CCP6 SM

Polar Regions
Supplementary Material

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SMCCP6.1 Climate Impact Drivers (Hazards) for Polar Regions

Table SMCCP6.1 | Estimates of change in climatic impact drivers in the Arctic and Antarctic to support Figure CPP6. Figures taken from the WGI-AR6 Interactive Atlas (https://interactive-atlas.ipcc.ch). Scenarios are grouped as *SSP1–2.6*, *SSP5–85*. Global warming levels for each scenario group in each period are shown in parentheses below scenarios. WGI reference regions for the estimates—Arctic: Arctic Ocean, Russian Arctic, northwest North America, northeast North America, Greenland/Iceland; Antarctic: Southern Ocean, East Antarctica, West Antarctica; CMIP6-projected median annual changes against the 1850–1900 baseline (in parentheses: P5–P95); GWL, global warming level. Only climatic impact drivers with estimates from the Atlas are shown.

Climatic impact driver	Region	Projected changes (WGI-AR6 Interactive Atlas)					
		Near term (2021–2040)		Medium term (2041–2060)		Long term (2081–2100)	
		SSP1–2.6 (1.5°C)	*SSP5–8.5* (1.5°C)	*SSP1–2.6* (2°C)	*SSP5–8.5* (3°C)	*SSP1–2.6* (2°C)	*SSP5–8.5* (4°C)
Sea level (relative m)	Arctic	0.1 (0.0–0.2)	0.1 (0.0–0.2)	0.2 (0.0–0.4)	0.2 (0.0–0.5)	0.3 (0.0–0.7)	0.5 (0.1–1.0)
	Antarctic	0.1 (0.0–0.2)	0.1 (0.0–0.2)	0.2 (0.0–0.3)	0.2 (0.1–0.3)	0.3 (0.1–0.5)	0.5 (0.2–0.8)
Sea surface temperature (°C)	Arctic	**0.9** (0.3–1.8)	**1.0** (0.3–1.6)	**1.1** (0.3–2.29	**1.6** (0.6–2.8)	**1.4** (0.3–2.7)	**3.7** (1.5–6.6)
	Southern Ocean:	**0.6** (0.2–1.0)	**0.7** (0.3–1.0)	**0.8** (0.3–1.1)	**1.0** (0.4–1.5)	**0.8** (0.3–1.5)	**2.0** (1.0–3–1)
Sea ice cover (%)	Arctic	**–11.1** (–12.5 to –5.2)	**–12.3** (–19.5 to –5.3)	**–14.3** (–21.8 to –7.0)	**–19.4** (–31.0 to –9.8)	**–16.0** (–27.6 to –6.9)	**–37.0** (–53.0 to –21.5)
	Southern Ocean	**–4.2** (–8.3 to –0.5)	**–4.4** (–8.5 to –0.3)	**–4.7** (–8.7 to –0.1)	**–6.1** (–11.4 to –0.3)	**–4.9** (–10.7 to –0.1)	**–11.2** (–19.6 to –1.7)
	West Antarctic	**–8.4** (–19.5 to –1.3)	**–8.7** (–18.1 to –0.5)	**–9.7** (–22.6 to –0.8)	**–13.8** (–28.4 to –1.8)	**–10.5** (–27.9 to –0.5)	**–28.0** (–58.2 to –6.1)
Ocean surface pH	Arctic	**–0.2** (–0.2 to –0.2)	**–0.2** (–0.2 to –0.2)	**–0.2** (–0.3 to –0.2)	**–0.3** (–0.3 to –0.3)	**–0.2** (–0.3 to –0.2)	**–0.6** (–0.6 to –0.5)
	Antarctic	**–0.1** (–0.1 to –0.1)	**–0.1** (–0.2 to –0.1)	**–0.2** (–0.2 to –0.1)	**–0.2** (–0.2 to –0.2)	**–0.1** (–0.2 to –0.1)	**–0.5** (–0.5 to –0.4)
Atmospheric temperature (°C)	Arctic	**3.5** (2.1–5.5)	**3.8** (2.2–5.9)	**4.2** (2.3–6.5)	**5.6** (3.5–8.2)	**4.6** (2.4–7.4)	**10.3** (7.1–14.4)
	Antarctic *All*	**1.4** (0.6–2.0)	**1.4** (0.6–2.2)	**1.6** (0.6–2.3)	**2.1** (0.9–3.1)	**1.7** (0.6–3.0)	**4.0** (1.9–5.9)
	West Antarctic	**1.9** (0.8–3.3)	**2.0** (0.7–3.5)	**2.3** (0.8–3.6)	**3.0** (1.5–5.2)	**2.3** (0.8–4.1)	**5.6** (2.6–9.1)
	East Antarctic	**1.8** (0.9–2.5)	**1.9** (1.0–2.7)	**2.1** (0.9–3.0)	**2.8** (1.5–4.1)	**2.3** (0.8–3.7)	**5.3** (3.0–8.0)
Precipitation (%)	Arctic	**11.1** (6.3–19.2)	**11.6** (5.8–19.7)	**13.4** (7.1–23.2)	**17.4** (9.5–29.1)	**15.1** (8.0–29.0)	**33.8** (19.8–53.7)
	Antarctic	**5.2** (2.3–7.9)	**5.3** (1.9–8.0)	**6.3** (2.5–9.6)	**7.9** (3.3–11.7)	**6.9** (2.7–11.5)	**15.4** (7.5–22.2)
Snowfall (mm d^{-1})	Arctic	**–0.6** (–1.1 to –0.2)	**–0.6** (–1.1 to –0.3)	**–0.7** (–1.3 to –0.3)	**–0.9** (–1.4 to –0.4)	**–0.2** (–0.3 to –0.2)	**–1.7** (–2.5 to –0.9)
	Antarctic	**1.9** (0.3–4.0)	**1.9** (0.4–4.0)	**2.1** (0.5–4.2)	**2.6** (0.5–5.4)	**2.1** (0.5–4.1)	**4.0** (0.4–8.6)

SMCCP6.2 SROCC Summaries of Human Dimensions

Table SMCCP6.2 | Summary of observed impacts and projected risks of climate change for human dimensions identified in Sections 3.2.4, 3.4.3 and Box 3.3 in Chapter 3 of the IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (Meredith et al., 2019).

