP6.2: Observed and projected climate changes across the Arctic (A, C-H) and Antarctic (B, I-N). Boundary lines in each plot are based on the polar regions defined in Figure CCP6.1. All data shown here are extracted from the IPCC WGI Interactive Atlas (Gutiérrez et al., 2021; Iturbide et al., 2021); data set details can be found in the Atlas (https://interactive-atlas.ipcc.ch/). Arctic (A) and Antarctic (B) are observed temperature trends (°C/decade) over land for the period 1980-2015, derived from ERA5 adjusted dataset. Projected changes from an ensemble of CMIP6 projections: annual mean temperature over land is depicted for 2°C (C, I) and 4°C (F, L). Global Warming Levels (GWL) in the Arctic and Antarctic, respectively; annual mean sea surface temperature is depicted for 2°C (D, J) and 4°C (G, M) GWL in the Arctic and Antarctic respectively; annual sea-ice (%) is depicted for 2°C (E, K) and 4°C (H, N) GWL in the Arctic and Antarctic, respectively.

CCP6.2 Observed Impacts and Future Risks

Table CCP6.2: Summary of observed impacts (and projected risks of climate change for polar marine, terrestrial and freshwater ecosystems identified in Section 3.2.3 and Box 3.4 in Chapter 3 of the IPCC SROCC (Meredith et al., 2019).

Affected system	Hazard *Cascading Effect	Observed impacts, future risks and natural adaptations identified in SROCC (Confidence Level)
Arctic marine ecosystems		
Primary Producers (PP-1)	Sea-ice loss * Freshening * Stratification	Impact: Timing (earlier and later blooms), distribution and magnitude (>30% increase in annual net primary production since 1998) (*high confidence*)
	Acidification	Adaptation: phytoplankton may compensate for decrease pH

Zooplankton	* PP-1	Impact: Changing production and community composition (*medium confidence*)
Benthos	* PP-1	Impact: Changing production and biodiversity (*medium confidence*)
	Acidification	Risk: Effects on zooplankton and pteropods depends on climate scenario and species' sensitivity/adaptive capacity
Fish	Warming * Prey changes	Impact: Northward expanding ranges of sub-Arctic/boreal species (e.g., Atlantic cod) in Bering Sea (Detection - *high confidence*, Attribution - *medium confidence*) negatively affecting Arctic polar cod (*medium confidence*)
	* Prey declines	Risk: Decreasing production of walleye pollock, Pacific cod and arrowtooth flounder, due to declines in large copepods (*medium confidence*)
Birds and Marine Mammals	Sea-ice loss	Impact: Phenological, behavioural, physiological, and distributional changes; Endemic marine mammals have little scope to move northwards in response to warming (*high confidence*)
Polar Bears	Sea-ice timing, distribution, thickness	Impact: Phenological shifts, and changes in distribution, denning, foraging behaviour and survival rates (*high confidence*)
Antarctic marine ecosystems		
Primary Productivity	Sea-ice loss * Freshening * Stratification	Impact: Little overall change in biomass at circumpolar scale from 1998–2006, but sub-regional differences (*medium confidence*); Changes difficult to detect and attribute to climate change.
Microbes	Acidification	Impact: Detrimental effect on primary production and changes to the structure and function of microbial communities (*medium confidence*)
Antarctic Krill	Warming	Impact: Declines in abundance in the South Atlantic sector (*medium confidence*); May not represent a long-term, climate-driven trend but a decline following a period of anomalous peak abundance (*low confidence*)
		Risk: Southward range shift due to changes in the location of the optimum conditions for growth and recruitment, with decreases most apparent in the areas with the most rapid warming, such as the southwest Atlantic/Weddell Sea region (*medium confidence*)
Zooplankton	Acidification	Risk: Vulnerability of pteropods through effects on eggs (*medium confidence*)
Benthos	Sea-ice loss	Risk: Increase of biomass on the Antarctic continental shelf as productivity from longer phytoplankton blooms outweigh ice-scour mortality (*low confidence*)
	Sea-ice loss	Risk: Shallow-water communities may become dominated by macroalgae due to increases in the amount of light (possible loss of endemic species by 12% due to warming temperatures) (*low confidence*)
Fish	Warming	Risk: Icefish may be displaced from shallow regions around sub-Antarctic islands (*low confidence*)

Birds and Marine Mammals	Sea-ice cover	Impact: Predictability of foraging grounds and sea-ice cover associated with climate are main drivers of population changes: Increases for gentoo penguins (decreases for Adélie, chinstrap, king and Emperor penguins) (*high confidence*)
Arctic terrestrial and freshwater ecosystems		
Vegetation	Warming	Impact: Greening (*high confidence*)
		Risk: Decrease tundra areal extent >50% by 2050; wood shrubs expected to increase (*medium confidence*)
Vertebrates	Warming	Impact: Expanding range into Arctic
Freshwater Primary Productivity	* Increased runoff * Increased permafrost thaw	Impact: Increased productivity in rivers, lakes and coastal areas
		Risk: Expected to mobilise stores of pollutants
Pathogens	Warming	Impact: Expanding range into Arctic
		Risk: Mobilisation may increase in high latitudes, including anthrax from frozen carcasses possibly released from permafrost
Fish	* Freshwater winter habitat * Increased discharge	Risk: Disruption of the life history of Arctic freshwater fish
	* Warming freshwater	Risk: May make some surface waters inhospitably warm for cold water fish species
Biodiversity	Warming	Impact: Subarctic biodiversity expanding into Arctic
Reindeer/ Caribou	Climate factors	Impact: Reindeer/caribou declined overall without adaptation (*high confidence*), with climate affecting many aspects of their life history (*medium confidence*)
		Risk: Domesticated reindeer/caribou can be affected by fire, which reduces pasture, as well as by increased ice-on-snow, which can cause starvation
Antarctic terrestrial and freshwater ecosystems		
Terrestrial Biota	* Increased coastal ice melt	Impact: Increasing coastal ice-free areas available for colonisation (*high confidence*)
Alien Species	Warming	Risk: Barriers to alien species reduce, affecting terrestrial biodiversity (*medium confidence*)

CCP6.2.1 Marine and Coastal Ecosystems

CCP6.2.1.1 Warming and sea-ice retreat cause shifts in distribution ranges of species

In Arctic seas, warming and other climate impact drivers, primarily sea-ice retreat, have led to range contractions of Arctic marine and ice-associated species and poleward expansions of boreal species (*very high confidence*) (Table CCP6.2) (Bouchard and Fortier, 2020; Huntington et al., 2020; Mueter et al., 2020) even though light and energetics at seasonal extremes may limit some range shifts (*limited evidence*) (Ljungström et al., 2021). Altered conditions allow more microorganisms to move poleward and provide opportunities for invasive species (Cavicchioli et al., 2019; Nielsen et al., 2020; Mustonen, 2021).

Phytoplankton communities harbour increasing numbers of taxa, including harmful species (Lovejoy et al., 2017) and the coccolithophore *Emiliania huxleyi*, which meanwhile forms regular blooms in the Barents Sea (Neukermans et al., 2018; Silkin et al., 2020). Northward shifts of pelagic, benthic and demersal species and subsequent changes in Arctic community composition have been observed in the Bering, Greenland and Barents Seas (Grebmeier et al., 2018; Mueter et al., 2020), as have higher numbers of economically important boreal species such as haddock and Pacific and Atlantic cod (CCP6.2.3). Cold-adapted Arctic fish species such as polar cod (*Boreogadus saida*) are expected to decline further and lose spawning habitats at global warming levels >1.5 °C, mainly due to a lack of phenotypic plasticity, as well as increasing interspecific competition with and predation from invading boreal species (Dahlke et al., 2018; Marsh and Mueter, 2020). Numerous mammals and seabirds respond to changes in the distribution of their preferred habitats and prey by shifting their range, altering the timing or pathways for migration or switching prey (*very high confidence*) (Hamilton et al., 2017; Loseto et al., 2018; Meredith et al., 2019). Ice-breeding seals (e.g., harp seals - *Pagophilus groenlandicus*) often have little scope to shift distribution, leading to increases in strandings and pup mortality in years with little ice cover (*medium confidence*) (Table CCP6.2) (Boveng et al., 2020). Recent studies confirm that polar bears (*Ursus maritimus*) are negatively affected by changing ice and snow conditions with decreases in denning, foraging, reproduction, genetic diversity and survival rates (*very high confidence*) (Table CCP6.2) (Boonstra et al., 2020; Johnson and Derocher, 2020; Maduna et al., 2021).

In the Southern Ocean, southward range shifts are expected to result from increased warming coupled with the narrow thermal tolerance of cold-adapted Antarctic species (Convey and Peck, 2019; Morley et al., 2019; Gutt et al., 2021). Such shifts have so far only been detected for Antarctic krill (*Euphausia superba*), with a poleward contraction of the highest densities of krill in the Atlantic sector (*medium confidence*) (Table CCP6.2); (Atkinson et al., 2019). Ocean warming is expected to put pressure on Antarctic phytoplankton (Pinkerton et al., 2021) and fish species unable to move further south in shelf areas, including waters off sub-Antarctic islands (*low confidence*) (Table CCP6.2) (Caccavo et al., 2021). Off the Antarctic Peninsula and sub-Antarctic islands, invasive benthic invertebrates and macroalgae have already been detected (*medium confidence*) (Fraser et al., 2018; Avila et al., 2020; Brasier et al., 2021), and projected changes will further favour the spread of invasive species (Fraser et al., 2020; Macaya et al., 2020). On a local to regional scale, the benthic recolonization of the newly exposed seabed after the disintegration of ice shelves shows typical succession patterns, with mass occurrences of few pioneer species followed by gradual shifts to a more diverse typical shelf community, driven by increasing pelagic primary production upon ice-shelf collapse and strengthening of the pelagic-benthic coupling (*high confidence*) (Brasier et al., 2021; Gutt et al., 2021). Range changes of Antarctic birds and marine mammals have been observed, which vary among sub-regions and are mostly attributable to changes in sea-ice extent and food availability (*high confidence*) (Table CCP6.2) (Gutt et al., 2018; Convey and Peck, 2019; Bestley et al., 2020). With projected sea-ice retreat and associated change in prey distribution (Henley et al., 2020), foraging areas of sub-Antarctic seabirds and marine mammals will shift southwards, leading to elevated pressure on populations due to higher foraging costs during the breeding season (*medium confidence*) (Ropert-Coudert et al., 2018; Bestley et al., 2020; Hindell et al., 2020; Hückstädt et al., 2020; Wege et al., 2021). These changes are particularly impacting emperor penguins (*Aptenodytes forsteri*) (Table CCP6.2), with the projected population declining close to extinction by 2100 under business-as-usual climate scenarios (*medium confidence*) (Jenouvrier et al., 2020; Trathan et al., 2020; Jenouvrier et al., 2021), whereas population decline is halted by 2060 under the 1.5°C climate scenario (*low confidence*) (Jenouvrier et al., 2020).

CCP6.2.1.2 Ocean warming and sea-ice changes affect marine primary productivity

In the central Arctic Ocean, primary productivity remains low (*medium confidence*), mostly due to persisting nutrient and light limitations (Randelhoff and Guthrie, 2016; Ardyna and Arrigo, 2020). In inflowing (Barents and Chukchi Sea) and interior shelf regions (Laptev, Kara, and Siberian Sea), changes in sea-ice extent, thickness and seasonal timing have altered light and mixing regimes, causing increasing overall productivity in open-water and under-ice habitats, and in leads (*high confidence*) (Table CCP6.2) (Ardyna and Arrigo, 2020; Lannuzel et al., 2020). Productivity changes are associated with the earlier onset phytoplankton spring blooms and the increasing occurrence of autumn blooms, particularly at lower latitudes of the Arctic (*high confidence*) (Table CCP6.2) (Tedesco et al., 2019; Ardyna et al., 2020). Ice algal communities are expected to change in productivity and species composition in response to the transition from a predominantly multi-year to a seasonal sea-ice pack (*high confidence*) (Meredith et al., 2019; Tedesco et al., 2019; Lannuzel et al., 2020). Thinner sea-ice increases the likelihood of surface flooding, resulting in the occurrence of snow-infiltration algal communities, which have been described in the Atlantic sector of the Arctic Ocean (Fernández-Méndez et al., 2018) and observed by Indigenous Peoples off northern Greenland (Box CCP6.2). The observed transition from marine-terminating to land-terminating glaciers has a negative impact on coastal ecosystems in Greenland (*medium confidence*) (Meire et al., 2017; Hopwood et al., 2018) and Svalbard (Halbach et al., 2019), as land-terminating glacial meltwater input increases stratification, which hinders vertical mixing and lowers local productivity, whereas marine-terminating glaciers can trigger upwelling, which supplies nutrients and enables higher productivity in the summer (Hopwood et al., 2020). Macroalgae and seagrass are generally expanding in the Arctic (*medium confidence*), though there are negative trends in some regions, partly due to increased runoff and turbidity from melting glaciers (Hopwood et al., 2020; Krause-Jensen et al., 2020). In the future Arctic Ocean, higher light availability in response to further sea-ice decline and reduced deep mixing is projected to generally increase primary productivity (*medium confidence*), leading to an increase in phytoplankton biomass from 2000-2100 by ~20% for SSP1-2.6 and ~30-40% for SSP5-8.5 (Chapter 3) (Kwiatkowski et al., 2020). However, productivity may increase less than predicted and eventually even decrease once nutrient limitation outweighs the benefits of higher light availability (*low confidence*) (Randelhoff et al., 2020; Seifert et al., 2020).

Despite large-scale environmental changes in the Southern Ocean, such as the deepening of the summer mixed layer (*medium confidence*) (Panassa et al., 2018; Sallée et al., 2021), and the expected impacts via altered nutrient entrainment, light availability and grazer encounter rates (Chapter 3) (Behrenfeld and Boss, 2014; Llort et al., 2019), assessments indicated no consistent changes in primary production at the circumpolar scale, as sectors and regions show different trends (*medium confidence*). Although a global assessment found no overall changes in circumpolar primary production from 1998-2015 (Table CCP6.2) (Gregg and Rousseaux, 2019), another study showed an overall increase in phytoplankton biomass in the mixed layer over the period 1997-2019 (Pinkerton et al., 2021). Primary productivity has increased in the Pacific sector and decreased in the Atlantic sector and the Ross Sea (*low confidence*) (Kahru et al., 2017; Henley et al., 2020; Pinkerton et al., 2021). Higher productivity has also been observed in regions where rapid environmental changes occurred, such as in the vicinity of retreating ice sheets and declining sea-ice cover off the Antarctic Peninsula (*medium confidence*) (Henley et al., 2020; Rogers et al., 2020), although diversity of phytoplankton may decrease with warming temperatures and less sea-ice (*limited evidence*) (Lin et al., 2021). In the future Southern Ocean, stronger upwelling due to strengthened westerly winds is projected to increase primary productivity at the circumpolar scale in the Antarctic Zone and to the north of the sub-Antarctic Front, but not in the sub-Antarctic Zone (*low to medium confidence*) (Chapter 3) (Henley et al., 2020; Kwiatkowski et al., 2020; Pinkerton et al., 2021). The largest changes are projected to occur after 2100 at 2-6°C warming of the surface ocean (Moore et al., 2018). Such an increase in Southern Ocean productivity will lead to a decline in global ocean productivity (*medium confidence*), due to nutrient trapping (Moore et al., 2018) and altered ocean carbon uptake through ecosystem feedbacks (Hauck et al., 2018).

CCP6.2.1.3 Impacts of ocean acidification vary spatially and among biotas

In Arctic seas, areas with acidification levels corrosive to organisms forming $CaCO_3$ shells or skeletons expanded between the 1990s and 2010 (*high confidence*), with instances of extreme aragonite under-saturation (Ding et al., 2017; Zhang et al., 2020). Key species of diatom and picoeukaryote phytoplankton species yet appear relatively resilient to decreasing pH levels over a range of temperature and light conditions (*medium confidence*) (Table CCP6.2) (Thoisen et al., 2015; Wolf et al., 2018; White et al., 2020). In contrast, there is evidence for species- and stage-specific sensitivities of zooplankton, pteropods and fishes (*high confidence*) (Table CCP6.2) (Bailey et al., 2016; Dahlke et al., 2018; Thor et al., 2018). Warming, rising river-sediment discharge and coastal erosion in Arctic shelf regions are expected to increase the input of labile, often permafrost-derived organic carbon, the remineralisation of which further increases acidification rates (*medium confidence*) (Semiletov et al., 2016; AMAP, 2018b; Bröder et al., 2018). Interactions with other physical changes, such as warming or freshening, are expected to aggravate the impacts of ocean acidification (Chapter 3) (Falkenberg et al., 2018).

In the Southern Ocean, calcifying organisms are also most vulnerable to ocean acidification (*high confidence*) (Table CCP6.2), as evidenced by rates of calcification declining by 3.9% between 1998-2014 (Freeman and Lovenduski, 2015). Calcifying species with low-magnesium calcite or mechanisms to protect their skeletons are less vulnerable to the corrosive effects of acidification than those using aragonite or high-magnesium calcite (*high confidence*) (Figuerola et al., 2021). In diatom-dominated communities, silicification diminishes with reduced pH levels, albeit with rates differing among taxa (*low confidence*) (Petrou et al., 2019). Species-specific responses exist regarding growth and primary production, which are further strongly modulated by iron and light availability (*high confidence*) (Hoppe et al., 2013; Trimborn et al., 2013; Hoppe et al., 2015; Henley et al., 2020; Seifert et al., 2020). A meta-analysis yielded different CO_2 thresholds for Antarctic organismal groups, e.g., negative impacts emerged at >1,000 µatm CO_2 in phytoplankton and at >1,500 µatm CO_2 in invertebrates, whereas bacterial abundance was positively affected by ocean acidification (Hancock et al., 2020). Species sensitivity can also differ strongly between life-cycle stages (Chapter 3.3.2). For instance, eggs and embryos of Antarctic krill are negatively impacted at >1,250 µatm CO_2 whereas adults can thrive even at 1,000-2,000 µatm CO_2 over one year (Kawaguchi et al., 2013; Ericson et al., 2018).

