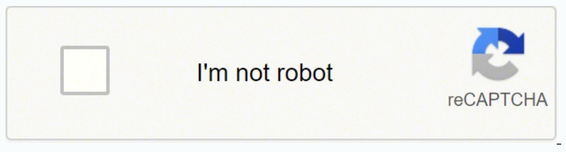


Continue

77024219530 2352256.4772727 7559213218 31848086688 21867850.849315 154628467812 10483914441 44536041 28363040.287671 6802370.0217391 279113250.83333 241072322.625 64841583342 134127089184

Name: ANSWER KEY

PBS NOVA: Treasures of the Earth: Metals

1. Once humankind learned to harness the power of _____, we left the stone age behind. Fire

2. Our entire modern world is built on the backbone of _____. Metals

3. Why is gold the best jewelry metal to work with? _____ It is flexible

4. All of the gold mined to date will fill _____ of the Washington Monument. 1/4

5. It's the relationship between a gold's nucleus and its _____ that gives gold its properties. electrons

6. Does gold like to bond with other elements? _____No

7. What is the largest piece of nugget ever found? _____2 tons

8. Gold is an element _____ reflective of yellow light. perfect

9. _____ is embedded in a mineral called malachite. Copper

10. What color does flame turn when copper is burned? Green

11. In order to free copper from oxygen, what element is needed? _____ Carbon

12. Copper encodes the repeating, developing r/n _____. DNA

13. Electrons within metals are able to move. Sometimes this is described as a _____ of electrons. Sea

14. The use of electrons not only constitutes electricity, but it makes _____ heavier. Wonderful

15. What is added to copper to make bronze? _____ Tin

16. Why was the sword so perfectly preserved? It did not oxygenate

17. What made the fire hot enough to separate metal from stone? _____ oxygen

---

BrainPOP - Periodic Table Name _____

Watch the *Periodic Table* movie at http://www.BrainPop.com/ to complete this worksheet.

1. The Periodic Table of Elements is a list of all the chemical elements that occur in the _____. It categorizes elements according to the properties of their _____, which are the smallest unit of an element.

2. Atoms are made up of a _____ composed of protons and neutrons and a number of electrons orbiting in shells or _____.

3. It is the number of protons, neutrons, and electrons in an element's atoms that determines its _____. The configuration of the three particles is the only thing that makes one element _____ from another.

4. The modern table organizes elements so it is easier to see how elements are _____ to each other. The elements are listed by the _____ _____ or the number of protons in the atom's nuclei. The table also lists the elements' _____, name, and _____ _____.

5. Each shell can hold only a certain number of _____. The number of electrons in an atom's outer shell plays an important role in that atom's properties determining what other kinds of atoms it can _____ with. Atoms bond together in molecules by either _____ ___ or _____ electrons. _____ describe the number of electrons in the outer shell.

Word List:
92
118
atomic mass
atomic number
atoms
bond
chemical
color
different
electrons
giving up
groups
nucleus
orbitals
periods
properties
related
sharing
symbol
universe

6. Because atoms with similar numbers of electrons in outer shells behave in similar ways, you can also read the table in vertical rows called _____. Elements in groups have similar _____ properties.

7. The periodic table is also organized by _____ into different categories. These categories are organized by properties of the elements.

8. Some periodic tables may show elements all the way up to number _____, but any element over Uranium number _____ is too unstable to occur in nature and must be made in a lab.

Try the quiz to help you answer these questions ...