		Affected system	Hazard > cascading effect	Observed impacts and projected risks
Arctic				
Food, fibre and ecosystem products	Impacts	Food	> northern ecosystems > travel conditions	Food insecurity rising for Indigenous Peoples—impacting access to hunting grounds; may result in subsistence and culturally important food species no longer being accessible or in familiar areas (*high confidence*)
	Risks	Commercial fish and shellfish	Warming	Spatial distribution/productivity of some marine species changing under most climate change scenarios (*medium confidence*) (Table CCP6.2)—impacts on distribution and economic viability of commercial fisheries (*high confidence*)
Economic activities	Impacts	Shipping	Sea ice	Activity during the summer increased over the past two decades in regions with less sea ice (*high confidence*), enabling increased marine and cruise tourism (*high confidence*), but resulting in increased accidents, ship noise and air pollution, and disruption of subsistence hunting
	Impacts	Roads	Warming	Ice roads are being impacted in winter
	Risks	Travel	Landfast sea ice	Coastal communities will be impacted by reduction of landfast sea ice, which facilitates travel in winter (*high confidence*)
Settlements and communities	Risk	Infrastructure	Permafrost	Structural stability and functional capacities of infrastructure located on ice-rich frozen ground are threatened
Human health and wellness	Impacts	Culture	Warming	Culturally important time on land and sea, and place attachment, for Indigenous communities are being impacted, disrupting intergenerational knowledge transmission/use, affecting individual and collective mental/emotional health, and spiritual and social vitality and autonomy
	Impacts	Disease	Climate	Foodborne and waterborne disease are of increasing concern in the Arctic
	Impacts	Diet	Climate	Reduced food security along with globalisation of food, impacting dietary health of Indigenous communities
Antarctic				
Food, fibre and ecosystem products	Risk	Krill	Warming	Effects on krill will occur in the areas currently most important for the Antarctic krill fishery (Scotia Sea, northern Antarctic Peninsula), but changes in the fishery are expected to be driven by global issues external to the Southern Ocean
Economic activities	Impacts	Shipping	Warming	Reductions in sea ice increasing accessibility of marine and cruise tourism opportunities in Antarctic Peninsula (*high confidence*), which pose risks and opportunities to natural systems and people

SMCCP6.3 Adaptation to Climatic Risks for Fishing Communities

Table SMCCP6.3 | Examples and approaches for climate change adaptation in fisheries.

Type/category		Summary	Reference
Ecosystem-based management	Decision making and management	Ecosystem-based fisheries management forestalls declines and stabilises some fisheries under climate change but does not prevent collapse under RCP8.5 (occurs after 2050).	(Holsman et al., 2020; Reum et al., 2020)
Ecosystem-based management	Decision making and management	Using Ecosystem-based management to incorporate uncertainty around the ecology of krill and the ecosystems they support can improve management of the krill fishery. Inclusion of climate risks in decision rules for setting catch limits in Antarctic fisheries.	(Constable et al., 2017; Meyer et al., 2020)
Sustainable intensification	Decision making and management	Global analyses suggest that effective management and sustainable intensification of fisheries through increased efficiency and optimised policies have the potential to offset many climate-driven declines in yield in moderate to high mitigation scenarios, but risk remains higher under RCP8.5 than 2.6 and both are higher relative to status quo.	(Cheung et al., 2018; Gaines et al., 2018; Free et al., 2020)
Transboundary /conflict	Decision making and management	Transboundary and novel opportunities will increase potential for conflict in fisheries.	(Pentz and Klenk, 2017; Pentz et al., 2018; Pinsky et al., 2018; Mendenhall et al., 2020; Palacios-Abrantes et al., 2020)
Fisheries management approaches	Decision making and management	Rights-based fisheries are most sustainable in stationary conditions, but low diversity in harvest portfolios can increase climate change risk, especially to climate shocks.	(Kasperski and Holland, 2013; Ojea et al., 2017)
Fisheries management approaches	Decision making and management	Adaptive co-management is key for climate readiness in fisheries.	(Wilson et al., 2018)
Resilience through diversification	Individual or community-level adaptation	Flexibility and diversification (income and food security) underpin resilience to climate shocks in coastal communities. Increasing value of a declining resource can create a 'gilded trap' that locks fishers into a declining population and eventual collapse.	(Fisher et al., 2021)
Participatory decision making	Decision making and management	Inclusive and participatory decision making underpins long-term resilience to climate change, but high cost of participation can disproportionately favour entities with strong investment and ample resources and may contribute to lock-in/maladaptation.	(Lynham et al., 2017)
Regional management adaptation/planning	Decision making and management	Perceptions of change and impact increase with proximity to social ecological system (based on evaluation of differences between tribal and non-tribal resource managers in Arctic Alaska (AK) (North Slope).	(Blair and Kofinas, 2020)
Regional management adaptation/planning	Decision making and management	Regional fisheries management largely practices 'business as usual', and only 2 of 17 regional plans explicitly include climate change in management plan; few observations of fisheries management climate adaptation planning or action.	(Lindegren and Brander, 2018; Sumby et al., 2021)
Regional management adaptation/planning	Decision making and management	Regional fisheries management organisations (RFMOs) are likely not to change, so to address the 'responsiveness gap' between climate impacts and management response there is a need to increase the speed of climate-informed scientific advice to decision makers. Critical elements necessary for RFMOs to address climate change include '(1) timely and accurate climate change science and advice, (2) monitoring and enforcement, (3) increase in MPAs, and (4) political analysis of the decision making process.' Emphasises importance of international treaties and agreements.	(Pentz and Klenk, 2017; Pentz et al., 2018)
	IK, co-management, and marine protected areas (MPAs)	Inuvialuit IK provides critical understanding of Beluga whale population dynamics and climate change impacts.	(Loseto et al., 2018)
	IK and co-management	The importance of Indigenous co-management and bridging of Indigenous and Western knowledge systems to manage living marine resources and prepare and respond to climate change.	(Raymond-Yakoubian et al., 2017; Raymond-Yakoubian and Daniel, 2018)