CCP6.2.1.4 Climate change alters food web dynamics

Climate change has transformed Arctic marine ecosystems from sea-ice-associated to open-water production regimes, with profound impacts on trophic energy transfer efficiencies and pathways (*high confidence*) (Behrenfeld et al., 2017; Meredith et al., 2019; Huntington et al., 2020) as well as benthic-pelagic coupling (*medium confidence*) (Birchenough et al., 2015; Degen et al., 2016; Solan et al., 2020). Shifts in bloom phenology favour small phytoplankton and smaller zooplankton over large lipid-rich macro-zooplankton, leading to longer, less efficient food chains (*medium confidence*) (Aarflot et al., 2018; Feng et al., 2018; Kimmel et al., 2018; Weydmann et al., 2018; Møller and Nielsen, 2020). In the Beaufort Sea and Svalbard waters, earlier spring phytoplankton blooms have resulted in a mismatch in dynamics between microalgae and herbivorous copepods (Renaud et al., 2018; Dezutter et al., 2019). In the Bering Sea, zooplankton declines following the particularly pronounced sea-ice retreats in 2017 and 2018 were associated with reduced forage fish production (Duffy-Anderson et al., 2019), as well as multitrophic mortality of ctenophore, fish, bird, and mammal species, coupled with severe emaciation, reproductive failure, disease, and high mortality rates of seabird predators (Section 14.4.4.2) (Jones et al., 2019; Maekakuchi et al., 2020; Piatt et al., 2020; Romano et al., 2020). Species range shifts have restructured higher trophic levels in Arctic food webs (*high confidence*) (Table CCP6.2; CCP6.2.3.3 Chapter 3) (Huntington et al., 2020). In the northern Barents Sea, increased predation mortality for key species and incursions of boreal fish have induced entire ecosystem reorganization (Degen et al., 2016; Pecuchet et al., 2020a; Pecuchet et al., 2020b). Regional taxonomic and functional diversity increased with immigration of boreal species, although the ongoing decline in Arctic species suggests high species turnover (Table CCP6.2) (Frainer et al., 2017). Recent marine heatwaves induced rapid and profound food web changes unprecedented over the last four decades (Siddon et al., 2020).

Climate impacts on Arctic marine food webs will be profound and intensify with global warming levels (*high confidence*), regardless of mitigation scenarios due to multidecadal lags in sea-ice extent and atmospheric carbon (WGI) (Jones et al., 2020). However, the exact nature of these impacts remains unclear due to attenuating and amplifying dynamics of both top-down and bottom-up processes in polar food webs and the management of fisheries (*high confidence*) (Chapter 3) (Cavicchioli et al., 2019; Meredith et al., 2019). Projected sea-ice loss is associated with a >50% decline in the density of large zooplankton species by 2100 (relative to early 21st century levels) in the southern Bering Sea and a net increase in large zooplankton in the northern Bering Sea in scenarios without carbon mitigation (RCP8.5), whereas these declines are roughly half the magnitude under moderate mitigation scenarios (RCP4.5) (Hermann et al., 2019; Kearney et al., 2020). Warming is expected to reduce the quantity and quality of lipid-rich copepod prey (*high confidence*) (Aarflot et al., 2018; Kimmel et al., 2018; Bouchard and Fortier, 2020; Møller and Nielsen, 2020; Mueter et al., 2020), leading to declines in survival and growth of multiple upper-trophic level fish species; these impacts are amplified over time under low mitigation scenarios (RCP8.5) (*high confidence*) (CCP6.2.1.1) (Dahlke et al., 2018; Holsman et al., 2020; Mueter et al., 2020; Oke et al., 2020; Reum et al., 2020; Thorson et al., 2020; Whitehouse et al., 2021). Marine mammals and seabirds will continue to attenuate climate change impacts by shifting their diets and behaviour (*medium confidence*) (Table CCP6.2) (Hamilton et al., 2017; Lowther et al., 2017; Lydersen et al., 2017; Vihtakari et al., 2018; Boveng et al., 2020). However, seabirds generally have low temperature-mediated plasticity of reproductive timing, making them vulnerable to mismatches with their prey and limiting long-term adaptation (*medium* *confidence*) (Keogan et al., 2018; Kharouba and Wolkovich, 2020; Piatt et al., 2020; Samplonius et al., 2021).

Many factors have contributed to changes in Antarctic food webs, including historical exploitation of fish and marine mammals as well as changes driven by the ozone hole and climate factors (Meredith et al., 2019; Morley et al., 2020; Grant et al., 2021). Most documented changes resulting from warming and sea-ice losses relate to shifts in ranges and dynamics of species, with most impacts occurring around the Antarctic Peninsula (CCP6.2.1.1; Table CCP6.2).

The projected general rise in primary production in Antarctic seas by 2100 (CCP6.2.1.2) suggests a concomitant increase in the abundance of higher trophic species, but changes in the structure and function of food webs will vary (McCormack et al., 2021; McCormack, accepted) depending on regional differences in changing drivers (Morley et al., 2020; Cavanagh et al., 2021; Grant et al., 2021). Primary production in open water habitats is expected to be supported by smaller phytoplankton species in the future (Henley et al., 2020), which could increase the relative importance of the copepod-mesopelagic fish pathway (McCormack, accepted), because krill prefer larger diatoms as food (Siegel, 2016). The optimum habitat for Antarctic krill is expected to decline with a shortening of suitable season for krill growth and reproduction, particularly in the northern Scotia and Bellingshausen Seas (*medium confidence*) (Veytia et al., 2020), although changes may be difficult to distinguish from natural variability until later in the century (Sylvester et al., 2021). More subtle and unpredictable changes may occur in the structure and relative importance of energy pathways in the food webs (Trebilco et al., 2020). Small mesopelagic fish are increasingly recognized for their importance as mid-trophic level species in the Southern Ocean, particularly in the sub-Antarctic zone (Caccavo et al., 2021) and Central Indian Sector (Subramaniam et al., 2020; McCormack et al., 2021). Although salps have long been considered to be competitors of Antarctic krill (Suprenand and Ainsworth, 2017; Rogers et al., 2020), they provide a third energy pathway in pelagic food webs, and, given the changing ocean conditions and their preference for smaller phytoplankton, may increase in importance for copepods (*low confidence*) (Plum et al., 2020; Trebilco et al., 2020; McCormack et al., 2021; Pauli et al., 2021; McCormack, accepted). Declining ice shelves, such as those off the Antarctic Peninsula, will open up new pelagic and benthic habitats (CCP6.2.1.1) with expected increases in productivity of benthic assemblages in the new areas (Barnes, 2017; Morley et al., 2020; Brasier et al., 2021; Gutt et al., 2021).

CCP6.2.2 Terrestrial and Freshwater Ecosystems

Since the publication of AR5 (IPCC, 2014) and SROCC (IPCC, 2019) and their findings (Table CCP6.2), more studies confirm rapid changes in Arctic terrestrial and freshwater systems including increased permafrost thaw, changes to tundra hydrology and vegetation (overall greening of the tundra, regional browning of tundra and boreal forests), coastal and riverbank erosion (*high confidence*) (Canadell et al., 2021; Mustonen and Shadrin, 2021), reduced duration of snow cover and river and lake ice, increased rain-on-snow events, and reduced land-ice extent and thickness (Bieniek et al., 2018; Brown et al., 2018). Climate change continues to alter vegetation and attendant biodiversity, with divergent regional trends across the Arctic due to disparities in local conditions and changes in growing seasons (Zhu et al., 2016; Taylor et al., 2020). Warming facilitates woody vegetation growth in northeastern Siberia, western Alaska, and northern Quebec (Song et al., 2018; García Criado et al., 2020), as well as a northward expansion of shrub vegetation and sub-Arctic and boreal species (Davidson et al., 2020).

Further evidence shows that warming and changes to the Arctic hydrologic cycle increase the risk of wildfire (*medium confidence*) (Mustonen and Shadrin, 2021). Both the frequency of and the area burned by wildfires during recent years are unprecedented compared to the last 10,000 years (*high confidence*) (Meredith et al., 2019; Irannezhad et al., 2020). Fire risk levels are projected to increase across most tundra and boreal regions, and interactions between climate and shifting vegetation (Song et al., 2018) will influence future fire intensity and frequency (*medium confidence*) (Curtis et al., 2018).

For all warming scenarios, declines in snow cover in the Arctic by 2050 (Table CCP6.1) may accelerate vascular plant, moss, and lichen extinction rates (32% for Arctic–alpine and 12% for boreal species), especially after the tipping point of 20−30% decrease in snow cover duration is passed (Niittynen et al., 2018). Even though the overall regional water cycle will intensify, including increased precipitation, evapotranspiration and river discharge to the Arctic Ocean (Table CCP6.1), snow and permafrost decline may lead to further soil drying (*medium confidence*) (Meredith et al., 2019). Glacial ice melt poses a risk to ecosystems and people through remobilization of sequestered hazardous waste and transported pollutants (Table CCP6.3) (Wang et al., 2019).

In the Antarctic, there is further *high agreement* since the publication of SROCC that melt and ice-free areas are causing increases in the rates of colonisation and utilization of coastal environments by terrestrial biota and land-based colonies of seals and birds (Gutt et al., 2021), although colonisation rates remain variable (Ruiz-Fernandez et al., 2017; Bokhorst et al., 2021). Soil temperatures along the Antarctic Peninsula are now sufficient for germination of non-native plants; invasions by non-endemic species are expected to increase with rising temperatures (*high confidence*) (Bokhorst et al., 2021), posing a risk to endemic polar species (*medium confidence*) (Chown and Brooks, 2019; Gutt et al., 2021).

Vegetation responses to warming are contingent on water availability and local temperature (*medium confidence*) (Guglielmin et al., 2014; Royles and Griffiths, 2015; Amesbury et al., 2017; Cannone et al., 2017; Charman et al., 2018; Robinson et al., 2018; Stelling et al., 2018), which vary greatly around Antarctica (Figure CCP6.1) (Turner et al., 2020a). Antarctic terrestrial ecosystem responses to changes in water availability are not homogeneous (Ball and Levy, 2015; Sadowsky et al., 2016; Fuentes-Lillo et al., 2017; Gooseff et al., 2017; Schroeter et al., 2017; Lee et al., 2018). West Antarctica is showing evidence of greening in the dominant cryptogrammic vegetation, with greater growth in mosses (*high confidence*) (Casanova-Katny et al., 2016; Amesbury et al., 2017; Shortlidge et al., 2017; Charman et al., 2018; Prather et al., 2019). Peatland ecosystems may increase on the west Antarctic Peninsula with future warming (*low confidence*) (Yu et al., 2016; Loisel et al., 2017). In contrast, some parts of East Antarctica and the subantarctic islands to the north have been experiencing a drying climate, with declining health of mosses and other vegetation (*high confidence*) (Bergstrom et al., 2015; Bramley-Alves et al., 2015; Robinson et al., 2018; Bergstrom et al., 2021).

Antarctica encountered its first reported heatwave in 2020 (Table CCP6.1). Such abrupt heating can cause wide-ranging effects on biota, from flash-flooding damage and dislodgement of plants to excess melt waters supplying moisture to arid Antarctic ecosystems. This suggests that increased melt may reverse the drying trend if plant communities remain connected to melt streams and there is sufficient precipitation (*high agreement, limited evidence*) (Bergstrom et al., 2021).

Warming of the Antarctic Peninsula has resulted in increased soil microbial abundance and biomass. However this trend is not as great in southern colder locations (*medium confidence*) (e.g., Kim et al., 2018; Newsham et al., 2019), as the microbial community structure is affected by vegetation cover and water availability (*high confidence*) (Dennis et al., 2019; Newsham et al., 2019).

Antarctic terrestrial invertebrate communities on the West Antarctic Peninsula may be controlled more by vegetation and water availability than by air temperature (*medium confidence*) (Bokhorst and Convey, 2016; Knox et al., 2016; Andriuzzi et al., 2018; Prather et al., 2019; Newsham et al., 2020). Evidence from laboratory studies, field programs and sedimentary records indicate that Antarctic freshwater ecosystems may become more productive under climate warming scenarios (*medium confidence*) (e.g., Schiaffino et al., 2011; Borghini et al., 2016; Píšková et al., 2019; Čejka et al., 2020).

CCP6.2.3 Food, Fiber, and other Ecosystem Products

Food and fiber production underpins regional identities, cultures, and communities of practice and place in polar regions, are vital to local and distant economies (Table CCP6.4) and they represent for fisheries a critical source of global nutrition and food security (Hicks et al., 2019). Since SROCC, there is further evidence that climate change alterations of polar ecosystems increasingly challenge production of, and access to, sufficient, healthy, and nutritious food, posing risks to future food and nutritional security within and beyond polar regions (*high confidence*).

CCP6.2.3.1 Arctic subsistence resources

Subsistence harvest of fish, seabirds, and marine mammals is the basis for economic, cultural and spiritual connections with Arctic marine systems (Box CCP6.2)(Fall et al., 2013; Haynie and Huntington, 2016; Raymond-Yakoubian et al., 2017; Slats et al., 2019) and nature-based livelihoods (e.g., caribou and reindeer (*Rangifer tarandus*) herding, fishing, hunting, trapping, small-scale forestry) are fundamental to Indigenous Peoples across the Arctic as they have been for millennia (Koivurova et al., 2015; Betts, 2016; Gavin et al., 2018; Raheem, 2018; Mustonen and Shadrin, 2021). Climate change has impacted Indigenous subsistence resources across the Arctic (*very high confidence*) (SMCCP6.2), and future food systems and ecological connections are at risk from future climate change hazards interacting with non-climate pressures, some of which are mediated or amplified by novel conditions and opportunities in Arctic regions (*high confidence*) (Moerlein and Carothers, 2012; Fall et al., 2013; Raymond-Yakoubian et al., 2017; Meredith et al., 2019; Slats et al., 2019; Huntington et al., 2020; Huntington et al., 2021). Increasing heatwaves, wildfires, extreme precipitation, permafrost loss and rapid seasonal snow and ice thaw events will further threaten terrestrial subsistence food resources across the Arctic (*high confidence*) (Table CCP6.3). Although climate impacts and non-climate factors systematically undermine access to and productivity of subsistence resources, resilience is inherently high for Indigenous Peoples, illustrating critical elements underpinning successful adaptation to climate change (Box CCP6.2) (Huntington et al., 2021).

Table CCP6.3: Illustrative examples of climate change impacts on subsistence resources in the Arctic.

Changing Drivers	Observed impacts and projected risks	References
Snow, ice, river environments	Climate change is disrupting subsistence harvests for Indigenous Peoples in Arctic communities that depend on snow, ice and river environments for travel and access to subsistence resources.	(Wildcat, 2013; Meredith et al., 2019; Slats et al., 2019)
Multiple	Across the Canadian Arctic, multiple populations of reindeer and caribou are in decline with 95% of assessed herds listed as rare, decreasing or "threatened"; Reindeer and caribou abundances in the Alaska-Canada region have declined 56% over the past 20 years.	(Russell et al., 2018)
Multiple	Reindeer herding is an important economic and Indigenous cultural activity in the Eurasian Arctic and is being affected by non-climate and climate events, including changes to thaw cycles, drought and unpredictable summer weather, which threaten pasture areas in Siberia. Although changes in vegetation and the freeze thaw cycle are impacting Sami reindeer herding, adaptive measures by herders have been effective at offsetting multiple climate and non- climate impacts.	(Furberg et al., 2011; Uboni et al., 2020; Mustonen and Shadrin, 2021)
Sea-ice; winds; visibility	Loss of multiyear "mother ice", declines in seasonal sea-ice thickness and stability, as well as changes in winds and visibility have impacted the availability of, and access to, subsistence resources (*high confidence*) and have increased interactions between coastal communities and shipping, tourism and commercial fisheries, which directly impact human safety and well-being in Arctic communities (*high confidence*).	(Stephenson and Smith, 2015; Brinkman et al., 2016; Melia et al., 2016; Raymond-Yakoubian et al., 2017; Ford et al., 2019; Slats et al., 2019; Huntington et al., 2020; Huntington et al., 2021)
Multiple	MHW-induced ecosystem changes contributed to widespread mortality events and declines in Northern Bering Sea seabirds and disrupted subsistence harvests in western Alaska.	(Jones et al., 2019; Piatt et al., 2020; Siddon et al., 2020)
Storminess; sea-ice; whale migration timing; shipping	Although some communities have seen reduced whale harvests due to climate impacts on survival and productivity, changes in storminess and whale migration timing have lengthened the July harvest season for Inuvialuit from Inuvik, Aklavik and Tuktoyaktuk. Changes in Beluga migration routes have increased accessibility to communities of Ulukhaktok and Paulatuk. In Western Greenland, loss of sea-ice has both reduced access to sealing and increased subsistence and commercial harvest of Atlantic cod, halibut, and other fish species. Increased impacts of noise and ship strikes associated with shipping are expected to	(George et al., 2017; Hauser et al., 2018; Loseto et al., 2018; Mustonen et al., 2018a)

	impact subsistence species, especially seals and whales in Lancaster sound as well as the Pacific Arctic.	
Sea-ice	Changes in sea-ice will continue to undermine subsistence resources and disrupt access by smaller scale commercial and subsistence-based ice-edge fishing.	(Jacobsen et al., 2018; Ford et al., 2019)
Shifting distributions; Food web changes	Shifting species distributions and climate change mediated food web reorganization pose a risk to near-shore subsistence harvests that are essential to sustaining Indigenous Peoples in Western Greenland and the Northern Bering, Beaufort, and Chukchi Seas; , e.g., cod biomass in the Inuvialuit region is projected to decrease 17% by 2100 (RCP8.5). Climate-related declines in harvester access drive projected declines in subsistence availability in Alaska.	(Moerlein and Carothers, 2012; Fall et al., 2013; Brinkman et al., 2016; Loseto et al., 2018; Steiner et al., 2019; Marsh and Mueter, 2020; Ribeiro et al., 2021)

CCP6.2.3.2 Agriculture, forestry, livestock, and aquaculture

In addition to reindeer herding, Arctic agriculture primarily consists of local production of cool season crops, forage, small grains, and livestock (sheep and goats) (Westergaard-Nielsen et al., 2015; Natcher et al., 2019). Short growing seasons, cold conditions, permafrost, and moisture stress, especially along coasts, have historically limited production, but agriculture is generally increasing across the region (Westergaard-Nielsen et al., 2015). Although only ~ 0.2% of Alaska is farmland, area farmed and income from agriculture have increased 2% and 80% (respectively) since 2012 (United States Department of Agriculture, 2017). It is *likely* that growing seasons have extended by 1-3 days per decade in interior Alaska, although some coastal areas exhibit declines in growing season (Lader et al., 2018).

Arctic temperatures rarely exceed thermal tolerances for crops (e.g., 35-38°C across corn, rice and grain) and warming will provide new opportunities for food and forage production in areas such as SW Greenland and interior Alaska (Westergaard-Nielsen et al., 2015; Tripathi et al., 2016; Lader et al., 2018). Higher atmospheric CO_2 favours plant growth if soil quality and condition are sufficient, but benefits can be offset by increased heat and water stress associated with climate change (Tripathi et al., 2016; Unc et al., 2021). Growing seasons in Alaska will lengthen by 48-87 days per year relative to historical growing season length (1981-2010) and the start of growing season is expected to shift 1-4 weeks earlier (Lader et al., 2018). Feasible growing areas across the Arctic are expected to shift northward and increase within the 55°-69°N region (King et al., 2018). Permafrost thaw (Table CCP6.1) increases drainage, which is a potential benefit, but can also increase erosion, subsidence and irregular surfaces, inhibiting agriculture (Lader et al., 2018). Conversion of Arctic soils to croplands may also release carbon stored in vegetation and soils (Unc et al., 2021).