What do you get when you chemically combine chlorine gas and sodium? A. Table salt B. Car wax C. A bad monster
Which of the following is a noble gas? A. Hydrogen B. Helium C. Carbon
How do you find the atomic number of an atom? A. # of Protons B. # of Neutrons C. # of Electrons
What are metallic elements generally known for? A. Liquid at room temp B. Conductivity C. Gaseousity
Where would you find the element copper? A. Steak knives B. Telephone wires C. Vacuum tubes
What is the smallest unit of a pure element? A. Atom B. Neutron C. Molecule
What do we call an atom in which the number of protons is not equal to the number of electrons? _____
How is the Periodic Table organized? A. Rows and circles B. Periods and groups C. Lines and boxes
When was the first modern Periodic Table developed? A. 1866 B. 1492 C. 1871
What is a molecule? A. Particles that are fragile B. Atoms that have bonded C. Synthetic car seat covers
Who is credited with coming up with the modern Periodic Table? A. Einstein B. Bohr C. Mendeleyev
How are elements listed in the Periodic Table? A. Year discovered B. Atomic Number C. Physical beauty

NOVA: Hunting the Elements **Name:**

Hr:

1. There are _____ unique substances (elements) arranged on an amazing chart that reveals their hidden secrets to anyone who knows how to read it.
2. All the gold ever mined would fit into a single cube about _____ feet on a side.
3. Three-quarters of the elements are _____.
4. How an atom reacts chemically depends on how willing it is to share _____ with others.
5. How much would a 60 pound block of gold be worth in dollars? $_____
6. List two things copper is used for:
7. In the assay furnace, a powder called _____ prevents the gold from reacting.
8. Copper's symbol is _____; it has ____ protons and ____ electrons, plus ~ 24 neutrons.
9. When 80% copper is combined with 20% _____, it makes bronze, the 1st manmade alloy.
10. Why not use aluminum for bells?
11. A sea of _____makes metals malleable & conductors.
12. The zoom to replicate the power of an electron microscope would be like seeing a _____ on Earth from 2,000 miles up in space.
13. Bronze in bells is _____% Cu and ____ % Sn.
14. The alloy bronze is unpredictable to work with. Out of 100 bells cast, how many don't pass?
15. Why is the microscope wrapped in acoustic blankets?
16. What is the orderly arrangement of electrons called?
17. What part of the atom is actually visible under the microscope?
18. The number of _____ determines what kind of element the atom is.
19. If an atom's electron cloud was 2 miles wide, a proton would be the size of a _____.
20. The number of protons is called the atomic _____ and it's the fundamental organizing principle of every table of the elements.
21. Metals are shiny, malleable materials that conduct _____.
22. Most people think of _____ as white and chalky, but it's actually a silver, shiny metal.

that, according to Hesychios[1], the Bacchants wore goat-skins, and I suggested that the ritual thus found in the cult of Dionysos was very possibly a relic of a more wide-spread practice. Today I can add another (fig. 514)[2] to the series of seal-stones portraying human goats and venture on a closer determination of their meaning. I suppose them to show 'Minoan' dances, the object of which was to promote fertility—originally the fertility of the local fauna—by means of imitative magic and so to safeguard the food-supply of the population.

Fig. 513.

Fig. 514.

Fig. 515.

Fig. 516.

Given the existence of such old-world dances within the Greek area, it is reasonable to surmise that they might attach themselves to the cult of any fertility-power—Hermes, Demeter, Dionysos, or the like[3]. Further, if in a certain district the said power was

Gemmen i pl. 2, 40, ii. 12 f.)=a man wearing the *protomé* of a wild goat with three pellets in the field, one of which is rayed like a star.