SMCCP6.4 Climate change and mental health risks in the Arctic

Table SMCCP6.4 | Climate change and mental health risks in the Arctic: evidence supporting the pathways through which climate change increases mental health risks (via hazard, exposure and vulnerability) in the Arctic.

Risk	References
Vulnerability	
Indigenous identity	(Cunsolo Willox et al., 2013a; Cunsolo Willox et al., 2013b; Petrasek MacDonald et al., 2013; Cunsolo Willox et al., 2014; Durkalec et al., 2015; Harper et al., 2015; Ostapchuk et al., 2015; Clayton et al., 2017; Cunsolo and Ellis, 2018; Markon et al., 2018; Council of Canadian Academies, 2019; ITK, 2019; Minor et al., 2019; Middleton et al., 2020a; Middleton et al., 2020b)
Socioeconomic inequities	(Markon et al., 2018; ITK, 2019)
Reliance on land-based livelihoods	(Furberg et al., 2011; Cunsolo Willox et al., 2012; Cunsolo Willox et al., 2013a; Cunsolo Willox et al., 2013b; Durkalec et al., 2015; Harper et al., 2015; Ostapchuk et al., 2015; Clayton et al., 2017; Cunsolo and Ellis, 2018; Dodd et al., 2018; Jaakkola et al., 2018; Jantarasami et al., 2018; Markon et al., 2018; Council of Canadian Academies, 2019; Minor et al., 2019; Middleton et al., 2020a)
Pre-existing health conditions (e.g., chronic physical and mental health conditions)	(Cunsolo Willox et al., 2013a; Cunsolo Willox et al., 2014; Clayton et al., 2017; Minor et al., 2019)
Lack of access to health-sustaining resources	(Furberg et al., 2011; Cunsolo Willox et al., 2013a; Cunsolo Willox et al., 2014; Durkalec et al., 2015; Harper et al., 2015; Jaakkola et al., 2018; Jantarasami et al., 2018; Kowalczewski and Klein, 2018)
Gender (genders differentially, yet equitably, affected)	(Cunsolo Willox et al., 2013a; Cunsolo Willox et al., 2013b; Harper et al., 2015; Ostapchuk et al., 2015; Jaakkola et al., 2018; Markon et al., 2018; Middleton et al., 2020a)
Age (e.g., youth and elders particularly at risk)	(Petrasek MacDonald et al., 2013; Ostapchuk et al., 2015; Petrasek MacDonald et al., 2015; Clayton et al., 2017; Jaakkola et al., 2018; Kowalczewski and Klein, 2018; Middleton et al., 2020a)
Hazards	
Acute events (e.g., storms, floods, wildfires)	(Cunsolo and Ellis, 2018; Dodd et al., 2018; Jaakkola et al., 2018; Jantarasami et al., 2018; Council of Canadian Academies, 2019; ITK, 2019; Middleton et al., 2020a)
Chronic changes (e.g., sea ice loss, sea level rise, coastal erosion, permafrost melting, rising temperatures, changing seasonal and environmental norms, changes in wildlife and vegetation, change in place	(Furberg et al., 2011; Cunsolo Willox et al., 2012; Cunsolo Willox et al., 2013a; Cunsolo Willox et al., 2013b; Petrasek MacDonald et al., 2013; Durkalec et al., 2015; Harper et al., 2015; Ostapchuk et al., 2015; Clayton et al., 2017; Jaakkola et al., 2018; Jantarasami et al., 2018; Markon et al., 2018; Council of Canadian Academies, 2019; ITK, 2019; Minor et al., 2019; Middleton et al., 2020a; Middleton et al., 2020b)
Exposure	
Direct exposure(s) (e.g., experiencing an acute or chronic hazard event)	(Furberg et al., 2011; Cunsolo Willox et al., 2012; Cunsolo Willox et al., 2013a; Cunsolo Willox et al., 2013b; Durkalec et al., 2015; Harper et al., 2015; Ostapchuk et al., 2015; Clayton et al., 2017; Cunsolo and Ellis, 2018; Dodd et al., 2018; Jaakkola et al., 2018; Jantarasami et al., 2018; Markon et al., 2018; Council of Canadian Academies, 2019; ITK, 2019; Minor et al., 2019; Middleton et al., 2020a; Middleton et al., 2020b)
Indirect exposure(s) (e.g., disruptions to food systems, cultural activities, place-based knowledge sharing, and livelihoods; displacement and relocation)	(Furberg et al., 2011; Cunsolo Willox et al., 2012; Cunsolo Willox et al., 2013a; Cunsolo Willox et al., 2013b; Petrasek MacDonald et al., 2013; Durkalec et al., 2015; Harper et al., 2015; Ostapchuk et al., 2015; Petrasek MacDonald et al., 2015; Clayton et al., 2017; Cunsolo and Ellis, 2018; Dodd et al., 2018; Jaakkola et al., 2018; Jantarasami et al., 2018; Kowalczewski and Klein, 2018; Markon et al., 2018; Council of Canadian Academies, 2019; ITK, 2019; Minor et al., 2019; Middleton et al., 2020a; Middleton et al., 2020b)
Vicarious exposure(s) (e.g., seeing friends and family suffer, mediated experience of climate change; anticipating future changes)	(Furberg et al., 2011; Cunsolo Willox et al., 2013b; Cunsolo Willox et al., 2014; Durkalec et al., 2015; Cunsolo and Ellis, 2018; Dodd et al., 2018; Jaakkola et al., 2018; Kowalczewski and Klein, 2018; Middleton et al., 2020a; Middleton et al., 2020b)