Arctic aquaculture contributes approximately 2% to global farm production (primarily Norwegian salmon (*Salmo salar*), as well as finfish in Iceland and Sweden and shellfish in Alaska), and will face increasing challenges from climate change (Troell et al., 2017) including increased frequency of storms (impacting sea farms), extreme temperatures, and warmer conditions that favour pathogens, parasites and harmful algal blooms. Aquaculture feeds often depend on small pelagic fish or krill and supply may be affected by climate impacts on fisheries (Table CCP6.6) (Troell et al., 2017; Chen and Tung, 2018; Mørkøre et al., 2020). Integrated policies and coordination across multiple food production sectors in Arctic regions are needed to address climate opportunities and challenges (Altdorff et al., 2021; Unc et al., 2021).

CCP6.2.3.3 Commonalities in impacts and risks across polar fisheries

Fisheries play an increasingly important role in addressing global food and nutritional deficits (Section 3.6.3)(Béné et al., 2016; Ding et al., 2017; Hicks et al., 2019; Costello et al., 2020), especially as climate change has already reduced global yields from key crops (Myers et al., 2017; Ray et al., 2019; Thiault et al., 2019). Antarctic and Arctic systems support some of the world's largest fisheries, including those for Antarctic krill and Arctic walleye pollock (*Gadus chalcogrammus*), which constitute a critical source of protein and macronutrients to a growing population of seafood consumers, as well as various aquaculture and livestock feeds (Cross-Chapter Box MOVING PLATE in Chapter 5) (Table CCP6.4) (Huntington et al., 2013; Raheem, 2018; Hicks et al., 2019; Steiner et al., 2019; FAO, 2020; Cavanagh et al., 2021; Grant et al., 2021; Murphy et al., 2021). Marine sources of protein and nutrition are important in transformational future scenarios where dietary shifts and provisioning policies provide multiple co-benefits to equity, food security and carbon mitigation (Springmann et al., 2016; Poore and Nemecek, 2018; Thiault et al., 2019; Kim et al., 2020). Shifting spatial distributions of fish stocks have led to transboundary management challenges in the Atlantic, Bering Sea, and Arctic areas previously inaccessible due to sea-ice (Table CCP6.6) (Gullestad et al., 2020).

Cascading and interacting effects of climate change impacts in polar regions (Table CCP6.1) will reduce access to, and productivity of future fisheries, and pose significant risks to regional and global food and nutritional security that increase with atmospheric carbon levels and declines in sea-ice (*high confidence*) (Table CCP6.6). Although it is expected that fisheries will continue to contract poleward under future warming (Cross-Chapter Box MOVING PLATE in Chapter 5) (Table CCP6.4) (Alabia et al., 2018; Morley et al., 2018; Stevenson and Lauth, 2019; Caccavo et al., 2021; Grant et al., 2021), global and regional models differ in their projections of fisheries catch potential for the polar regions under climate change. For example, some global-scale models project increases in potential fishery yields in Arctic Canada (Cheung, 2018; Bindoff et al., 2019; Tai et al., 2019), whereas many observational studies and high resolution regional projections suggest overall declines in biomass, productivity, and yield associated with warming and loss of sea-ice in multiple regions such as the Bering Sea (*medium confidence*) (Free et al., 2019; Hollowed et al., 2020; Holsman et al., 2020; Mueter et al., 2020; Reum et al., 2020). Reduced production of macronutrients and protein by polar marine sources will disproportionately impact people already experiencing food and nutritional scarcity (Myers et al., 2017), marine-dependent communities within and beyond polar regions, and women and children who require higher quantities of macronutrients (*high confidence*).

Large-scale commercial fisheries are expected to continue to operate in polar regions (*high confidence*) (Barange et al., 2018; Cavanagh et al., 2021; Grant et al., 2021), and will shift poleward (*high confidence*) toward geopolitical and management boundaries (*high confidence*) (CCP6.3.2.3; Table CCP6.6). Warming and climate impacts will continue to impact transboundary stocks and increase the potential for conflict in fisheries management (Pinsky et al., 2018; Mendenhall et al., 2020; Palacios-Abrantes et al., 2020; Sumaila et al., 2020). Increased distances from ports to redistributed fishing grounds, as well as increased frequency of storms and other extreme events are expected to increase risks and costs for fishery operations (*medium confidence*) and impact shore-based infrastructure and emergency response services (CCP6.2.4). Observed and expected increases in mobile ice combined with abrupt wind can create major hazards for fish operators in Antarctica and the Arctic, with consequences to human safety and total revenue (Dawson and et al., 2017; Barber et al., 2018; Grant et al., 2021). There will be increased demand for new port infrastructure across the Arctic (*high confidence*); new ports have already been proposed for the northern Bering Sea, and small craft harbour investments are being considered across Arctic Canada and Greenland. Ecosystem-based management, increasing diversity and flexibility in harvest portfolios, access to high-resolution ecological forecasts and projections, and climate-informed advice will promote adaptation and climate resilience in fisheries (Dawson and et al., 2017; Brooks et al., 2018; Karp et al., 2019; Hollowed et al., 2020). Coupling adaptation measures with global carbon mitigation strategies substantially decreases climate change risks to polar fisheries (*very high confidence*) (CCP6.3).

[START FAQ CCP6.1 HERE]

FAQ CCP6.1: How do changes in ecosystems and human systems in the polar regions impact everyone around the globe? How will changes in polar fisheries impact food security and nutrition around the world?

Polar regions are commonly known to be experiencing particularly fast and profound climate change, which strongly affects areas and people all around the world in several ways. Physical processes taking place in these regions are critically important for the global climate and sea level. Less known is that regional climate-driven changes of ecosystems and human communities will also have far-reaching impacts on a number of sectors of human societies at lower latitudes.

Climate change has triggered rapid, unprecedented, and cascading changes in polar regions that have profound implications for ecosystems and people globally. Although physically remote from the largest population centers, polar systems are inextricably linked to the rest of the world through interconnected ocean currents, atmospheric interactions and weather (IPCC, 2021), ecological and social systems, commerce, and trade. The nutrient-rich waters of the polar regions fuel some of the most productive marine ecosystems on earth, which in turn support fisheries for species packed with vital macronutrients that are essential for human health and wellbeing. The largest most sustainable fisheries in the world are located in polar waters, where a mix of ice, seasonal light, and cold nutrient-rich waters fuel schools of millions of fish that swell and retract in numbers across the years, reflecting interlaced cycles of icy cold waters, lipid-rich prey, and abundant predators. Polar systems thus exist in a productive balance that has supported vibrant ecocultural connections between Indigenous Peoples and the Arctic for millennia and has supported global food production and trade for centuries. Climate change increasingly destabilizes this balance with uncertain outcomes for Indigenous Peoples and local residents in the Arctic as well as for the rest of the world. Triggered by warming oceans and air temperatures, accelerated melting of sea-ice, glaciers and ice sheets in polar regions in turn impacts ocean salinity, sea levels, and circulation throughout the global ocean. Warming waters have also pushed cold-adapted species poleward, eroded the cold barrier between boreal and Arctic species, and induced rapid reorganization of polar ecosystems. Studies increasingly indicate that the complex web of physical and biological connections that have fuelled these productive regions will falter without the strong regulating influence of cryospheric change. At the same time the global demand for food is increasing, particularly the demand for highly nutritious marine protein, placing increasing importance on stabilizing polar ecological systems and minimizing climate change impacts and risks.

[END FAQ CCP6.1 HERE]

Table CCP6.4: Climate change impacts on Arctic and Antarctic fisheries and fishing communities. Additional detail in Table SMCCP6.3.

Driver	Observed impacts and projected risks	References
Current and past climate change impacts		
Warming	Fisheries productivity declined in multiple stocks across the Arctic including the EBS while Atlantic cod and other fisheries have increased.	(Free et al., 2019; Cheung and Frölicher, 2020)
Extreme heat	Commercially important fish species declined rapidly during recent MHWs (2016-2019), in the EBS due to reduced recruitment, increased metabolic demand, and increased predation mortality and it is probable that climate impacts have contributed to the closure of Pribilof islands blue king crab (*Paralithodes platypus*) fisheries.	(Zheng and Ianelli, 2018; Duffy-Anderson et al., 2019; Stabeno et al., 2019; Basyuk and Zuenko, 2020; Reum et al., 2020; Thorson et al., 2020)
Temperature; shifting species distributions	In the Barents Sea, northward redistribution of stocks led fisheries into previously unfished habitats, exposing benthic ecosystems to novel trawling impacts. Large-scale redistributions of Pacific cod (>1000 km decade^{-1}) and other groundfish species have challenged fisheries management in the EBS; ~50% of the biomass is now located in the NBS, outside of historical survey areas and in a region where bottom trawling is prohibited (although pelagic gear is permitted).	(Christiansen et al., 2014; Jørgensen et al., 2019; Spies et al., 2019; Stevenson and Lauth, 2019)
OA, warming, winds	Shellfish species such as snow crab are undergoing range contractions poleward in the Barents and Northern Bering Seas, with increased catches in the north and declines in the south.	(Jørgensen et al., 2019; Fedewa et al., 2020) (Cross-Chapter Box MOVING PLATE in Chapter 5)
Warming; poleward expansion	Poleward expansion of Pacific salmon into Arctic watersheds and Greenland fjords presents both new opportunities and novel threats to key subsistence and commercial species such as Arctic char and Atlantic salmon.	(Bilous and Dunmall, 2020; Nielsen et al., 2020)
Warming; HABs	Altered seasonal freshwater habitats are impacting salmon productivity and phenology of important salmon resources in	(Brattland and Mustonen, 2018; Cline et al., 2019; Mustonen and

	Alaska and in the Fennoscandian North, with subsequent community-specific impacts on commercial and subsistence resources.	Feodoroff, 2020; Mustonen and Shadrin, 2021)
Multiple; sea-ice	Losses of winter sea-ice to the north and west of the Antarctic Peninsula have enabled krill fishing vessels to fish all year round in that area.	(Meredith et al., 2019)
Future climate change impacts and risks		
Multiple	Climate change impacts on the ecology and physiology of polar cod species contribute to expected increases in biomass and catch potential under high to moderate mitigation (RCP2.6 and RCP4.5) and reductions in groundfish recruitment and yield under low mitigation (RCP8.5) scenarios (CCP6.2.2) across range of multispecies models.	(Laurel et al., 2016; Spencer et al., 2016; Lotze et al., 2018; Spencer et al., 2019; Dahlke et al., 2020; Grüss et al., 2020; Hollowed et al., 2020; Reum et al., 2020; Thorson et al., 2020)
Climate x management interaction	Assuming no climate adaptation in current Ecosystem Based Management (EBM), 50% declines (relative to projections under persistent current climate conditions) in Eastern Bering Sea pollock and cod yield is *likely* under moderate carbon mitigation scenarios (RCP4.5), and *very likely* under low mitigation scenarios (RCP8.5).	(Holsman et al., 2020; Reum et al., 2020; Whitehouse et al., 2021)
Warming; OA	Warming, Ocean Acidification, fish predators, and thermal tolerance differentiate impacts across crab species in the Arctic; increased productivity and redistribution offshore is expected for tanner crab; red king crab and snow crab are projected to continue to shift north and decrease in productivity. OA is expected to impact demographies, altering harvest recommendations and biological reference points for some species of some shellfish and flatfish (e.g., red king crab, Northern rock sole) in projection simulations.	(Punt et al., 2014; Sawatzky et al., 2020; Punt et al., 2021)
Climate x management interaction	Multiple rights-based fisheries operate in the Arctic, increasing investment in long-term sustainability but reducing harvest portfolio diversity and increasing vulnerability to climate shocks.	(Kasperski and Holland, 2013; Ojea et al., 2017)
Multiple; sea-ice	Physical and biological changes in Antarctic waters are expected to result in net declines in krill habitat and growth potential, although one study indicates a potential increase. Reduction in the Antarctic ice pack is as *likely as not* to increase total season length in areas near to land-based predators.	(Melbourne-Thomas et al., 2016; Piñones and Fedorov, 2016; Klein et al., 2018; Rogers et al., 2020; Veytia et al., 2020)
Phytoplankton and temperature	Projected changes in primary production and temperature are expected to cause declines in krill growth and availability to predators; impacts may be countered by reducing fisheries, signifying a potential conflict between fisheries and top predators.	(Piñones and Fedorov, 2016; Klein et al., 2018)

CCP6.2.4 Economic Activities

Climate change presents significant risks to economic activities in the polar regions (*very high confidence*) and simultaneously enables development possibilities for fisheries (CCP6.2.3.3), agriculture (CCP6.2.3.2), the sharing and subsistence economy (CCP6.2.3.1) (SMCCP6.2) (*high confidence*), maritime trade (Box CCP6.1), natural resource development (CCP6.2.4.1) (*medium confidence*), tourism (CCP6.2.4.2), and transportation (including shipping) (CCP6.2.4.3; FAQ CCP6.2). Hundreds of billions of dollars are expected to be invested in the polar regions in the next several decades (Lloyd's, 2012; Barnhart et al., 2016; Pendakur, 2017; Tsukerman et al., 2019) and, as this unfolds, there are opportunities to simultaneously implement adaptation strategies that support climate resilient development pathways in line with self-determination for Indigenous Peoples and local communities and locally derived visions of successful adaptation and development (CCP6.3.2, CCP6.4.3) (Jorgenson, 2007; Ritsema et al., 2015; Ready and Power, 2017; Larsen and Petrov, 2020).

CCP6.2.4.1 Changing access to natural resources with consequences for safety, economic development and climate mitigation

Climate change is improving access to natural resources in the Arctic with consequences for human safety (*high confidence*), economic development (*very high confidence*) and global mitigation efforts (*medium confidence*). Reductions in sea-ice combined with improved extraction and transportation technologies have increased accessibility to natural resources across the Arctic (Eliasson et al., 2017; Dawson et al., 2018b; Stephen, 2018); a situation that could support continued global dependence on relatively cheap and abundant fossil fuels resources and contribute to further warming. By 2040 (RCP4.5) it is expected that sea-ice will have receded enough to make gas production technologically feasible in the European off-shore Arctic (Petrick et al., 2017). However, increased sea-ice mobility, iceberg abundance, storm surge, and surface wave action (Ng et al., 2018; Howell and Brady, 2019; Casas-Prat and Wang, 2020) will also increase risks to ships servicing mines in a region that already exhibits disproportionately high accident rates (Council of Canadian Academies, 2016) (CCP6.3.1, Table CCP6.1). Season lengths for ship-based support to mines and extraction sites will increase with sea-ice change, while access via ice roads will decrease with warming (Perrin et al., 2015; Council of Canadian Academies, 2016; Trofimenko et al., 2017; Southcott and Natcher, 2018). By 2050, climate change impacts to the Tibbitt to Contwoyto Winter Road servicing mines in the northeastern region of the Northwest Territories, Canada could cost between $55 million to $213 million CAD to maintain for a shorter period of time than at present (Perrin et al., 2015). Changes in submarine permafrost, critical to mining infrastructure, such as pipelines and offshore infrastructure (Bashaw et al., 2016; Paulin and Caines, 2016), are expected to increase production costs and impact safety for workers (Riedel et al., 2017). By mid-century, regardless of emissions scenario, it is expected that risks from permafrost thaw will be disproportionately high for industrial infrastructure along major pipeline systems in Alaska and natural gas extraction areas in the Yamal-Nenets region in northwestern Siberia, Russia (Hjort et al., 2018).

CCP6.2.4.2 Changing demand, opportunities and risks for polar tourism

Climate change has increased risks to, and demand for, polar tourism experiences related to increased maritime accessibility (*high confidence*), lengthening of warm weather season lengths (*very high confidence*) and development of a 'last chance tourism market' (*medium confidence*). Reductions in sea-ice extent have facilitated increased access for polar cruising (Dawson et al., 2018b; Stewart et al., 2020). Demand for Arctic cruises has increased by 20.5% over the past five years and resulted in 27.2 million passengers in 2018 (Shijin et al., 2020). In the Antarctic, tourist numbers increased by 27% from 1992-2018 and attracted 75,000 visitors in 2019-2020 (IAATO, 2020; Shijin et al., 2020), making it the largest economic sector in the entire region (Stewart et al., 2020). The recent increase in polar tourism is due in part to the development of a niche market called 'last chance tourism', which involves explicitly marketing vulnerable or vanishing destinations or features (i.e., glaciers, polar bears, landscapes) and encouraging tourists to see them 'before they are gone' (Dawson et al., 2018a; Groulx et al., 2019). However, tourism development opportunities will also contend with ongoing risks related to the COVID19 pandemic, which halted tourism globally in 2020-2021 (Frame and Hemmings, 2020; Lorenzo et al., 2020), as well as those related to increased climatic risks limiting participation and reducing safety and security. By 2100 under RCP8.5, snow cover season length suitable for winter recreational activities is projected to decrease by 21−49% in West Greenland (Schrot et al., 2019). Reduced sea-ice and snow cover creates hazards for and could limit dog sledding, cross country skiing, snowmobiling and floe edge tours, with limited adaptation strategies available for low elevation areas (Stephen, 2018; Palma et al., 2019).

CCP6.2.4.3 Risks and opportunities in transportation systems

Climate hazards create risks to transportation sectors with consequences for human safety (*very high confidence*), security (*low confidence*), and economic development (*high confidence*). Remote polar regions are highly reliant on transportation systems (air, road, sea) to support and service communities (Arctic) and scientific stations (Antarctic and Arctic). Changes in permafrost, snow, ice, and precipitation patterns have increased the risk of rail infrastructure and of using permanent roads and semi-permanent trails that service Antarctic research stations, connect Arctic communities, and support Indigenous food harvesting activities

(Calmels et al., 2015; Council of Canadian Academies, 2016; Ford et al., 2019; Stewart et al., 2020). Warming temperatures have particularly decreased the reliability, safety level, and season length of winter ice roads (Perrin et al., 2015; Council of Canadian Academies, 2016; Gädeke et al., 2021) in the northern Baltic (Finland) (Kiani et al., 2018), James Bay (Canada) (Hori et al., 2018a; Hori et al., 2018b), and Yakutia (Russia) (Mustonen and Shadrin, 2021). Dog sled travel in northwest Greenland has experienced shorter season lengths (Nuttall, 2020), Alaskan whale hunters have had difficulty finding suitable ice for safe harvest activities (Huntington et al., 2016; Nyland et al., 2017), and unpredictability in break-up and freeze-up of sea-ice has compromised safe travel to and from culturally significant hunting and camping areas in Canada (Dawson et al., 2020; Simonee et al., 2021), and northeast Siberia (Ksenofontov et al., 2017; Mustonen and Shadrin, 2021). Fog (*low confidence*) and an increase in precipitation falling as ice pellets or hail (*high confidence*) (Kochtubajda et al., 2017) is expected to continue to cause operational delays and create safety issues for aviation in the Polar regions (Debortoli et al., 2019).

[START FAQ CCP6.2 HERE]

FAQ CCP6.2: Is sea-ice reduction in the polar regions driving an increase in shipping traffic?

The polar seas have captured the imagination of global nations for centuries for its natural resource, tourism, scientific, and maritime trade potential. As the polar regions are warming at two to three times the rate of the global average leading to rapid reductions in sea-ice extent and thickness, international attention has been reinvigorated and investments are being made by Arctic and non-Arctic nations alike with a view to utilize newly accessible seaways. Between 2013 and 2019 ship traffic entering the Arctic grew by 25% and the total distance travelled increased by 75%. Similar shipping growth trends are evident in the Antarctic albeit to a lesser extent. Expected growth in Arctic shipping will influence a suite of cascading environmental and cultural risks with implications for Indigenous Peoples.

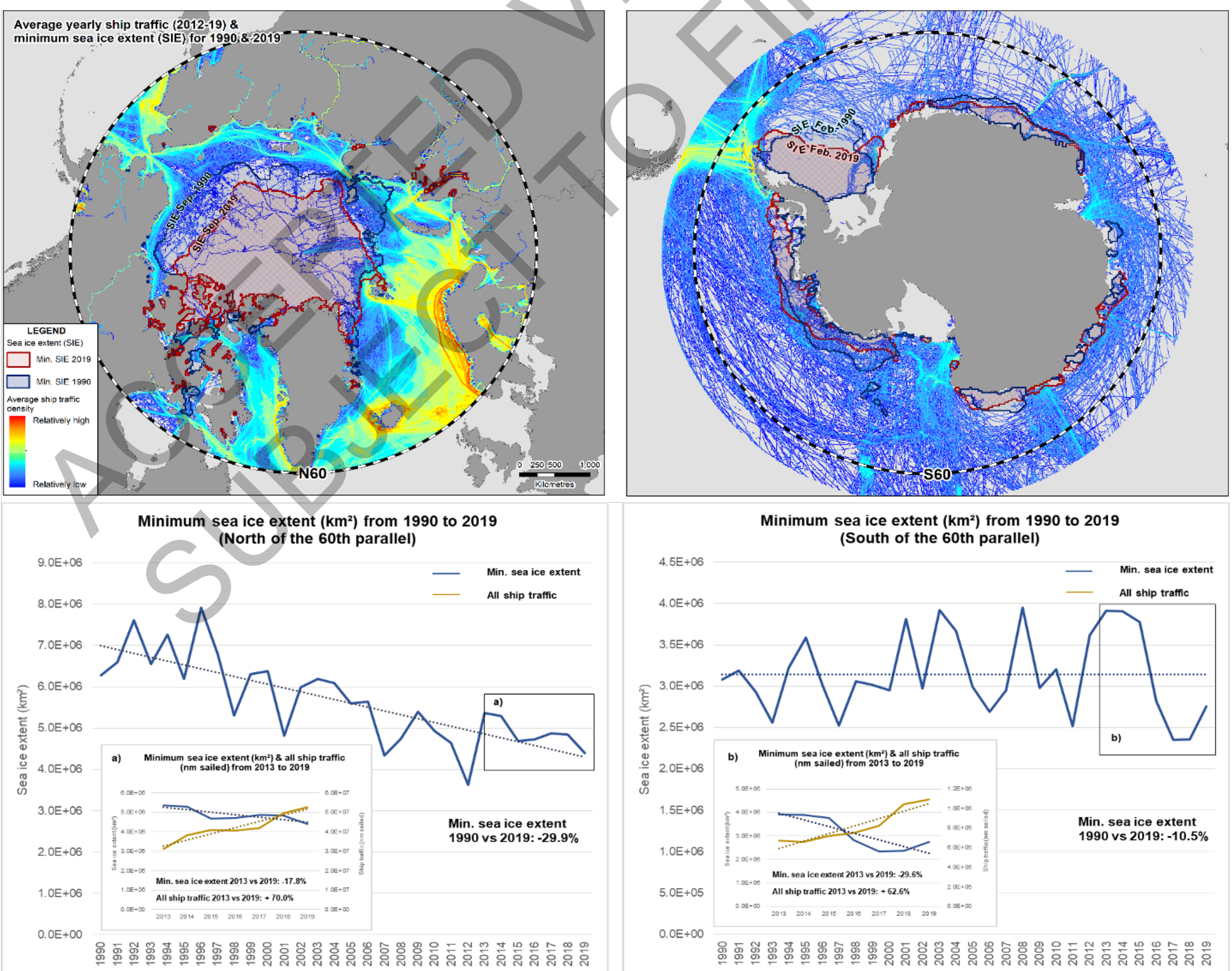

Figure FAQ CCP6.2.1: Projected operational accessibility along Arctic maritime trade routes (Northwest Passage, Transpolar Route, and Northern Sea Route) under future warming (left) and observed increases in commercial ship traffic along the routes from 2012-2019

There has been debate among shipping stakeholders, rightsholders, and experts about the extent to which climate change and sea-ice change is directly influencing increases in shipping activity in the polar regions relative to other social, technological, political, and economic factors such as commodity prices, tourism demand, global economic trends, infrastructure support, and service availability. Understanding the connection between climate change and polar shipping activity will allow for more reliable projections of possible future traffic trends and will aid in identifying appropriate adaptation and infrastructure needs required to support future management of the industry. Recent studies have observed increasing statistical correlations between sea-ice change and shipping trends in the polar regions and many have concluded that although economic factors remain the main driver of shipping activities, followed by infrastructure availability, climate change does indeed play a varying but important role in influencing operator intentions. The 'opening of polar seaways' due to sea-ice reduction is indeed 'enabling' opportunities for polar shipping among all types of vessels due to increasingly accessible areas that were previously covered by multiyear ice, but the extent to which climate change will specifically 'drive' an increase in shipping demand remains highly dependent on the vessel type and the reasons for operation. There are certain vessel types, such as those supporting international trade, mining operations or community re-supply, where analysis shows no correlation or weak correlations with sea-ice change suggesting that climate change is enabling these types of ships via increased open water areas and season lengths but that it is not necessarily driving demand. Conversely, there are certain vessel types, such as yachts and cruise ships, where correlations between sea-ice change and traffic increases are stronger, and where there is evidence to suggest that these vessels are indeed driven to visit the polar regions because they perceive waterways as exotic and exciting due to being newly accessible or they want to have a Polar experience before it disappears or is irreversibly changed as is the case with last chance tourists. As sea-ice recedes and polar shipping opportunities grow there will be an increased need to better identify and implement Indigenous self-determined and equitable shipping governance frameworks that facilitate benefits and minimize risks.

[END FAQ CCP6.2 HERE]

[START BOX CCP6.1 HERE]

Box CCP6.1: Climate Change and the Emergence of Future Arctic Maritime Trade Routes

Discovering a viable maritime trade route linking the Atlantic and Pacific oceans through the Arctic has captured the collective global imagination for centuries (Bockstoce, 2018). Geographically shorter than southern trade routes via the Panama and Suez Canals, the Arctic presents the possibility for more economical and timely commercial trade, but has historically been limited by thick multi-year ice and other navigational challenges. Amplified warming in the Arctic has caused September sea-ice extent to decline at a rate of -13% per decade (Serreze and Meier, 2019) and reduced sea-ice thickness by 66% (2 m) between 1958-1976 and 2011-2018 (Kwok, 2018). Regardless of mitigation efforts, it is expected that before mid-century the Arctic will be seasonally ice free for the first time in 2,600,000 years (defined as < 1,000,000 km2) (Knies et al., 2014; SIMIP Community, 2020; Fox-Kemper et al., 2021; Lee et al., 2021) and will make Arctic maritime trade a reality (Eguíluz et al., 2016; Melia et al., 2016; Pizzolato et al., 2016; Bennett et al., 2020; Wei et al., 2020).

There are three identified trade routes in the Arctic: Northern Sea Route (NSR), Northwest Passages (NWP), and the Transpolar Sea Route (TSR). Over the last decade economic trends and reductions in sea-ice have facilitated significant increases in ship traffic in the NSR (Aksenov et al., 2017; Li et al., 2020), including a 79% increase in total transit tonnage from 2010 to 2017 (Babin et al., 2020) related mostly to domestic resource development. Relative to an early 21st century baseline, it is expected that the NSR will become 18% more accessible by mid-century (Stephenson et al., 2013) and could navigable even for non-ice strengthened vessels for 101-118 days annually by 2050 and 125-192 days by 2100 (Khon et al., 2017). The NWP has experienced a tripling of km travelled by ships since 1990, attributed mostly to resource extraction and increases in tourism opportunities (Johnston et al., 2017; Dawson et al., 2018a). The NWP could become 30% more accessible by 2050 compared to current conditions (Stephenson et al., 2013). Before 4°C global warming above pre-industrial, re-supply vessels (Polar Class 7) in the western NWP could gain an additional month of operating time, whereas the eastern NWP could gain just two weeks (Mudryk et al., 2021) due to the dynamic import of mobile and hazardous ice from the Arctic Ocean (Haas and Howell, 2015; Howell and Brady, 2019). Comparatively, the TSR has historically only been viable for nuclear icebreakers, submarines, and occasional military and scientific activity due to thick multiyear ice regimes (Bennett et al., 2020). However, this most sought-after route offers the greatest reduction in sailing times compared to southern routes (19-24 days) of all Arctic Sea routes and could be 56% more accessible by mid-century compared to current conditions (Stephenson et al., 2013; Melia et al., 2016).

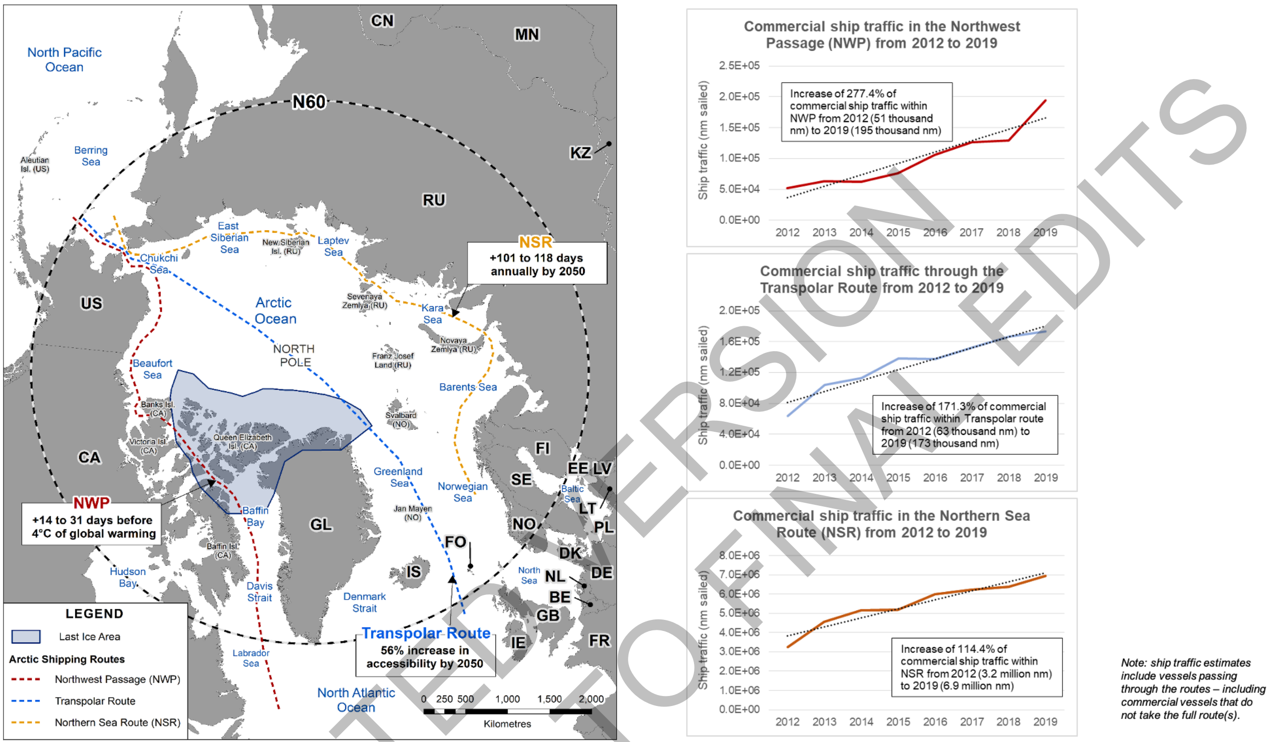

Figure Box CCP6.1.1: Arctic trade routes and projected operations related to sea-ice loss.

Growth in Arctic maritime trade will result in increased emission of black carbon (Stephenson et al., 2018; Zhang et al., 2019; Wang et al., 2021), increases in ship-source underwater noise impacts on marine mammals (Halliday et al., 2017), higher rates of accidents and incidents among vessels from increasing mobile sea-ice and newly accessible ice-free waters that lack charting (Haas and Howell, 2015; Howell and Brady, 2019), impacts to cultural sustainability for Indigenous Peoples (Olsen et al., 2019; Dawson et al., 2020) (*high confidence*), the potential for the introduction and propagation of invasive species (Chan et al., 2019; Rosenhaim et al., 2019), and sovereignty tensions with implications for global geopolitics (Drewniak et al., 2018) (*medium confidence*). Globalization and the almost universal adherence to economic growth models among nations will continue to fuel maritime trade (Box 14.5). As sea-ice decreases facilitates growth in Arctic maritime trade and transportation specifically, adaptation strategies designed to facilitate mitigation co-benefits and that target the cascading implications and double exposure of climate change and Arctic shipping impacts will be essential in reducing risks (Ng et al., 2018; Pirotta et al., 2019; Bennett et al., 2020; Zeng et al., 2020). Electric and solar powered vessels, new engine and emission reduction technologies, investment in wind, water, ice, and climate forecasting technologies and services (Haavisto et al., 2020; Stewart et al., 2020; Simonee et al., 2021), and efforts by the International Maritime Organization to reduce sulphur and the use of heavy fuel oils (PAME, 2020; van Luijk et al., 2020) could play a key role in limiting emissions and reducing risks related to the environmental and cultural impacts of fuel spills in ice-infested Arctic waters. The development of low impact shipping corridors (Chénier et al., 2017; Dawson et al., 2020) and multilateral agreements such as those implemented by the Arctic Council and Indigenous Peoples' organizations on joint search and rescue (Arctic Council, 2011) and shared spill responsibilities

(Arctic Council, 2013) represent important co-governance efforts that will be increasingly important in the future due to projected climate related risks.

[END BOX CCP6.1 HERE]

CCP6.2.5 Arctic Settlements and Communities

Polar settlements range from large well-serviced cities such as Tromsø, Murmansk and Reykjavik, to remote fly-in Indigenous communities, to scientific outposts and research stations. Polar settlements are at significant risk from climate change through shoreline erosion, permafrost thaw, and flooding (*high confidence*) (CCP6.2.2). Opportunities for community development in small communities are underestimated as they are emergent and unknown (*highly likely*) (CCP6.2.5).

Degradation of ice-rich permafrost can threaten the structural stability and functional capacities of community-based infrastructure (i.e. airports and roads; CCP6.2.5), and can have implications for local economies with coupled impacts for local livelihoods, health and wellbeing (CCP6.2.5, CCP6.2.6) (*high confidence*). For instance, in Canada, infrastructure damage from permafrost instability caused temporary closures of schools in Yukon, permafrost degradation contributed to runway damage at Iqaluit International Airport in Nunavut, and flooding from heavy rains resulted in thermal erosion of river banks that interrupted water and sewage service in Nunavut (Oldenborger and LeBlanc, 2015; Council of Canadian Academies, 2016; Lemmen et al., 2016). In northeast Siberia, the floods of Alazaeya river attributed to thawing permafrost have severely affected Andreyushkino in Yakutia (Mustonen and Shadrin, 2021).

By 2050, 69% of fundamental human infrastructure in the Arctic are projected to be at risk under an RCP4.5 scenario, including more than 1,200 settlements and 36,000 buildings, leaving 4,000,000 people living in areas with high potential for thaw (Hjort et al., 2018). Widespread permafrost thaw could increase the cost of infrastructure lifecycle replacement by 27% by mid-century under RCP8.5 (Suter et al., 2019). Northern Canada and Western Siberia are at particularly high risk, which are projected to cost additional annual spending of over 1% of annual gross regional product to maintain existing infrastructure (Suter et al., 2019). For instance, under an RCP8.5 scenario, climate change could affect over 19% of structures and infrastructure assets in Russia, which would cost an estimated $84.4 billion USD to mitigate damages (Streletskiy et al., 2019). 54% of residential buildings are projected to be affected by significant permafrost degradation by the mid-century, costing an additional estimated $52.6 billion USD (Streletskiy et al., 2019). SLR and reduced sea-ice protection is projected to compound permafrost thaw damages, including low lying coasts (e.g., along southern Beaufort Sea), low-lying barrier islands (e.g., along Chukchi Sea), and deltas (e.g., Mackenzie, Lena) (Fritz et al., 2017; Lantz et al., 2020). In Alaska, proactive adaptation was substantially cost-saving (reducing costs by $2.9 billion USD for RCP8.5 and $2.3 billion USD for RCP4.5), highlighting the financial benefit of investing in adaptation now (Melvin et al., 2017). Permafrost damage and SLR may result in tipping points, leaving some communities no longer habitable. In Alaska, US, many communities at-risk of flooding and storm surges are already engaged in community-led relocation planning processes (e.g., Shishmaref) (Melvin et al., 2017; Farbotko et al., 2020; Rosales et al., 2021).

Climate change has important intangible loss and damage implications in the Arctic, with negative impacts ranging from livelihoods to spirituality to solastalgia (i.e. distress caused by environmental change) (Cunsolo and Ellis, 2018; Middleton et al., 2020b; Sawatzky et al., 2020; Mustonen and Shadrin, 2021). Permafrost thaw, SLR, and reduced sea-ice protection also presents risk to socio-cultural assets, including heritage sites in all Arctic regions (*very high confidence*) (Friesen, 2015; Hollesen et al., 2016; Radosavljevic et al., 2016; O'Rourke, 2017; Hillerdal et al., 2019; Fenger-Nielsen et al., 2020; Jensen, 2020). A large number of archaeological sites are at risk from climate change in southwest Greenland; Yukon's Beaufort coast, Canada; and Auyuittuq National Park Reserve, Nunavut, Canada (Westley et al., 2011; Hollesen et al., 2018; Irrgang et al., 2019; Fenger-Nielsen et al., 2020). Siberian nomadic reindeer herding and fishing livelihoods are vulnerable to permafrost thaw, which alters northern landscapes and lakes, as well as rain-on-snow events, and rapidly changes landscapes and terrestrial and aquatic habitats (Mustonen and Mustonen, 2016; Brattland and Mustonen, 2018; Mustonen and Huusari, 2020) (CCP6.2.2). The intangible loss and damage to nomadic cultures could cascade to losses of identity and social challenges (CCP6.2.6; Chapter 13).