SMCCP6.5 Key Risk Development and Analysis

Using the expert opinion of the Cross Chapter Paper 6 author team across a range of expertise, we conducted a rapid risk assessment of sectors by WGI hazards in order to identify potential key risks (Table CCP6.6). Authors were asked to identify the risk of a (climate change) caused increase in a hazard on a given sector in the Arctic or Antarctic. These key risks were then evaluated further during the assessment, and results of the rapid assessment are presented in Figure CCP6.4. A subset of case studies from the rapid assessment were evaluated for burning ember diagrams. 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*) or low/not detected/positive (risk is low or not detectable). Blank cells are those where the assessment was not applicable or not conducted. This analysis led to the development of seven key risks: KR1: risk to marine ecosystems and species, KR2: risks to terrestrial and freshwater ecosystems and species, KR3: risk to economic activities and infrastructure, KR4: risk to food and nutritional security, KR5: risk from increased polar shipping cascading from sea ice change, KR6: risk to mental health, well-being, and culture of northern and Indigenous Peoples, and KR7: risk from polar change to global processes (including sea level rise (SLR)).

Table SMCCP6.5 | Supplemental table for key risk assessment (Table CCP6.6; Figure CCP6.4).

Sector	Citation	Region	Climate scenario	Time period	Hazard score	Vulnerability score	Exposure score	Risk assessment
KR1								
Oceans: marine species	(Wallhead et al., 2017)			2050–2069		3	3	Moderate
	(Hoppe et al., 2018)		~1000 µatm pCO_2 (vs. present day) ~RCP8.5		1	2	3	Moderate
			~1000 µatm pCO_2 (vs. present day) ~RCP8.5		2	2	3	High
	(Dahlke et al., 2018)	Atlantic sector	RCP2.6	2100	1	2	1	Undetectable
		Atlantic sector	RCP4.5	2100	2	2	2	Moderate
		Atlantic sector	RCP8.5	2100	3	2	3	High
	(Hancock et al., 2020)	Southern Ocean			1	2		Moderate
		Southern Ocean			1	1		Undetectable
		Southern Ocean			1	1		Undetectable
	(Tedesco et al., 2019)		RCP8.5	2061–2100				High
KR2								
Terrestrial and freshwater: freshwater species	(Brattland and Mustonen, 2018)		RCP8.5					High
	(Pertierra et al., 2017)	Antarctic Peninsula						High
KR3								
Energy resources: fossil resources	(Leong and Donner, 2015)	Canada Western Arctic	RCP2.6	2050	3	2	1	Moderate
		Canada Western Arctic	RCP4.5	2050	3	2	2	High
		Canada Western Arctic	RCP8.5	2050	3	1	2	Moderate
		Canada Western Arctic	RCP2.6	2100	3	1	2	Moderate
		Canada Western Arctic	RCP4.5	2100	3	2	2	High
		Canada Western Arctic	RCP8.5	2100	3	3	2	High
Terrestrial and freshwater: polar ecosystem	(Sakai et al., 2016)	Northeast Siberia			3	3	3	High
Food and fibre: fisheries and aquaculture	(Ksenofontov et al., 2017)	Northeast Siberia			2	3	2	High
Poverty and livelihoods: Indigenous traditions		East Siberia			2	2	2	High

Sector	Citation	Region	Climate scenario	Time period	Hazard score	Vulnerability score	Exposure score	Risk assessment
KR4								
Food and fibre: fisheries and aquaculture	(Thiault et al., 2019); Table CCP6.5; Table SMCCP6.3	USA	RCP2.6	2100	1	1	1	Undetectable
		USA	RCP8.5	2100	1	1	1	Undetectable
		Canada	RCP2.6	2100	1	2	1	Undetectable
		Canada	RCP8.5	2100	2	2	1	Moderate
		Greenland	RCP2.6	2100	3	3	1	High
		Greenland	RCP8.5	2100	3	3	1	High
		Norway	RCP2.6	2100	3	3	1	High
		Norway	RCP8.5	2100	1	3	1	Moderate
		Norway	RCP2.6	2100	3	3	1	High
		Norway	RCP8.5	2100	3	3	1	High
Food and fibre: crops		USA	RCP2.6	2100	1	1	1	Undetectable
		USA	RCP8.5	2100	1	1	1	Undetectable
		Canada	RCP2.6	2100	3	1	1	Undetectable
		Canada	RCP8.5	2100	3	1	1	Undetectable
		Greenland	RCP2.6	2100	2	1	1	Undetectable
		Greenland	RCP8.5	2100	2	1	1	Undetectable
		Norway	RCP2.6	2100	3	1	1	Moderate
		Norway	RCP8.5	2100	3	1	1	Moderate
		Norway	RCP2.6	2100	3	2	1	High
		Norway	RCP8.5	2100	3	2	1	High
KR5								
Poverty and livelihoods: marine transportation	(Melia et al., 2016)	All Arctic	RCP2.6	2050	3	1	2	Moderate
		All Arctic	RCP8.5	2050	3	2	3	High
		All Arctic	RCP2.6	2100	3	2	3	Moderate
		All Arctic	RCP8.5	2100	3	3	3	High
	(Khon et al., 2017)	Russian Arctic		2050	3	3	3	High
				2100	1	2	2	Moderate
	(Mudryk et al., 2021)	Arctic Canada	2C above pre-industrial		2	3	3	High
			4C above pre-industrial		2	2	2	Moderate
	(Stephenson et al., 2013)	All Arctic	RCP2.6	2050	3	3	3	High
			RCP8.5	2050	2	2	2	Moderate