[START FAQ CCP6.3 HERE]

FAQ CCP6.3: How have Arctic communities adapted to environmental change in the past and will these experiences help them respond now and in the future?

For thousands of years Arctic Indigenous Peoples and local communities have survived several major changes to the ecosystems in which they rely; however, the present changes in climate are more challenging than pre- and early historic changes in the Arctic and new unprecedented risks will now face polar communities.

The challenges for responding to present change are due to the multiple imposed and simultaneous drivers combined with elimination and/or removal of endemic capacity to respond in culturally and locally appropriate ways. Adapting in the past may therefore inform and produce novel solutions for the present and convey baselines of important contextual information on significance of change. Arctic communities, especially Indigenous Peoples, have been marginalized in terms of their autonomous responses spaces and self-assessment that could be made without external pressures. Therefore, in order to increase the possibility of community-led adaptation, colonialism and the resultant lack of upheld rights, resources and equity need to be solved simultaneously with the present climate change impacts. New research, governance, policy, and collaborations are needed in order to effectively adapt to risks that are projected to emerge in the polar regions as a result of rapid climate change.

[END FAQ CCP6.3 HERE]

CCP6.2.6 Human Health and Wellness in the Arctic

Climate change continues to have wide-ranging physical human health risks in the Arctic, particularly for Indigenous Peoples (*high confidence*); however, future projections of physical risks are nascent. Climate change has already challenged food and nutritional security (CCP6.2.5). Climate change also creates safety concerns for those who access the land, ice, and water for food, cultural, and recreational purposes, with changing environmental conditions linked to injury and death (Durkalec et al., 2014; Clark et al., 2016a; Clark et al., 2016b; Driscoll et al., 2016; Brattland and Mustonen, 2018). Foodborne disease risks are expected to increase in the Arctic, with warming temperatures linked to increased risk of microbial contamination of locally harvested foods (Grjibovski et al., 2013; Harper et al., 2015), chemical contamination of locally harvest foods (Hansen et al., 2015; Long et al., 2015; Alava et al., 2017), compromised structural integrity and utility of ice cellars used to store locally harvested meat (Nyland et al., 2017; Markon et al., 2018), and new challenges to traditional food preparation techniques (Shadrin, 2021). Waterborne disease risks have increased, with decreased drinking water quality and quantity, water treatment infrastructure failures, and new waterborne pathogens emerging in the Arctic (Berner et al., 2016; Thivierge et al., 2016; Markon et al., 2018; Yoder, 2018; Masina et al., 2019; Sachal et al., 2019; Harper et al., 2020; Mustonen and Shadrin, 2021). Emerging environmental exposures to pathogens is also a concern. In 2016 a Nenets boy and over 200,000 reindeer died from anthrax linked to warming environments (Ezhova et al., 2021) - a risk which is projected to increase with climate change (Liskova et al., 2021). Thawing permafrost increases smallpox risk in former nomadic campsites and graveyards (Mustonen and Shadrin, 2021; Shadrin, 2021). Arctic health systems - which are often already stressed - will be further challenged by climate change (Harper et al., 2015; Clark and Ford, 2017), especially in conjunction with other system shocks (e.g., COVID-19) (Cross-Chapter Box COVID in Chapter 7) (Zavaleta-Cortijo et al., 2020). While physical health impacts have been observed, research examining future health projections or evaluating the efficacy of health adaptations are rare (Dobson et al., 2015; Harper et al., 2020; Harper et al., 2021).

Climate change has negative, widespread and cumulative impacts on mental health in the Arctic, particularly for Indigenous Peoples (*very high confidence*) (Figure CCP6.3). Climate-sensitive mental health outcomes are complex, overlapping, and interrelated, and have multiple direct and indirect pathways stemming from: acute (e.g., major storms, flooding, wildfires) and chronic (e.g., temperature increases, sea-ice loss, permafrost thaw) environmental conditions, and resulting disruptions to livelihoods, culture, food systems, social connections, health systems, and economies (Cunsolo Willox et al., 2013a; Cunsolo Willox et al., 2013b; Cunsolo Willox et al., 2014; Beaumier et al., 2015; Durkalec et al., 2015; Hamilton et al., 2016; Clayton et al., 2017; Dodd et al., 2018; Jaakkola et al., 2018; Markon et al., 2018; ITK, 2019; Minor et al., 2019; Middleton et al., 2020a; Middleton et al., 2020b; Feodoroff, 2021).

Negative mental health outcomes from climate change include: emotional reactions (e.g., sadness, fear, anger, distress, and anxiety); psychosocial outcomes (e.g., depression, post-traumatic stress disorder, and generalized anxiety); experiences with grief and loss (i.e. ecological grief); increased drug and alcohol usage, family stress, and domestic violence; increased suicide ideation and suicides; loss of cultural knowledge and continuity, disruptions to intergenerational knowledge transfer; and deterioration and loss of place-based identities and connections (i.e. solastalgia) (Cunsolo Willox et al., 2013a; Cunsolo Willox et al., 2013b; Cunsolo Willox et al., 2014; Durkalec et al., 2015; Harper et al., 2015; Cunsolo and Ellis, 2018; Hayes et al., 2018; Jaakkola et al., 2018; Markon et al., 2018; Minor et al., 2019; Middleton et al., 2020a; Feodoroff, 2021).

The negative mental health impacts from climate change are amplified among those most reliant on the environment for subsistence and livelihoods, those who already face chronic physical or mental health issues, and those facing socio-economic inequities and marginalization, particularly for Indigenous Peoples (*high confidence*). These climate change related mental health impacts are unequally distributed (Cunsolo Willox et al., 2014; Minor et al., 2019), and may vary by gender (Beaumier et al., 2015; Harper et al., 2015; Feodoroff, 2021) and age (Petrasek MacDonald et al., 2013; Ostapchuk et al., 2015; Petrasek MacDonald et al., 2015; Kowalczewski and Klein, 2018).

Climate change will increase mental health risks in the Arctic in the future (*medium confidence*). Future risks include exposures to severe weather events and changing precipitation patterns, sea-ice loss, wildfires, and changing place attachment, as well as disruptions to underlying determinants of mental health and social support networks (Cunsolo Willox et al., 2014; Cunsolo and Ellis, 2018; Markon et al., 2018; Council of Canadian Academies, 2019; ITK, 2019; Middleton et al., 2020a; Middleton et al., 2020b).

There is *limited evidence* assessing adaptation options that effectively reduce climate-related mental health risks, but developing or enhancing access to mental health resources and infrastructure are critical, such as land-based healing programs, enhanced access to culturally-appropriate mental health resources, and climate-specific counselling services to support individual and community psychosocial resilience, particularly among Arctic Indigenous Peoples (Cunsolo and Ellis, 2018; Middleton et al., 2020a). Incorporating a climate-sensitive mental health lens into mitigation and adaptation planning holds potential for increasing mental health and resilience in the Arctic, as well as supporting other social, economic, and cultural co-benefits.

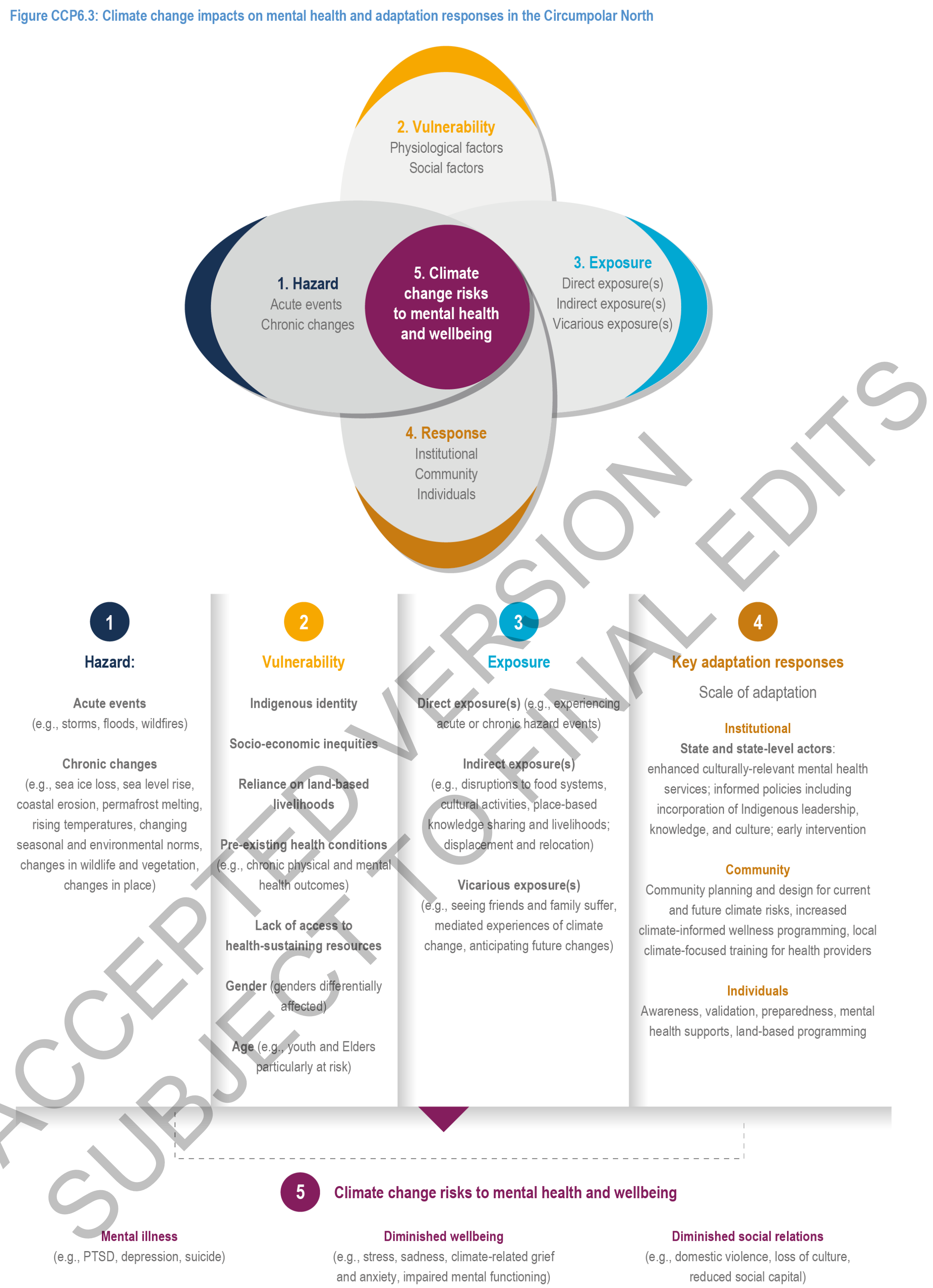

Figure CCP6.3: The pathways through which climate change impacts mental and emotional health in the Arctic.

[START BOX CCP6.2 HERE]

Box CCP6.2: Arctic Indigenous Self-determination in Climate Change Assessment and Decision-making

Similar to Indigenous Peoples globally (Cross-Chapter Box INDIG in Chapter 18), climate change vulnerability for Arctic Indigenous Peoples is often rooted in colonialism, which has led to land dispossession and displacement, carbon-intensive economies, discrimination, racism, marginalization, and social, cultural, and health inequities (Whyte, 2016; Whyte, 2017; Whyte et al., 2019; Chakraborty and Sherpa, 2021). Therefore, effective responses to climate change risks for Indigenous Peoples are self-determined and underpinned by Indigenous knowledge (*very high confidence*).

Indigenous knowledge systems are diverse among and within Arctic Indigenous Peoples, and reflect deep and rich knowledge that situates and contextualizes values, traditions, governance, and practical ways of adapting to the ecosystem over millennia (Raymond-Yakoubian et al., 2017; Brattland and Mustonen, 2018). Indigenous knowledge is a valuable source of knowledge; a method to detect change, evaluate risk, and inform adaptation approaches; and a cultural ecological service (Brattland and Mustonen, 2018; Crate et al., 2019; Meredith et al., 2019) that is critical for decision-making (Mustonen and Mustonen, 2016; Huntington et al., 2017). For instance, Kalaallit knowledge in Greenland has been used to detect and attribute long-term (over 50 years) marine change that reaches beyond scientific instrumental data (Mustonen et al., 2018b).

This Box was written by Indigenous authors, recognizing that Indigenous knowledge and local knowledge are intellectual property (Cross-Chapter Box INDIG in Chapter 18), alleviating the risk of this knowledge being misinterpreted (David-Chavez and Gavin, 2018; Hughes, 2018; Raymond-Yakoubian and Daniel, 2018), and acknowledging that meaningful inclusion of Indigenous Peoples strengthens and supports Indigenous self-determination (ITK, 2019). Self-determination signifies and values the capacity and decisions made by these peoples in their own right and from their own autonomous cultural positioning. Following the format used in SROCC, this Box prioritizes Indigenous voices by presenting climate change assessments premised on Indigenous knowledge and written by Indigenous Peoples.

Climate change, nomadic lifestyles, and preservation of traditions

Perspectives from the Yukaghir Council of Elders and Russian Association of Indigenous Peoples, Russia

Climate change threatens reindeer herding, hunting, fishing, and gathering, which form the basis of Siberian Indigenous societies. Nomadic herding lifestyle is premised on Indigenous knowledge which has accumulated over millennia. IK, including the ability to predict weather, has played a substantial role in the adaptation to the extreme conditions. According to Shadrin (2021) present, rapid changes are changing Indigenous concepts of reality - they are increasingly finding themselves in situations where their experience and knowledge cannot help them. An Elder in Northeast Siberia explained that “nature does not trust us anymore” (Mustonen and Shadrin, 2021).

A major problem for nomadic reindeer herding is the degradation of reindeer pastures (Mustonen and Shadrin, 2021). The expansion of willows and shrubs into the tundra has resulted in losses of pastures. In other nomadic communities, these changes have led to the expansion of moose into tundra area and effects of reindeer populations, as well as changes in wild reindeer migration routes leading to the destruction of domestic reindeer pastures (Mustonen and Shadrin, 2021).

Due to the steady changes in precipitation in recent years, a deeper than usual snow cover has formed in Northeast Siberia (Mustonen and Shadrin, 2021). This alters the capacity of reindeer to access lichen, their primary food source. Late onset of cold weather has led to difficulties in the herds moving to their winter pastures. In the summer, increased rainfall has led to waterlogging of low-lying pastures. The most important challenge is the instability of the weather (Mustonen and Shadrin, 2021). These include frequent, never-before-seen warming, combined with rains in the late winter and early spring. Sharp temperature drops of over 30 degrees occurring within a few hours leads to formation of an ice crust on the ground which becomes a challenge for reindeer, especially in autumn, and are becoming more frequent. Furthermore, the number of summer storms and rapid cooling accompanied with snowfall during July has increased. Using Indigenous knowledge to predict weather is the basis of effective survival. It has become extremely difficult due to the unprecedented fast changing conditions (Mustonen and Shadrin, 2021) (Shadrin, 2021). All of these events lead to increased risks in the lives of Indigenous Peoples (Mustonen and Shadrin, 2021).

Climate change impacts Indigenous Peoples' health. Degradation of the quality of surface waters has increased, resulting from new floods and the thawing of permafrost, which increases risk of gastrointestinal diseases (CCP6.2.8). The 2007 flood on Alazaya river was of special importance and was locally identified to have produced the first regional "climate refugees" (Mustonen and Shadrin, 2021). Warming has expanded the distribution of new disease-carrying insects and ticks into new territories (Mustonen and Shadrin, 2021). Ancient cemeteries and campsites, as well as the burial sites of reindeer, become dangerous as permafrost thaws and coastal erosion proceeds.

Traditional food security is under threat. Permafrost-based storage facilities have deteriorated (CCP6.2.6) (Mustonen and Shadrin, 2021). There is an increase in the number of people who are forced to abandon the consumption of raw fish. As a result, the likelihood of losing cultural traditions is growing. These combined climate change impacts result in loss of Indigenous knowledge and nomadic lifestyles, thus, losing important aspects of their identity as distinct Indigenous Peoples (Mustonen and Shadrin, 2021).

Climate change impacts on Sámi women

Perspectives from Sámi in Finland

Feodoroff (2021) stresses that many Sámi women are central to Indigenous-led adaptation. Indigenous women use their bodies as gauges of change. For example, the restoration work in Näätämöjoki River in Finland (Ogar et al., 2020; Feodoroff, 2021) is based on the knowledge of traditional fishers and reindeer herders. Indigenous knowledge and Western science offer possibilities to reflect on changes that the waters in Indigenous bodies have known of events of the past (Feodoroff, 2021). Changes in temperature, pain and the gradual passing of pain, waves, and intrusions within Indigenous bodies are knowledges that are difficult to communicate according to Feodoroff (2021). Women are sensitive to receiving messages from their home environments. Feodoroff (2021) stresses that Indigenous conservation work is a bodily commitment. This realisation is linked with difficult questions of what or who controls Indigenous bodies. Feodoroff (2021) links present change with lingering impacts of global environmental damage that has not been dealt with or addressed. It may lead to real pain in Indigenous bodies and minds, causing feelings of being nauseated and ultimately causing fade out, wilt, wither and extinguishment of Indigenous Peoples.

Adaptation successes underpinned by Inuit knowledge

Perspectives from Inuit Circumpolar Council

Inuit have survived and thrived in Inuit Nunaat, their homelands, for millennia. In an environment that presents unique challenges, they have cultivated resourceful and innovative approaches tailored to their surroundings. Their values and knowledge guide their relationships with all that is within the Arctic and this has informed their decisions and management practices that continue to be in place today (Inuit Circumpolar Council Alaska, 2020). They are experts in adaptation. Now more than ever, in the time of anthropogenic climate change, living in the fastest warming region on the planet requires this expertise and capacity.

The extraordinary developments in the field of Indigenous Knowledge have crystallized the main tenant of interaction with the natural world that is "integral to a cultural complex that also encompasses language, systems of classification, resource use practices, social interactions, ritual and spirituality" (UNESCO, 2017). Inuit have used their knowledge of the land and coastal seas to design technology, monitoring systems (Atlas of Community-Based Monitoring in a Changing Arctic, 2021), and new hunting routes that respond to the changes they face (Inuit Circumpolar Council, 2017; Nunavut Climate Change Center, 2018; SIKU, 2020). Such examples of 'adaptation success' across Inuit Nunaat have been showcased and celebrated nationally and internationally (Youth Climate Report, 2019) and all are underpinned by Inuit knowledge and pivot on their right to self-determination. This is also embodied, for example, in Canada, the National Inuit Climate Change Strategy outlines the collective Canadian Inuit plan for climate action, centering on Inuit-determined priorities to protect their culture, language, and way of life, and guiding partners in how to work with Inuit on implementing this strategy (ITK, 2019). Their action on adaptation also spans scales from local to international. As far back as 1977, Inuit have been organized and involved at the international level. Inuit were present at the Rio Earth Summit and have participated in diverse but interrelated United Nations conventions to protect their homelands (e.g., UNFCCC, CBD, Stockholm

Convention). This history gives us unique insight and positions us as both leaders and partners with the ability to engage directly with governments, business, and others.

However, while Inuit are often recognized as leaders in adaptation, too often the academic literature ends there, citing 'successful Inuit-led adaptation to climate change' but not going further to explore towards what END this adaptation is designed. We have demonstrated leadership and set an example for the world in how to respond to change, but successful adaptation is not enough, it is not the end goal.

Central to their significant capacity to adapt is that it is done in recognition of the need to move beyond adaptation. Indeed, Inuit-led adaptation action is founded on the intention of contributing to and moving towards reformation and eventual transformation of systems to create a 'climate resilient' Arctic. This concept has surfaced in academic climate change literature and discussion and has begun to filter into the climate policy arena, especially within the context of the current COVID-19 pandemic that challenges us all to think about our world differently. With acknowledgement that reform and transformation is needed, the question remains, 'What does this look like?'

Inuit have an answer. System reform and transformation is grounded in self-determination. It is based in a human rights framework and rooted in Indigenous knowledge and culture. It recognizes and respects interconnectedness and builds this into solutions. It demands collaboration and true partnership towards action. And it comes from thinking big and across scales. Shaping this change calls for willingness and support to rethink the current economic and governance models that have failed us. For example, decentralizing governance and management, while it remains largely unconventional, has been shown to create some of the strongest systems we have. This is, in a large part, due to the way in which decentralization places more value and responsibility on the 'self' in self-determination. Decentralized processes in the Arctic have Indigenous knowledge holders playing a key and lead role in determining, defining, deciding how to work towards positive change.

Across Inuit Nunaat, examples of direct management and control over lands, territories and resources, have demonstrated that working from what is happening on the ground throughout their homelands, from their priorities and interests, has served to strengthen the health of their environment and their communities. For example, a comparative analysis on factors supporting and impeding Inuit food sovereignty between Alaska and the Inuvialuit Settlement Region found that the difference in outcomes within these regions is dependent on explicit respect for and recognition of the Inuit right of self-determination (Inuit Circumpolar Council Alaska, 2020). Furthermore, a new agreement achieved in Nunavut by the Qikiqtani Inuit Association related to the marine environment touted as an exemplary model for marine management is rooted in Inuit-determined structures and policies, and manifested by Inuit themselves (QIA, 2019).

Emphasis on decentralized management and substantial funding to do so at the grassroots level has been recognized by the IPCC previously in the SROCC. Ultimately, going beyond reform to system transformation requires, as Oren Lyons has stated, "value change for survival" (Lyons, 2020). Valuing decentralization, self-determination, Inuit knowledge, interconnectedness – core values held by Inuit – can move us in a climate-resilient direction.

[END BOX CCP6.2 HERE]

CCP6.3 Key Risks and Adaptation

CCP6.3.1 Key Risks

Key risks arising from changing climate hazards are presented in Table CCP6.6 (details in SMCCP6.4). Changing levels and magnitude of climate hazards translate into different levels of risks for ecosystems, industry, society and infrastructure (Figure CCP6.4) (see Meredith et al., 2019 Figures 3.5, 3.10 (Arctic), Figure 3.6 (Antarctic). In the Arctic, these risks are often also shaped by non-climatic factors (Huntington et al., 2019; Ford et al., 2021), including ongoing colonial legacies, land dispossession, landscape fragmentation, and resulting challenges in the valuing and meaningful use of Indigenous knowledge and local knowledge (Box CCP6.2) (Huntington et al., 2019; Kelman and Næss, 2019; Ford et al., 2020).

Available literature enabled assessment of particular polar assets based on projected future risk and including consideration of non-climatic compounding factors under 1°, 2°, 3° and 4°C global warming above pre-industrial including sea-ice ecosystems, marine mammals, sea birds, fisheries, infrastructure (Arctic only), local mobility (Arctic only), and coastal erosion (Arctic only) (Figure CCP6.5) (details in SMCCP6.4).

Table CCP6.5: Key risks and illustrative examples in polar regions identified through the processes described in Chapter 16 and SMCCP6.4.

Key Risk	Direct and indirect factors contributing to risk
KR1. Risk to marine ecosystems and species (CCP6.2.2; CCP6.2.3)	-Warming, marine heatwaves, sea-ice loss, glacial and ice sheet melt, ocean acidification, invasive species, harmful algae blooms -Narrow thermal niches, altered marine habitat, hampered calcification, higher corrosivity for $CaCO_3$ shell/skeleton, phenological mismatch, physiological/life history effects, sensitive food web relationships, reduced trophic (energy) transfer efficiencies, increased light availability, nutrient limitation, and changes to salinity, stratification, oxygen levels
KR2. Risk to terrestrial and freshwater ecosystems and species (CCP6.2.4)	-Warming, hydrological changes, terrestrial heat waves, change in rain and snow events, increased wild- and mega-fire events in Arctic, permafrost thaw, and erosion -Vegetation browning/greening, narrow thermal niches, physiological/ life history effects, sensitive food web relationships, parasites and disease
KR3. Risk to commercial and private infrastructure (CCP6.2.6)	-Permafrost freeze-thaw, extreme heat and precipitation, rapid warm-thaw events, storms, increased wave activity, storm surges, flooding, landslides and erosion. -Roads, airstrips, railways, ports, commercial buildings, private homes, ice cellars, traditional snow/ice/water travel routes, other infrastructure. -Permafrost freeze-thaw and SLR impacting cultural assets, including cultural heritage sites.
KR4. Risk to food and nutritional security (CCP6.2.5)	-Warming, ocean acidification, sea-ice loss, permafrost loss, changes to precipitation, wildfires, hydrological changes. -Access to marine areas increased, to coastal and terrestrial areas decreased; effects on subsistence and commercial species.
KR5. Increased polar shipping traffic with cascading risks for navigation, safety, ecosystems, and culture (CCP6.2.4; CCP6.2.5; Box CCP6.2; FAQ CCP6.1)	-Substantial reduction in sea-ice extent and thickness. -Marine subsistence species; coastal communities; Inuit hunters; ship operators; tourism operators; mining companies.
KR6. Increased mental health challenges and impacts on Indigenous Peoples and culture (CCP6.2.6.4; CCP6.2.7; CCP6.2.8. Box CCP6.2; FAQ CCP6.3)	-Warming temperature; heatwaves; ice changes; changes in snow cover; permafrost thaw; coastal erosion; changing landscapes.
KR7. Risk from polar change for global processes and SLR (FAQ CCP6.1)	-Reduction in Arctic sea-ice, sheets, and glaciers have implications for planetary albedo and ocean stratification and salinity, acceleration of global warming, potential effects on global overturning circulation and northern hemisphere weather patterns -cultural and resource connections to global sustainable development

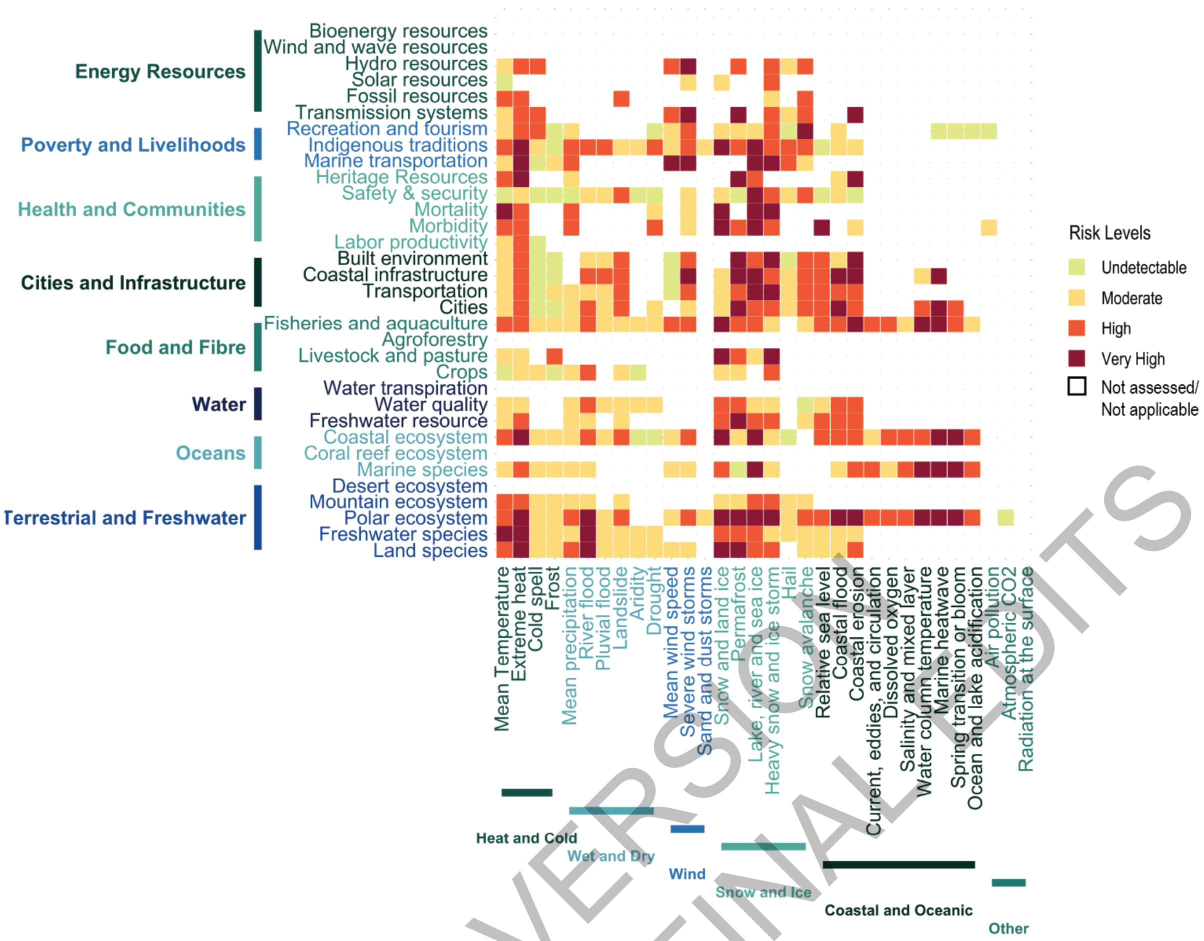

Figure CCP6.4: Rapid assessment for relative risk by sector (y-axis) and climate hazard (x-axis) for polar regions based on an assessment of asset-specific vulnerability and exposure across climate hazards (see SMCCP6.4 for methodological details). For each unique combination, the hazard by sector risk was ranked as very high (very high risk and high confidence), high (significant impacts and risk, high to medium confidence), medium (impacts are detectable and attributable to climate change, medium confidence), low/ not detected /positive (risk is low or not detectable). Blank cells are those where the assessment was not applicable or not conducted. Risks identified through the rapid assessment were further evaluated in the chapter assessments (see corresponding sector text for full assessment of risk and impacts).

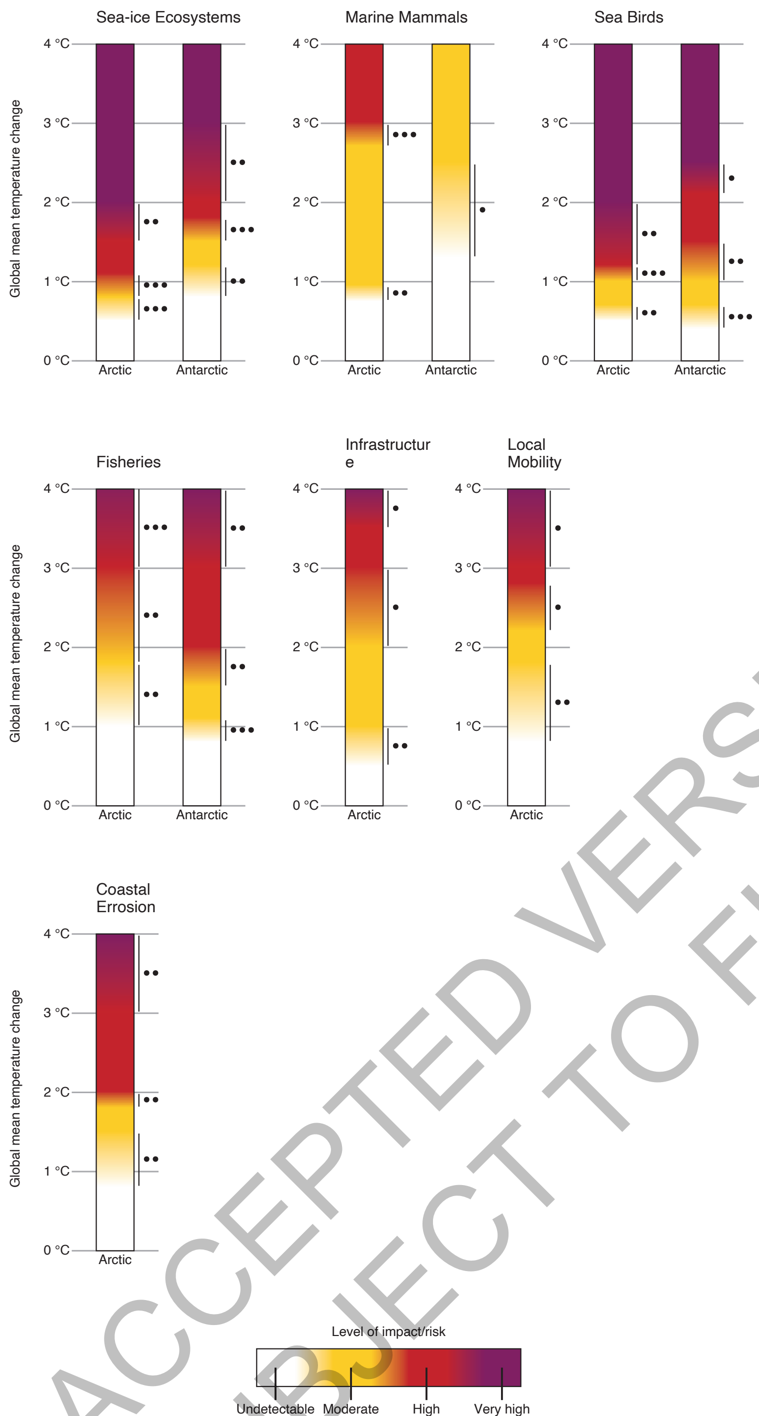

Figure CCP6.5: Burning ember of the relative risks to select assets in the Polar regions as a function of global mean surface temperature increase since pre-industrial times including: 1) sea-ice ecosystems, 2) marine mammals, 3) sea birds, 4) fisheries, 5) infrastructure (Arctic only), 6) local mobility (Arctic only), and 7) coastal erosion (Arctic only). The supporting literature and methods are provided in SMCCP6.5

CCP6.3.2 Adaptation

CCP6.3.2.1 Current adaptation

Across polar regions, adaptation responses to climate change impacts have ranged from rapid and incremental (e.g., shifting phenologies, alternative harvest or herding strategies) to large and transformative (e.g., switching livelihoods, social-ecological system transformation) (Figure CCP6.6). Some adaptation measures and opportunities induce novel risks to other sectors or systems resulting in cascading and compounding consequences that are sometimes hard to predict or prepare for (Huntington et al., 2015)

(Table CCP6.6). Adaptation planning and implementation is greater in the Arctic than Antarctic regions, in part due to disparate magnitudes of realized climate impacts and change between regions (Figure CCP6.2; Table CCP6.1), but also because of the differing governance systems in place (Meredith et al., 2019). In the Antarctic region, a climate action plan has been developed for terrestrial systems but not for the Southern Ocean (Meredith et al., 2019), although strategies for adapting to climate change have been proposed, including incorporation of precaution in decision-making (Constable et al., 2017). In the Arctic, climate change information is increasingly integrated into research, policy, and decision-making including incorporation of climate change projections, forecasts, and early warnings (AMAP, 2017; AMAP, 2018a; Marshall et al., 2019; Dorn and Zador, 2020; Hollowed et al., 2020; Stram et al., 2021).

The majority of adaptations in the Arctic are occurring at sub-regional levels in response to both observed and projected climate change, with evidence of increasing regional level action driven by climate planning processes of subnational governments (AMAP, 2017; Labbé et al., 2017; AMAP, 2018a; Canosa et al., 2020). Implemented adaptation includes alterations to building codes and infrastructure design (Shiklomanov et al., 2017; Flynn et al., 2019; Standards Council of Canada, 2020), surveillance (Ruscio et al., 2015; Ford and Clark, 2019; Meredith et al., 2019), information sharing (Berner et al., 2016), changes to survey and monitoring design (Stevenson and Lauth, 2019), hazard mapping (Flynn et al., 2019), use of new technologies (Tejsner and Veldhuis, 2018; Galappaththi et al., 2019), the development of regional and municipal adaptation plans (Labbé et al., 2017), shifting stocks and changes in fishery operations and location (Jørgensen et al., 2019; Fedewa et al., 2020; Thompson et al., 2020), alterations to subsistence harvesting activities (Anderson et al., 2018; Ford et al., 2018; Galappaththi et al., 2019), co-production of knowledge (Raymond-Yakoubian and Daniel, 2018), and application of Indigenous knowledge for resource management (Robards et al., 2018) and to monitor storms (Rosales et al., 2021; Simonee et al., 2021). Pan-Arctic and national-level adaptation remains limited (Ford et al., 2014; Canosa et al., 2020), although there have been few efforts to examine the nature of adaptation responses in Arctic regions and large gaps in understanding.

Illustrative examples of direct and cascading risks, enabling principles of climate resilience pathways, anticipated future conditions (with certainty levels and compounding risks for key sectors within polar regions are outlined in Table CCP6.6. A list of adaptation options responding directly to the challenges outlined for each sector, including an analysis of adaptation effectiveness and feasibility and cross referenced with key risks assessed in this chapter (Table CCP6.5) is provided in Figure CCP6.6

Table CCP6.6: Assessment of risks needing adaptation by sector in the polar regions.