Sector	Citation	Region	Climate scenario	Time period	Hazard score	Vulnerability score	Exposure score	Risk assessment
KR6								
Health and communities: morbidity	(Cunsolo Willox et al., 2013b)	Arctic Canada			3		3	High
	(Cunsolo Willox et al., 2012)	Arctic Canada		Lifetime of community members particularly 2009–2010	3		3	High
		Arctic Canada		Lifetime of community members particularly 2009–2010	1		3	Moderate
		Arctic Canada		Lifetime of community members particularly 2009–2010	3		3	High
		Arctic Canada		Lifetime of community members particularly 2009–2010	2		3	Moderate
		Arctic Canada		Lifetime of community members particularly 2009–2010	3	2	3	High
		Arctic Canada		Lifetime of community members particularly 2009–2010	3		3	High
		Arctic Canada		Lifetime of community members particularly 2009–2010	2		3	Moderate
	(Dodd et al., 2018)	Arctic Canada		Lived experiences of 2014 wildfire season	3		3	High
		Arctic Canada		Lived experiences of 2014 wildfire season	3	2	3	High
		Arctic Canada		Lived experiences of 2014 wildfire season	3	3	3	High
		Arctic Canada		Lived experiences of 2014 wildfire season	1		3	Moderate
		Arctic Canada		Lived experiences of 2014 wildfire season	2		3	Moderate
		Arctic Canada		Lived experiences of 2014 wildfire season	1		3	Moderate
	(Durkalec et al., 2015)	Arctic Canada			3		3	High
		Arctic Canada			2		3	Moderate
		Arctic Canada			1		3	Moderate
	(Harper et al., 2015)	Arctic Canada		Lifetime of participants	3	3	3	High
		Arctic Canada		Lifetime of participants	3	3	3	High
		Arctic Canada		Lifetime of participants	3	3	3	High
		Arctic Canada		Lifetime of participants	2	3	3	High

Sector	Citation	Region	Climate scenario	Time period	Hazard score	Vulnerability score	Exposure score	Risk assessment
Terrestrial and freshwater: polar ecosystem	(Mustonen and Feodoroff, 2020)	Fennoscandia			3	3	3	High
KR7								
	(Cohen et al., 2014)	Global						Moderate
	(Overland et al., 2015)	Global						Moderate
	(Vihma, 2014)	Global						Moderate
	(Kretschmer et al., 2018b)	Global						Moderate
	(Kretschmer et al., 2018a)	Global						Moderate
	(Blackport et al., 2019)	Global						Undetectable
	(Zhang et al., 2016)	Global						Moderate

SMCCP6.6 Detailed Methods for Burning Ember Diagrams

The burning embers diagram in Cross Chapter Paper 6 (Polar Regions) (Figure CCP6.5) outlines risks associated with climate change as a function of global warming by degrees warming above pre-industrial level. The method used to develop the embers was adapted from Zommers et al. (2020) to include an extensive analysis of key risks and the development of a risk assessment database that helped to reveal appropriate ember focus areas. Once focus areas for ember development were established within the author team a formal expert elicitation protocol based on Zommers et al. (2020) and Oakley and O'Hagen (2016), Gosling et al. (2018) was used to develop threshold judgements on risk transitions. Figure SM CCP6.1 outlines the formal five-step process used to generate the burning ember diagrams.

Expert elicitation process for burning ember development

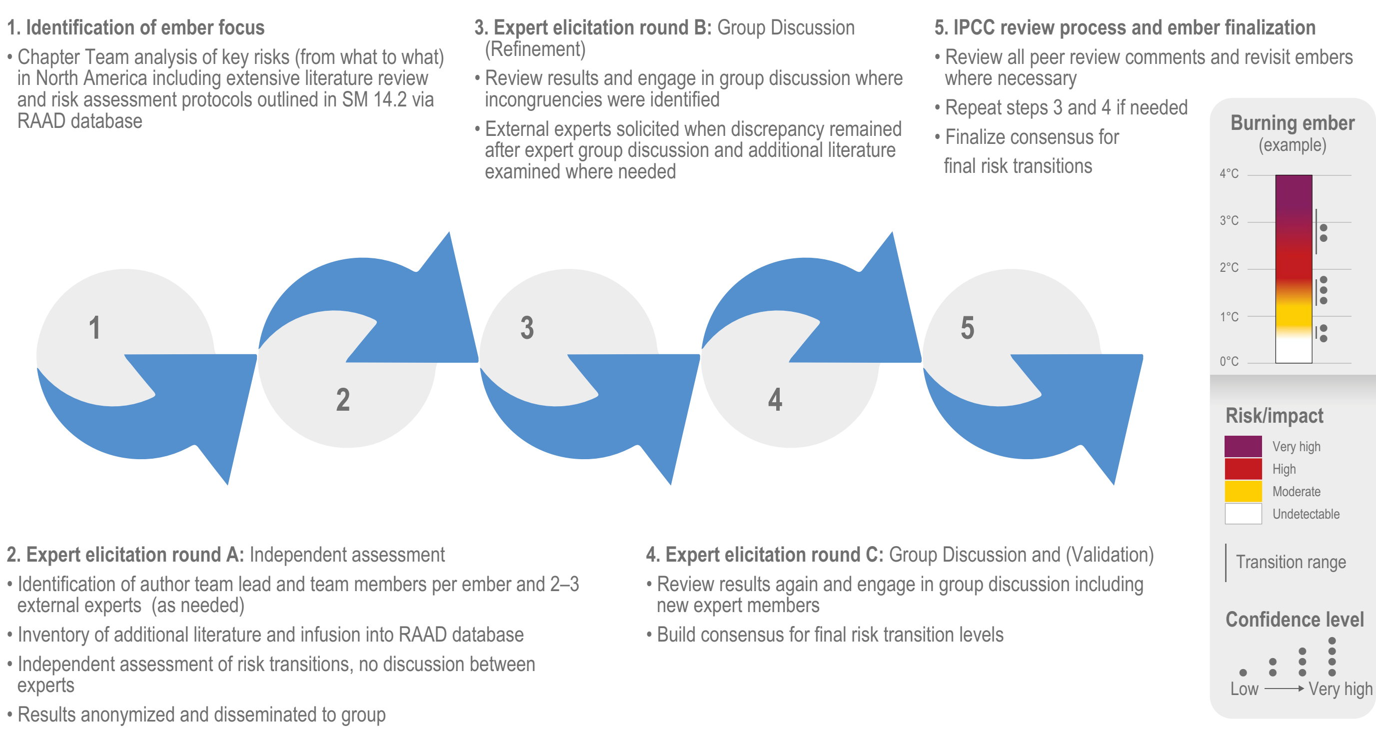

Figure SMCCP6.1 | Expert elicitation process for burning ember development.

Based on chapter team risk assessment and key risks identification protocols (SMCCP6.5), it was decided that existing literature would enable robust assessments of risks to: (1) sea ice ecosystems, (2) marine mammals, (3) sea birds, (4) fisheries, (5) infrastructure, (6) local mobility and (7) coastal erosion. All analyses cover the Arctic region, and 1–4 also cover the Antarctic region. The author team was unable to make assessments on all features for the Antarctic owing to either a lack of relevance or a lack of available literature. Further information on the authors involved and literature reviewed can be found in Table SMCCP6.6. A summary of risk transitions assessments can be found in SMCCP6.7.

Table SMCCP6.6 | Authors and references associated with burning embers figure in Cross Chapter Paper 6 (Polar Regions).

Burning ember	Main authors involved	Key references utilised*
Sea ice ecosystems	Jackie Dawson, Bjoern Rost, Dieter Piepenburg, Kirstin Holsmon, Bjorn David Babb	*Arctic* (Jahn et al., 2016; Notz and Stroeve, 2016; Sanderson et al., 2017; Jahn, 2018; Loseto et al., 2018; Sigmond et al., 2018; Screen and Deser, 2019; Landrum and Holland, 2020; SIMIP Community, 2020) *Antarctic* (Bintanja et al., 2015; Roach et al., 2020)
Marine mammals	Andrew Constable, Kirstin Holsman, Bjoern Rost, Dieter Piepenburg, Jackie Dawson	*Arctic* (Galappaththi et al., 2019; Meredith et al., 2019; Slats et al., 2019; Albouy et al., 2020; Boveng et al., 2020) *Antarctic* (Hückstädt et al., 2020; Wege et al., 2021)
Sea birds	Andrew Constable, Kristin Holsman, Bjoern Rost, Dieter Piepenburg	*Arctic and Antarctic* (Gutt et al., 2018; Keogan et al., 2018; Convey and Peck, 2019; Meredith et al., 2019; Bestley et al., 2020; Hindell et al., 2020; Jenouvrier et al., 2020; Kharouba and Wolkovich, 2020; Piatt et al., 2020; Romano et al., 2020; Samplonius et al., 2021)
Fisheries	Kirstin Holsmon, Andrew Constable, Jackie Dawson	*Arctic* (Holsman et al., 2020; Huntington et al., 2020; Reum et al., 2020) *Antarctic* (Melbourne-Thomas et al., 2016; Piñones and Fedorov, 2016; WMO and WWRP, 2017; Rogers et al., 2020; Veytia et al., 2020; Sylvester et al., 2021)
Infrastructure	Jackie Dawson, Kirstin Holsmon, Sheri Harper, Julia Boike, Dmitry Streleskiy	*Arctic* (Perrin et al., 2015; Hjort et al., 2018; Streletskiy et al., 2019; Suter et al., 2019; Gädeke et al., 2021)
Local mobility	Jackie Dawson, Sheri Harper, Gita Ljubicic, Emma Stewart	*Arctic* (Clark et al., 2016a; Clark et al., 2016b; Clark and Ford, 2017; Dawson et al., 2017; Debortoli et al., 2019; Ford et al., 2019; Haavisto et al., 2020; Stewart et al., 2020)
Coastal erosion	Jackie Dawson, Chris Derksen, Stephen Howell, Merce Casa-Prat	*Arctic* (Casas-Prat and Wang, 2020a; Casas-Prat and Wang, 2020b)

SMCCP6.6.1 Sea Ice Ecosystems

Sea ice ecosystems are rapidly transforming (Lannuzel et al., 2020), resulting in an unprecedented cumulation of cascading effects that impact almost every sector of environment and society (CCP6.2.1, CCP6.2.3, CCP6.2.4, CCPBox 6.1). Increasing light penetration initiates earlier seasonal primary production, and albedo an increased warming, earlier growing season for ice algae and phytoplankton biomass, and changes in health and habitat of sea ice fauna, megafauna and fish species. Biophysical changes cascade to socioeconomic and cultural systems by impacting safe travel in ice, subsistence hunting, changing economic opportunities, and potential for Arctic maritime trade—all of which will lead to additional impacts, risks and transformations, some of which may be inevitable and irreversible. At current levels of warming, sea ice in the Arctic is already showing clear signs of transformation, and reduction in extent and thickness combined with increased mobility is expected to continue. In the Antarctic, sea ice change is more variable and future projections less certain (Bintanja et al., 2015; Jahn et al., 2016; Notz and Stroeve, 2016; Sanderson et al., 2017; Jahn, 2018; Sigmond et al., 2018; Screen and Deser, 2019; Landrum and Holland, 2020; Roach et al., 2020; SIMIP Community, 2020).