Sector	**Direct and cascading risks**	**Enabling principles of climate resilience pathways**	**Anticipated future conditions / level of certainty**	**Compounding risks (non-climatic factors)**
Coastal settlements (CCP6.2.5)	Change in extent of sea-ice with more storm surges, thawing of permafrost, sea level rise, and coastal erosion	Local leadership and community-led initiatives to initiate and drive processes, responsive agencies, established processes for assessments and planning, geographic options	Increasing number of communities needing relocation (*medium confidence*), rising costs for mitigating erosion (*high confidence*)	Limitations of government budgets, other disasters that may take priority, policies deficiencies for addressing mitigation and relocation
Human health (CCP6.2.6)	Increased food insecurity, waterborne disease, emerging pathogens, injury and death, and negative mental health outcomes	Resources to support public programs; Indigenous self-determination; access to technology; supporting Indigenous knowledge systems; interdisciplinary and integrated decision-making	The intersection of social determinants of health will modify or mediate climate change impacts on health (*very high confidence*)	Underlying health conditions, advances in diagnosis and treatment, and other health system shocks (e.g., COVID)

 Transportation (aviation, rail, road, ice roads) (CCP6.2.4.3)	Permafrost thaw, sea-ice change, storm surge, coastal erosion, changing precipitation patterns (ice pellets, hail), and extreme events create risks to transportation infrastructure with consequences to navigation, economics, safety, and security	Financial and human resources for: climate resilient infrastructure research, development and implementation; improved weather, water, ice and climate forecasting at appropriate scales; improved communications infrastructure; local search and rescue	Limits to adaptation exist (*high confidence*), but strategic investments in technologically innovative infrastructure that offers mitigation co-benefits will greatly enhance adaptation effectiveness (*very high confidence*)	Level of local, regional, and national infrastructure development, commitment of national and state level government to sustainable development pathways, global economic and political trends, commodity prices, unforeseen system shocks
 Shipping (Box CCP6.1; FAQ CCP2)	Sea-ice reduction leading to increased shipping related to trade, tourism, fisheries, resource development, and re-supply with cascading risks from ships such as: increased under-water noise, potential introduction of invasive species, fuel spill risks, release of black carbon and air emissions, impacts to cultural resources, implications for subsistence hunting and food security, increased accidents and incidents	Financial support for ship-building technologies (e.g., low emission fuels, propulsion technologies, hull strength); development of robust multi-national agreements (in addition to existing agreements); inclusion of Indigenous Peoples in decision-making; investment in multi-national and longitudinal research on shipping impacts; and enhancing modern digital maritime charting	Ship traffic will continue to grow in polar regions (*high confidence*) with Arctic trade routes becoming increasing accessible (*very high confidence*) albeit with more challenging navigation due to increases in mobile ice in the near-term compared to late century when ice is expected to diminish completely during the shipping season (*high confidence*)	Geopolitical and sovereignty debates; shipping insurance premiums; global economic trends; commodity prices; national policies and politics; level of infrastructure investment; availability of search and rescue assets, and modern charting
 Infrastructure (CCP6.2.5)	Loss and damage to infrastructure from permafrost thaw affecting stability of ground; coastal erosion; SLR	Resources for assessments, mitigation, and where needed, relocation	Increasing cost to maintain infrastructure and greater demand for technological solutions to prevent damages (*high confidence*)	Strength of regional and national economies, other disasters that divert resources
 Non-renewable resource extraction (Arctic only) (CCP6.2.4.1)	Reduced sea-ice improves access to non-renewable resources in remote Arctic regions, while warming temperature and thawing permafrost affect production levels, quality, and reliability and season length of ice roads leading to increased operational costs	Investment in climate resilient infrastructure and low emission transportation (shipping) and investment in solar powered ships and low impact modular mining camp infrastructure	Increase in mining in newly accessible marine regions (*medium confidence)*, frequent false starts (i.e., due to climatic and non-climatic factors) (*high confidence*), and high levels of operational uncertainty (i.e., commodity prices, economic trends, climate risks) (*very high confidence*)	Commodity prices; global economic trends and shocks; Indigenous rights and decisions; changing regulatory environments, geopolitics, global demand for resources
 Tourism (CCP6.2.4.2)	Increased demand for polar tourism activities including development of 'last chance tourism' market; Increased tourism improves economic conditions but leads to increased environmental and cultural impacts	Financial resources for service and infrastructure development; Indigenous self-determination and development of co-management approaches for natural and cultural attractions;	Polar tourism demand will continue to increase, especially for cruise and yacht experiences (*high confidence*) and enhance risks related to ship groundings, accidents, and incidents (*medium confidence*)	Limited search and rescue capacity, poor infrastructure, aging expedition cruise ship fleet, uncharted waters, geological and sovereignty debates, global economic trends, unforeseen events (i.e., SARS, COVID-19)

		development of multi stakeholder/rightsholder tourism task teams		altering tourism demand patterns
 Reindeer herding (CCP6.2.3.1; 6.2.3.2; 6.2.5; Box CCP6.2)	Rain-on-snow events causing high mortality of herds, especially in the autumn season; shrubification of tundra pasture lowering forage quality	Flexibility in movement to respond to changes in pastures, secure land use rights; adaptive management; continued economic viability and cultural tradition; self-determination in decision-making; adequate support for communication and technological services; Indigenous Rights upheld and protected	Increased frequency of extreme events and changing forage quality adding to vulnerabilities of reindeer and herders (*high confidence*); adaptation limits are being approached	Change in market value of meat; overgrazing; land use policies affecting access to pasture and migration routes, property rights; cost of feed
 Commercial fisheries (CCP6.2.3)	Loss of sea-ice, warming waters, and MHWs transform ecosystems in the Arctic with impacts on fisheries including declines in multiple regions; changes to Antarctic ecosystems affect southern fisheries productivity and distribution	Implementation of adaptive management that is closely linked to monitoring, research, and low cost and inclusive public participation in decisions, high resolution forecast and projection tools, climate-informed survey and monitoring design	Changes in availability and location of fishery resources will impact fish operations in the eastern Bering Sea and Barents Sea as well as the Convention for the Conservation of Antarctic Marine Living Resources area. Declines in catch impact livelihoods, coastal communities, and pose a risk to regional and global food and nutritional security (*very high confidence*)	Changes in global demand for seafood, demand and markets, changes in gear, changes in policies affecting property rights. Changes due to offshore development and transportation
 Marine subsistence (CCP6.2.3; CCP6.2.3.1)	Changes in species distribution and abundance (not all negative); impediments to access of harvesting areas especially sea-ice; increased interactions with shipping; safety; changes in seasonality; reduced harvesting success and process of food production (processing, food storage; quality); threats to culture and food security	Systems of adaptive co-management that allow for species switching, changes in harvesting methods and timing, secure harvesting rights, communication and relationship building, co-production of knowledge	Changes in distribution and abundance of resources combined with more regulations related to species at risk. Adaptation at the local, individual, and household level under low mitigation scenarios will be costly and possibly undermined by the scale and pace of change, including climate shocks and extreme events (*medium confidence*)	Changes in cost of fuel, land use affecting access, food preferences, harvesting rights; colonialism, international agreements to protect vulnerable species
 Marine ecosystems (CCP6.2.1)	Warming, sea-ice loss, ocean acidification resulting in poleward contraction of polar zones, invasive species introduction, displacement of polar species, and restructuring of food webs	Reduce effects of external and compounding risks and increase application of ecosystem-based management to meet biodiversity and management goals. Conservation of genetic diversity and biodiversity to preserve resilience, and	Without institutional investment in sustaining climate resilience in ecosystems across sectors there is a high risk of failure (*high confidence*)	Novel and expanding activities in ice free areas (shipping; fishing), energy development and mineral extraction, increased tourism, global markets and demand for polar resources, population growth and community

		supplementation and assisted migration may be needed		relocation to coastal areas
 Terrestrial and Freshwater ecosystems (CCP6.2.2)	Warming, hydrology changes (reduced ice on lakes and rivers, flooding, snow) and permafrost thaw lead to impacts on polar terrestrial and freshwater systems, food webs, the distribution of polar fish, implications for peat systems with consequent changes on dependent animal assemblages and increasingly favorable conditions for parasites and pathogens. Increased risk of wildfires in the Arctic	Improving biodiversity and redundancy to enhance resilience. Efforts to minimize and prevent extinctions; preservation of ecosystem processes and habitats during critical life stages; coordinated governance; measures and planning that consider dynamic interactions within and among social and ecological systems are more effective	Without institutional investment in sustaining climate resilience in ecosystems across sectors there is a high risk of failure (*high confidence*). Arctic regions have greater understanding of resilience needs but coordination is not widespread. Antarctic has established action plans to identify key management needs for conserving terrestrial and freshwater biota.	Novel and expanding activities in ice free areas (shipping; fishing), energy development and mineral extraction, increased tourism, global markets and demand for polar resources, population growth and community relocation to coastal areas

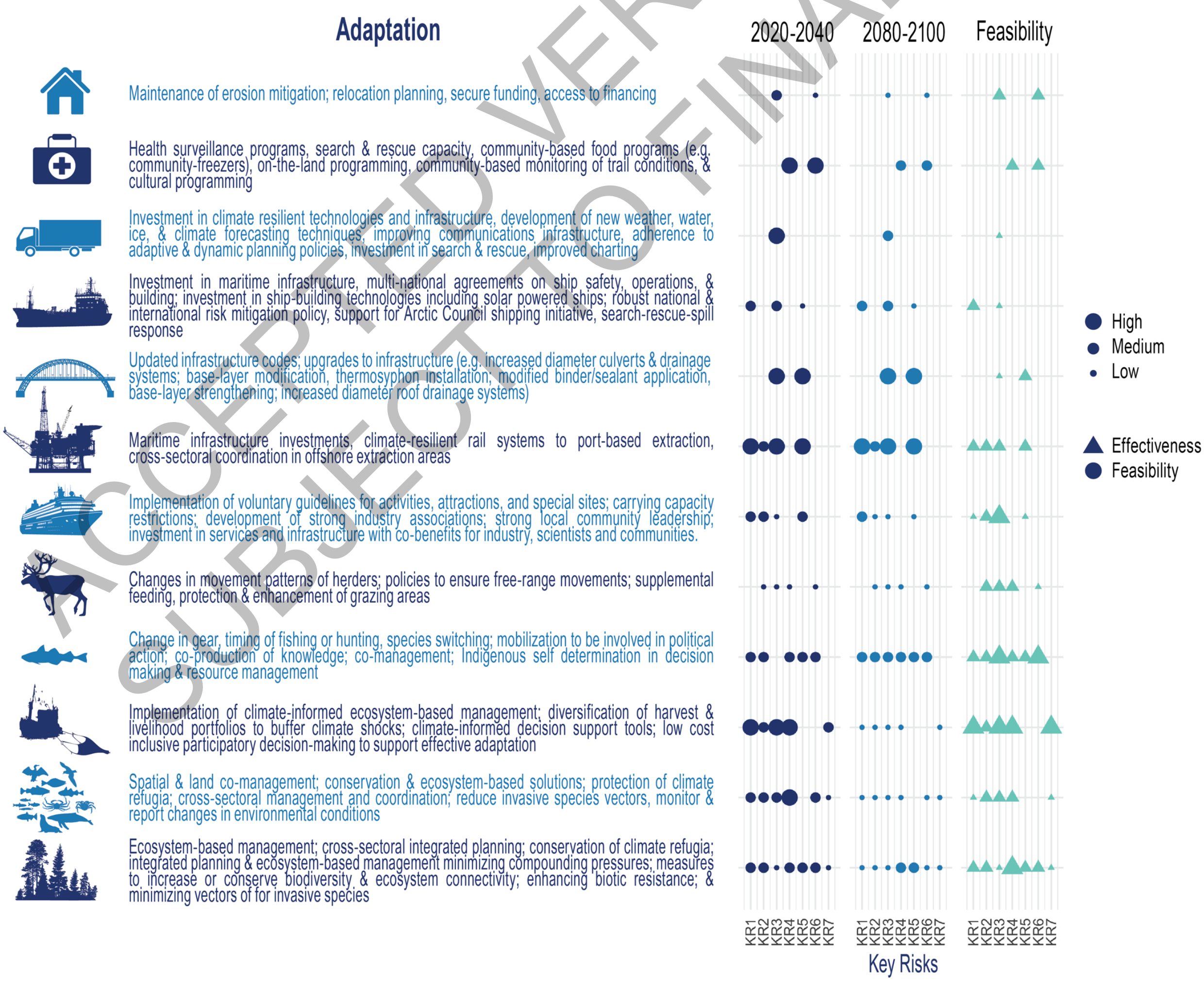

Figure CCP6.6: Assessment of feasibility and effectiveness of adaptation options by key risks in the polar regions (Table CCP6.6)

The need for self-determination for Indigenous Peoples and local communities in decision-making and cooperation across Arctic nations to manage a rapidly changing Arctic is increasingly recognized, particularly in a shipping and wildlife management context where climate impacts will be transboundary and multi-sectoral (Spence, 2017; Forbis and Hayhoe, 2018; Ford and Clark, 2019; Dawson et al., 2020) (CCP6.2.6; Box CCP6.2). Effective Indigenous and community-led adaptation efforts have been implemented across the Arctic to alleviate climate and non-climate stressors and build resilience through restoration and conservation (Huntington et al., 2017; Brattland and Mustonen, 2018; Hudson and Vodden, 2020; Mustonen and Feodoroff, 2020; Uboni et al., 2020; Huntington et al., 2021). For example, Indigenous knowledge and science has been used by the Skolt Sámi in Finland to attenuate warming, drought, and water quality impacts on salmonids through restoration of spawning and nursery habitats in the Vainosjoki river catchment (Brattland and Mustonen, 2018; Mustonen and Feodoroff, 2020; Ogar et al., 2020). This ecological restoration of damaged habitats for fish represents community-led actions. In Aasiaat, Greenlandic hunters have implemented community-based oceanographic and ecological monitoring to convey Indigenous knowledge observations of rapid change to the government and scientists. A special aspect of land use in the Russian North is the preservation of nomadic lifestyles of the Nenets and Chukchi (Mustonen and Mustonen, 2016), and while these traditional economies have undergone rapid change due to non-climate drivers, their land uses, observational frameworks and cultural matrixes remain of high importance in the context of climate change. Endemic responses (self-agency from within the culture) and Indigenous governance enable adaptation to the rapid and accelerating changes under way (Mustonen et al., 2018a). Therefore, community-based monitoring and inclusion of Indigenous knowledge in dialogue with science has been an effective mechanism to detect and respond to climate change.

CCP6.3.2.2 Adaptation gaps

In a study of adaptation progress across the Arctic from 2004−2019, 233 cases of adaptation were documented, with the majority of actions primarily behavioural and reactionary in nature and undertaken in the subsistence harvesting sector, with resource management, and infrastructure and transportation other prominent sectors where adaptation responses were documented to be occurring (Canosa et al., 2020). The study found few changes in the profile of adaptation over time, except for an increase in responses being motivated solely by climate impacts, and few cases of transformational change, although caution that a lack of data on adaptation actions makes documenting trends challenging. Human health is generally under-represented in adaptation initiatives, along with adaptations being developed within larger Arctic settlements (Ford et al., 2014; Canosa et al., 2020), and in many sectors decisions continue to be made without explicit inclusion of climate change impacts and risk in planning and design (*high confidence*) (Cherry et al., 2017; Lauta et al., 2018; Meredith et al., 2019). There is *limited evidence* of transformational adaptation taking place in the policy arena (e.g., U.S. Executive Order 13990, 2021), but many examples of how impacts and responses to climate change have transformed social-ecological connections, traditions, markets, trade, and livelihoods of Arctic residents and Indigenous Peoples (Ford et al., 2015).

CCP6.3.2.3 Maladaptation and limits to adaptation

In polar regions, multiple entities operate simultaneously to manage lands and resources, resulting in layered approaches and policies for the same sector or region, only some of which are synergistic and a few of which may counter each other (e.g., Southern Ocean: Solomonsz et al., 2021). Climate change and attendant uncertainty can undermine stakeholder confidence in management, leading to less effective management even when scientific understanding is stable (Mumby et al., 2017). In the Arctic, large landscapes, dispersed population centers, limited resources, and settler colonialism are structural barriers to effective planning, emergency response, and relief and recovery from climate impacts (*medium confidence*), which limit adaptation and sometimes exacerbate climate and non-climate pressures on social and ecological systems (Ford et al., 2015; Ford et al., 2020; Snook et al., 2020).

Adaptation strategies that are beneficial in the short term can result in long-term maladaptive outcomes. For Indigenous Peoples, strategies that fail to address colonialism, inequities, and injustices undermine effective adaptation (Canosa et al., 2020; Schipper, 2020; Ford et al., 2021). Large "responsiveness gaps" between impacts and implementation, approaches that fail to consider dynamic responses within social and ecological systems (which amplify or attenuate climate impacts), and a paucity of *a priori* planning can contribute to maladaptation (*high confidence*)(Pentz and Klenk, 2017; Turner et al., 2020b). For example, rationalization (privatization) can stabilize fisheries and incentivize long-term sustainability under stationary conditions, yet also promote low diversity in harvest (or livelihood) portfolios and when combined with behaviors to offset climate driven declines in yield (e.g., effort or price) rationalization can create lock-in to declining stocks, increasing the risk of income variability and collapse (Kasperski and Holland, 2013; Pinkerton and Davis, 2015; Holland et al., 2017; Ojea et al., 2017; Anderies et al., 2019; Fisher et al., 2021). Policies that foster stewardship yet also allow for diversification in fisheries may further attenuate climate shocks to individual fisheries (Kasperski and Holland, 2013; Fisher et al., 2021) and stabilize catches (e.g., US Bering Sea pollock fleet (Watson and Haynie, 2018)). Inclusive and participatory decision-making underpins long-term resilience to climate change (*medium confidence*)(Flynn et al., 2018; Ford et al., 2020), but a high cost of participation can disproportionately favor entities with strong investment, ample resources, and extreme viewpoints such that decision outcomes are not in the broad interest of polar societies (Lynham et al., 2017).

There are significant limits to adaptation in the polar regions related to the rate of warming and cascading changes that are occurring, which is equivalent to double and sometimes triple the global average depending on the region (Bush and Lemmen, 2019; IPCC, 2021). The rapid pace of change, such as sea-ice loss, can outpace ecological processes and induce substantial ecological shifts (CCP6.2)(*medium confidence*). The speed of climate change in the Arctic limits options for adaptation in communities who rely on a narrow resource base, when adaptation involves loss of culture and livelihoods, and when the costs of adaptation makes it infeasible (*medium confidence*) (Ford et al., 2015), such as for reindeer herding (Table CCP6.6; Figure CCP6.6; Figure CCP6.7) (Meredith et al., 2019). Adapting infrastructure in response to a rapidly changing cryosphere will be limited by available technologies and the relatively higher costs associated with updating infrastructure over vast polar regions (Schneider von Deimling et al., 2021).

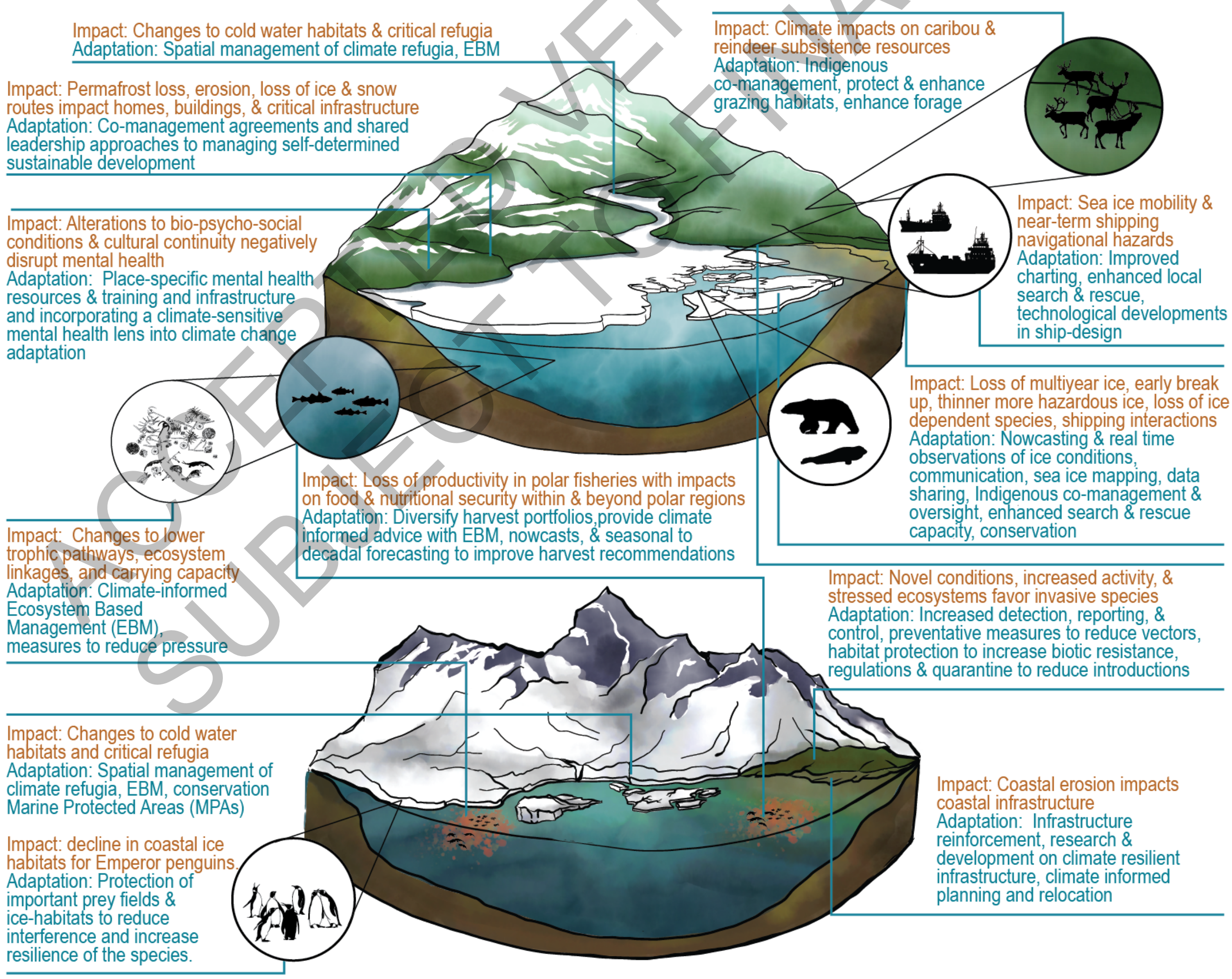

Figure CCP6.7: Climate change impacts, risks, and potential for adaptation in Arctic (upper panel) and Antarctic (lower panel) social ecological systems.

[START FAQ CCP6.4 HERE]

FAQ CCP6.4: When will climate change impacts in polar regions surpass our ability to adapt?

When environmental variability is within the range of the current adaptive management approaches, the social-ecological system can thrive. However, the rapidly changing polar systems are causing disruptions to societies, economies and ecosystems. The current management systems are yet to develop procedures for managing rapid change being experienced in warming waters, sea-ice declines, permafrost thaw and erosion, and poleward shifts in species. These challenges are expected to become more pronounced within a few decades rather than later this century.

Polar regions are naturally dynamic environments. Ecosystems in polar regions, and the people who rely on them, have adapted to natural variability and dynamic nature of polar environments. Fish populations in polar regions are known to exhibit cycles of productivity, and shift their distribution across hundreds of kilometers in response to changes in winter sea-ice cover and concomitant summer ocean conditions. Management of the productive fisheries in polar regions is also designed to allow for these changes, using adaptive and ecosystem based approaches that buffer populations from overexploitation and also stabilize fisheries, livelihoods, and food resources. Indigenous Peoples diversify their subsistence harvest across species and resources, and therefore similarly stabilize food and nutritional security. When environmental variability is within the range of these adaptive measures the social-ecological system can thrive. Thus, there are fundamental components in place in polar regions already to help ecosystems and people adapt to some degree of climate change. However, as climate change impacts like warming waters, sea-ice loss, permafrost thaw and erosion, systematically alter components of the system, shift species increasingly poleward, and disrupt linkages between species and people, the ability to adapt is reduced. There are critical tipping points (e.g., sea ice melt, permafrost thaw) where changes may cascade, self-reinforce and accelerate, outpacing adaptation actions and force natural and human systems irreversibly (on the scale of human existence) into novel regimes. The risk of crossing tipping points is greater and the probability much increased after mid-century under scenarios without global carbon mitigation (SSP5 8.5), where changes are largest and most rapid.

[END FAQ CCP6.4 HERE]

CCP6.4 Climate Resilient Development Pathways

The polar regions are expected to experience many economic development opportunities as a result of climate change, including increased accessibility for shipping and attractiveness for fisheries and tourism (CCP6.2.3.1, CCP6.2.4). For polar regions, equitable climate resilient development requires diverse perspectives in planning and implementation. In the Arctic, cultural, social and economic dimensions of Indigenous Peoples and local communities are critical (Ritsema et al., 2015; Huntington et al., 2021). For both poles, there are global cultural connections to polar systems (Roberts et al., 2021), along with important global and local needs for sustained ecosystems and their services, in the face of diminishing polar zonal conditions (Cavanagh et al., 2021; Murphy et al., 2021; Solomonsz et al., 2021).

Sustainable pathways integrating across sectors, and taking account of local and global connections, can be readily achieved in polar regions to balance trade-offs between economic, ecological, and socio-cultural imperatives, yet challenges remain (Murphy et al., 2021). Notably, terrestrial areas of greatest interest for infrastructure development, agriculture, and visitation potential are often also the same areas that have been identified as culturally and ecologically significant (PEW, 2016; Eliasson et al., 2017; Grant et al., 2021) (*high confidence*). Development of low impact shipping corridors in Arctic Canada is an example of an effective mechanism where climate resilient infrastructure can be prioritized and where regulation (voluntary and enforced) focused on cascading climatic risks can be implemented (Chénier et al., 2017; Dawson et al., 2020).

CCP6.4.1 Challenges to Climate Resilient Development Pathways

Decision-making in polar regions is complicated by globalization processes and the complexity of governance arrangements from local to global instruments and differing stakeholder perspectives and needs (Hughes et al., 2018; Stephen, 2018; Huntington et al., 2021; Murphy et al., 2021; Solomonsz et al., 2021). Substantial interest in and management of polar resources from non-polar states can lead to decision-making that lacks explicit consideration of local impacts and responses, thus reducing the effectiveness of adaptation, and in some cases causing maladaptation. Participatory decision-making is increasingly used in some sectors, but high costs of participation, a focus on consensus, and systematic erosion of resources can undermine outcomes (Mumby et al., 2017; Parlee and Wiber, 2018; Mendenhall et al., 2020). In the Arctic, the societal burden of climate change impacts and risks will manifest at the local level and thus the importance of local scale leadership and involvement in decision-making is essential for effective adaptation (AMAP, 2017).

Many losses and damages within Indigenous contexts are not able to be monetized but can be profound, such as loss of Indigenous languages (CAFF, 2013), loss of Indigenous knowledge associated with nomadic lifestyles and cultures (Box CCP6.2), and loss of geographical knowledge associated with an intimate knowledge of landscapes across seasons (Brattland and Mustonen, 2018), changing landscapes resulting in solastalgia and ecological grief (Cunsolo and Ellis, 2018), and some Indigenous practices and cultural assets, such as burial grounds, nomadic camp sites, graveyards, seasonal dwellings, and routes and pathways causing disruptions to mind and memory (Mustonen and Mustonen, 2016). Recognizing these intangible losses and damages is critical for understanding how to achieve climate resilience in the Arctic (Tschakert et al., 2019; Sawatzky et al., 2020).

For the Antarctic, the governance for managing climate impacts is emerging, particularly for terrestrial and nearshore habitats (*high confidence*) (Hughes et al., 2018; Chown and Brooks, 2019). However, it is poorly developed for marine ecosystems, despite its importance for decision-making (Trebilco et al., 2020; Goldsworthy and Brennan, 2021). A diversity of stakeholders are involved in developing evidence-based management for the region, which presents challenges for adaptation planning (Solomonsz et al., 2021), particularly in identifying sustainable practices in a changing environment (Constable et al., 2017; Brooks et al., 2018). Spatial management for enhancing the resilience of endemic polar biodiversity is increasingly proposed as the best option for managing risks of climate change (Chown and Brooks, 2019).

CCP6.4.2 Inclusive, Integrated Co-management

Inclusive, low-cost participatory decision-making can deliver equitable responses to climate change (*high confidence*). Land use, maritime activities, and subsistence fishery and other extracted resources in the polar regions are co-managed through multilateral and national government bodies. The capacity of governance systems in some Arctic regions to respond to climate change has strengthened recently (*high confidence*). Synthetic themes in adaptation for the Arctic have emerged from and since SROCC and include flexibility through diversity in livelihoods, and subsistence and harvest portfolios; co-management of resources; adaptive and ecosystem-based approaches; adoption of advanced technology, forecasts, and longer term projections to improve safety and resources management; and imperative need for low-cost, inclusive and participatory decision-making (Kasperski and Holland, 2013; Brattland and Mustonen, 2018; Parlee and Wiber, 2018; Galappaththi et al., 2019; Holsman et al., 2020; Huntington et al., 2021; Melbourne-Thomas et al., 2021; Mustonen and Van Dam, 2021). This was demonstrated in community-level adaptation by Pangnirtung Inuit to climate change impacts on fisheries (Galappaththi et al., 2019). Inclusive approaches to co-management, especially those that enable diverse perspectives, embrace conflict, and address equity and justice across power holders, can help alleviate the risk and promote solutions (Raymond-Yakoubian et al., 2017; Brattland and Mustonen, 2018; Parlee and Wiber, 2018; Raymond-Yakoubian and Daniel, 2018; Snook et al., 2020). Integration across levels of management and diverse regional perspectives can reduce climate risks and support equitable adaptation measures (Allison and Bassett, 2015; Raymond-Yakoubian et al., 2017; Raymond-Yakoubian and Daniel, 2018; Holsman et al., 2020).

Increased flexibility in management measures, greater investment in ecosystem monitoring, and more inclusive participatory methods and communication may help foster high levels of local investment and resilience and promote adaptive pathways (Cinner et al., 2016; Weymouth and Hartz-Karp, 2019), although explicit measures may be needed to reduce costs and increase representation, enhance transparency, embrace dissent, and clarify accountability are needed as these are not inherent outcomes (Lynham et al., 2017; Parlee and Wiber, 2018). Ecosystem-based management (EBM), which includes provisions aimed at sustaining critical connections within and among social and ecological systems, enhances resilience and attenuates climate impacts on ecosystems and provisioning services, e.g., EBM enhances climate resilience for Antarctic krill and Northeast Arctic cod fisheries (Troell et al., 2017; Meyer et al., 2020) and forestalls fishery collapse in the Bering Sea in the near-term (Holsman et al., 2020). Increasing likelihood of transboundary resources, interactions, and novel commerce may strain existing regulatory and international agreements suggests that *a priori* governance agreements that designed to manage climate risks and aimed at attenuating potential conflicts over resources and regions may be important for resolving these issues (Parlee and Wiber, 2018; Mendenhall et al., 2020).

CCP6.4.3 Enabling Climate Resilience in the Arctic: Self-determination and Indigenous Peoples' Rights

Climate change disproportionately impacts Indigenous Peoples (Box CCP6.2), which directly affects their livelihoods, health, and Sustainable Development Goal targets. For residents in the Arctic, a sustainable development pathway has been found to be highly effective if a self-determined development model is employed (*very high confidence*). Known determinants of Indigenous self-determined development in regions in the Arctic, include: 1) Indigenous self-determined decision-making (and inherent sovereignty); 2) effective and culturally legitimate institutions of government; 3) strategic vision and strategic thinking; and 4) public-spirited, nation-building leadership (Cornell and Kalt, 1992; Cornell and Kalt, 1998; Cornell and Kalt, 2007; Ritsema et al., 2015). For Indigenous Peoples, advances in recognition of self-governance, land and resource sovereignty, and resource co-management, particularly in the North American Arctic but also elsewhere, provide a strong basis for responding to climate impacts (Ford et al., 2015; Robards et al., 2018). These developments expand the solution space (Haasnoot et al., 2020) for responding to climate impacts, although historical and on-going forms of colonialism in research and government institutions continues to undermine Indigenous self-determination and reinforce climate change vulnerability (Marino and Lazrus, 2015; Whyte et al., 2019; Ford et al., 2020; Snook et al., 2020). Readiness for adaptation across Arctic nations continues to be challenged by a number of factors including the existence of pressing socio-economic challenges, institutional and governmental barriers, lack of meaningful inclusion of Indigenous knowledge in government planning and response, and lack of financial resources (Ford et al., 2015; Loring et al., 2016; AMAP, 2017; Ford et al., 2017; Birchall and Bonnett, 2019) (AMAP, 2018a). In Alaska, for example, the need to relocate high risk villages has been recognized by researchers, decision-makers, and communities themselves for some time, and while progress is being made in some locations (Ristroph, 2017), institutional barriers have generally resulted in negligible progress (Bronen and Chapin, 2013; Marino and Lazrus, 2015; Albert et al., 2018; Rosales et al., 2021).

CCP6.5 Summary and Conclusion

Rapid changes occurring in polar systems are clear and unequivocal, indicating that swift and effective responses are urgently needed to avoid substantial future impacts and reduce risks to polar social and ecological systems. Some underlying principles emerge from this assessment that appear fundamental to achieving climate resilient development in polar systems (Figure CCP6.8) because they could facilitate rapid, equitable and just responses to achieve climate resilience. These principles include having locally relevant and accessible tools and services (e.g., regional forecasts and projections) to support climate-informed decision-making, along with adequate and appropriate resourcing (including finance and integrated planning) for climate adaptation and for responding to emergencies. Effective decision-making processes integrate across sectors, all levels of governance, including through multinational instruments, and, most importantly, apply low cost and inclusive participatory processes to address gender, equitable and socially just outcomes. In the Arctic, there is evidence that overcoming colonialism through meaningful and explicit inclusion of Indigenous knowledge in research and resource management, as well as co-management and self-determination in decision-making, are effective measures to support equitable climate resilience across multiple sectors. Lastly, climate resilience is strongly dependent on both mitigation of climate change as well as effective adaptation to meet the challenges of unprecedented change in polar regions.

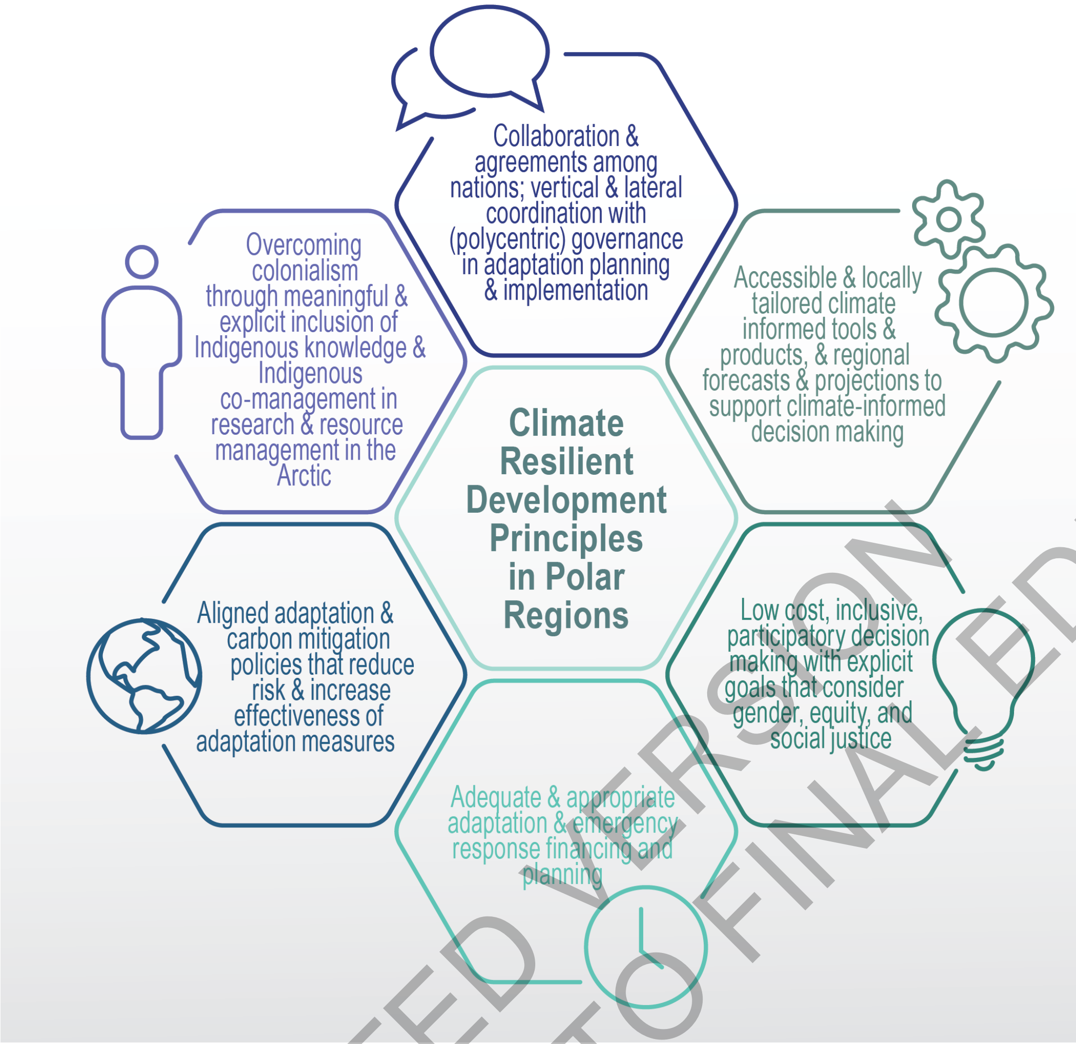

Figure CCP6.8: Six principles that support climate resilient pathways in the polar regions.

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