SMCCP6.6.2 Marine Mammals

Much of the observed impact on marine mammals in polar regions is linked to sea ice loss (Galappaththi et al., 2019; Meredith et al., 2019; Slats et al., 2019; Boveng et al., 2020). More evidence exists of the impact and risk of climate change for marine mammals in the Arctic compared with the Antarctic, where uncertainty remains. Marine mammals respond to changes in the distribution of their preferred habitats and prey by shifting their range and altering timing based on prey shifting (Post et al., 2013; Hamilton et al., 2017; Meredith et al., 2019). For example, Beluga whales in Arctic Canada (*Delphinapterus leucas*) have changed their migration in response to altered sea ice and other environmental conditions (Loseto et al., 2018). However, endemic marine mammals that are ice-affiliated for breeding sometimes have little scope to move and are at higher risk to climate change (Kovacs et al., 2012; Hamilton et al., 2015). Shifts in distribution and availability of suitable areas for ice-breeding seals have occurred (Bajzak et al., 2011; Boveng et al., 2020) with increases in strandings and pup mortality in years with little ice (Johnston et al., 2012; Soulen et al., 2013; Stenson and Hammill, 2014). Following record low sea ice in the Bering Sea in 2018 and 2019, ice seal mortality and strandings were five times the average number of reported strandings (Boveng et al., 2020). In the Antarctic, current projections are unable to determine the behaviour of sea ice relative to the location of prey fields, at least not at the scale of the ecologies of marine mammals, and thus it is uncertain when this mismatch might arise. However, we know it has arisen in the Antarctic Peninsula, although it is possible that this may recover to some extent with the recovery of ozone (Hückstädt et al., 2020; Wege et al., 2021). Risk transitions were established by reviewing vulnerability of over 50 species, averaging risk scores under RCP2.6 and RCP8.5 for the Arctic and Antarctic, and error bounds and anomalies were considered to come to consensus.

SMCCP6.6.3 Sea Birds

Similar to marine mammals, sea ice loss plays a key role in facilitating climate-related impacts for sea birds and the loss of sea ice facilitates risks for breeding and feeding (Constable et al., 2016; Hunt et al., 2016; Gutt et al., 2018; Convey and Peck, 2019; Meredith et al., 2019; Bestley et al., 2020; Romano et al., 2020). Sea birds generally have low temperature-mediated plasticity of reproductive timing, making them vulnerable to mismatches with their prey and limiting long-term adaptation (Keogan et al., 2018; Kharouba and Wolkovich, 2020; Piatt et al., 2020; Samplonius et al., 2021). Climate-driven population trends include increases for gentoo penguins (*Pygoscelis papua*) but decreases for Adélie (*P. adeliae*), chinstrap (*P. antarctica*), king (*Aptenodytes patagonicus*) and emperor (*A. forsteri*) penguins (Meredith et al., 2019). Under 1.5°C global warming above pre-industrial level and to a lesser extent under 2°C, the global population decline of emperor penguin colonies around the Antarctic continent would likely be halted by 2060 (Jenouvrier et al., 2020). Foraging areas of sub-Antarctic sea birds will shift southwards (Bestley et al., 2020; Hindell et al., 2020; Hückstädt et al., 2020) with projected sea ice retreat and associated change in prey distribution (Henley et al., 2020; McCormack, accepted), leading to elevated pressure on populations due to higher foraging costs during the breeding season (Bestley et al., 2020).

SMCCP6.6.4 Fisheries

Risk transition analysis was focused on cod and pollock species in the Bering Sea under scenarios that include status quo ecosystem-based measures including a limit on total groundfish yields (Holsman et al., 2020). These fisheries represent the largest (pollock) and one of the most valuable (Pacific cod) fisheries in the USA. Warming temperatures and change in sea ice, circulation and shifts in trophic pathways to less energy efficient food chains (Hermann et al., 2019; Huntington et al., 2020) were used to drive changes in survival (predation), growth and recruitment under future scenarios, and subsequent catch. Regional 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 (Melbourne-Thomas et al., 2016; Piñones and Fedorov, 2016; WMO and WWRP, 2017; Klein et al., 2018; Rogers et al., 2020; Veytia et al., 2020), but significant regional declines may not be detected until later in the century (Sylvester et al., 2021).

SMCCP6.6.5 Infrastructure

Infrastructure is at risk from a variety of climate change hazards including SLR, storm surge, permafrost thaw and coastal erosion, among others. Impacts have already been observed for sewage systems, municipal buildings, roadways, pipelines, railways, ice roads and local trails between communities (Calmels et al., 2015; Perrin et al., 2015; Bashaw et al., 2016; Paulin and Caines, 2016; Riedel et al., 2017; Council of Canadian Academies, 2019; Gädeke et al., 2021). Evaluation of risk transitions for infrastructure was based on observed and projected risks from relevant climate hazards to relevant Arctic infrastructure. Potential adaptation options available, including limits to adaptation (i.e., relocation, available technologies, potential for new technologies, existing building codes), were considered during expert evaluation.

SMCCP6.6.6 Local Mobility

Indigenous and northern residents rely on sea ice for local travel between communities and to hunting areas (Ford et al., 2019; Stewart et al., 2020). Risk of injury or mortality is increasing with reductions in sea ice extent, diminishing reliability in Indigenous knowledge and local knowledge of sea ice conditions owing to rapid changes in ice conditions and a lack of reliable and locally relevant weather, water, ice and climate forecasting services (WMO and WWRP, 2017; Haavisto et al., 2020). Risk transitions considered all of these factors and additional data related to search and rescue rates which occur in the greatest frequency around –2°C and during freeze–thaw conditions; for example, 80% of search and rescue (SAR) occurs between –12°C and +6°C (Clark et al., 2016a; Clark and Ford, 2017). Changes to landfast sea ice (i.e., immobile sea ice) duration impacts where human mobility occurs. Projections show that landfast duration (i.e., earlier break and later freeze-up) across the Canadian Arctic is expected to decrease under RCP8.5 (Cooley et al., 2020) and thus reduce local mobility. Although landfast ice duration is projected to decrease under RCP8.5, it still is projected to be present at least 5 months of the year (Laliberté et al., 2018) and thus still be utilised for local mobility. *Low confidence* in future projections exists because not all climate model simulations capture landfast ice very well, thus not converting to models very well (Laliberté et al., 2018). Another consideration is that the thickness of landfast ice (i.e., thickness impacts its duration) is more influenced by changes in snow cover than in temperature (Howell et al., 2016).

SMCCP6.6.7 Coastal Erosion

Insufficient literature on coastal erosion in Antarctic prohibited analysis. For coastal erosion in the Arctic, we attribute changes under global warming primarily to decreases in sea ice extent across the Arctic Ocean leading to large expanses of open water (fetch), which facilitate larger waves. Warming causes the sea ice to retreat away from the coast and increases ocean wave heights, and the longer you have open water, the greater the risk of coastal erosion. The impact of global warming on coastal erosion is high. For ember transition analysis, we associate coastal erosion with the duration of open water and the probability of a sea-ice-free Arctic under levels of global warming from model simulations. The probability of a sea-ice-free Arctic at 3°C is 63% but only 19% at 2°C of warming (Sigmond et al., 2018). Model simulations also suggest that coastal regions will be covered by ice for only half of the year by 2070 (Barnhart et al., 2016). Under the RCP8.5 scenario, wave heights in Arctic waters ocean are projected to increase by 6 m, which is approximately two to three times larger than in 1979–2005 (~1°C of warming) (Casas-Prat and Wang, 2020a). We have *medium confidence* in the model projections of Arctic sea ice extent over the wide expanse of the Arctic Ocean compared with the landfast regions and the Archipelago across the Arctic.

Table SMCCP6.7 | Burning ember risk transitions for polar regions burning embers.

Ember focus	Region	Risk transition	Global mean surface temperature change above pre-industrial levels (°C)		Confidence
Sea ice ecosystems	Arctic	Undetectable to moderate	Min	0.5	*High*
			Max	0.8	
		Moderate to high	Min	0.8	*High*
			Max	1.1	
		High to very high	Min	1.5	*Medium*
			Max	2.0	
	Antarctic	Undetectable to moderate	Min	0.8	*Medium*
			Max	1.2	
		Moderate to high	Min	1.5	*Medium*
			Max	1.8	
		High to very high	Min	2.0	*Medium*
			Max	3.0	
Marine mammals	Arctic	Undetectable to moderate	Min	0.8	*Medium*
			Max	1.0	
		Moderate to high	Min	2.7	*High*
			Max	3.0	
		High to very high	Min		Does not meet this threshold
			Max		
	Antarctic	Undetectable to moderate	Min	1.3	*Low*
			Max	2.5	
		Moderate to high	Min		*Low*
			Max		
		High to very high	Min		*Low*
			Max		
Sea birds	Arctic	Undetectable to moderate	Min	0.5	*Medium*
			Max	0.7	
		Moderate to high	Min	1.0	*High*
			Max	1.2	
		High to very high	Min	1.2	*Medium*
			Max	2.0	
	Antarctic	Undetectable to moderate	Min	0.4	*High*
			Max	0.7	
		Moderate to high	Min	1.0	*Medium*
			Max	1.5	
		High to very high	Min	2.1	*Low*
			Max	2.5	

Ember focus	Region	Risk transition	Global mean surface temperature change above pre-industrial levels (°C)		Confidence
Fisheries	Arctic	Undetectable to moderate	Min	1.0	*Medium*
			Max	1.8	
		Moderate to high	Min	1.8	*Medium*
			Max	3.0	
		High to very high	Min	3.0	*High*
			Max	4.2	
	Antarctic	Undetectable to moderate	Min	0.8	*High*
			Max	1.1	
		Moderate to high	Min	1.5	*Medium*
			Max	2.0	
		High to very high	Min	3.0	*Medium*
			Max	4.0	
Infrastructure	Arctic	Undetectable to moderate	Min	0.5	*Medium*
			Max	1.0	
		Moderate to high	Min	2.0	*Low*
			Max	3.0	
		High to very high	Min	3.5	*Low*
			Max	4.0	
Local mobility	Arctic	Undetectable to moderate	Min	0.8	*Medium*
			Max	1.8	
		Moderate to high	Min	2.2	*Low*
			Max	2.8	
		High to very high	Min	3.0	*Low*
			Max	4.0	
Coastal erosion	Arctic	Undetectable to moderate	Min	0.8	*Medium*
			Max	1.5	
		Moderate to high	Min	1.8	*Medium*
			Max	2.0	
		High to very high	Min	3.0	*Medium*
			Max	4.0	

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