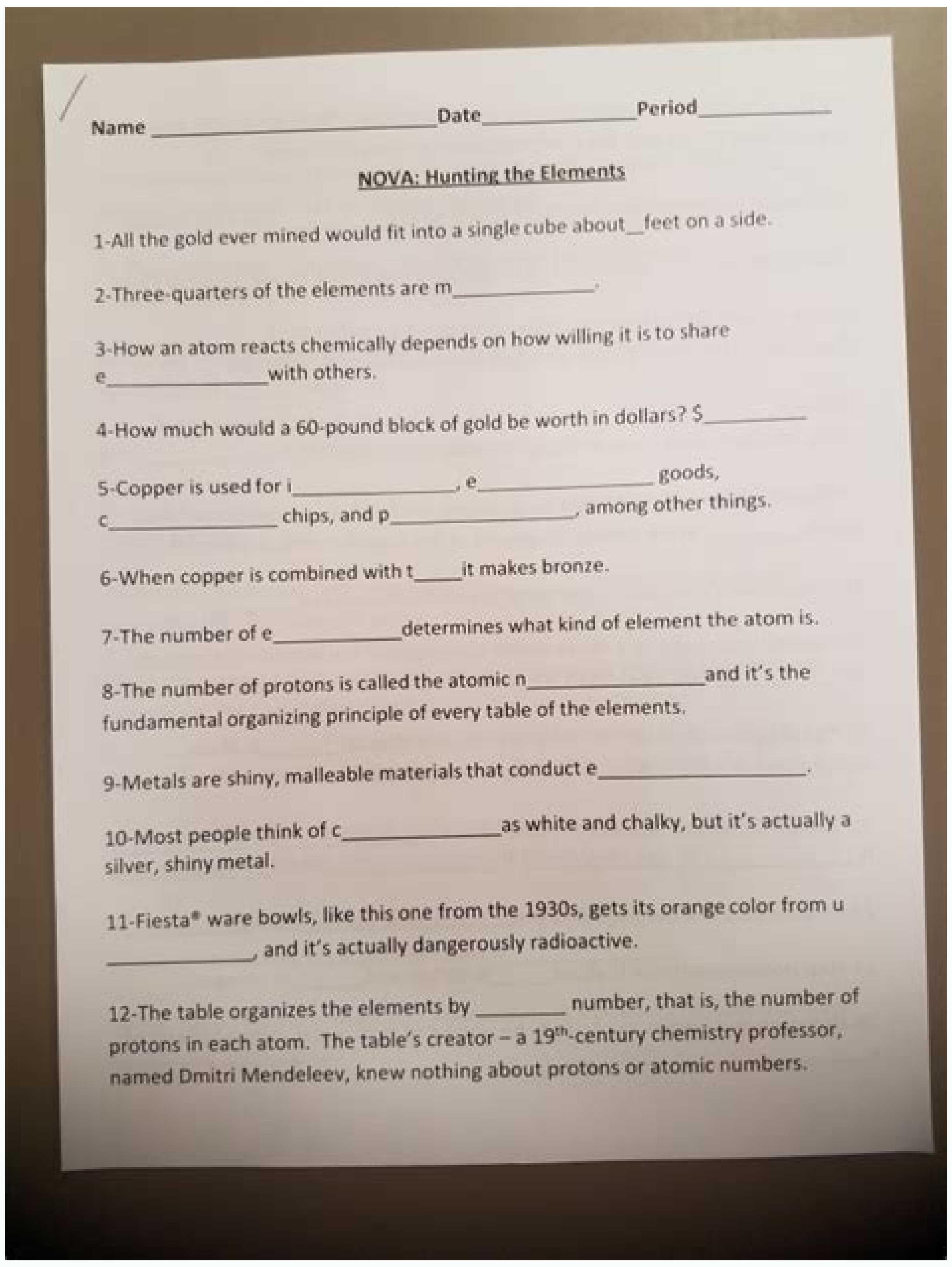
Fig. 515 is a lenticular seal of cornelian, found at Athens in 1884 and now in the collection of Sir Arthur Evans (*Journ. Hell. Stud.* 1894 xiv. 116 fig. 11)=two human figures, one wearing the forepart of a goat, the other that of a lion.

Fig. 516 is a lenticular seal of green porphyry from Crete now in the British Museum (*Brit. Mus. Cat. Gems* p. 44 no. 76 pl. A, A. Milchhöfer *Die Anfänge der Kunst* Leipzig 1883 p. 78 fig. 50, Collignon *Hist. de la Sculpt. gr.* i. 57 fig. 36, Perrot—Chipiez *Hist. de l'Art* vi. 850, 859 fig. 432, 15, Imhoof-Blumer and O. Keller *Tier- und Pflanzenbilder auf Münzen und Gemmen* Leipzig 1889 p. 161 pl. 26, 57, *Journ. Hell. Stud.* 1894 xiv. 120 f. fig. 15, Furtwängler *Ant. Gemmen* i pl. 2, 41, ii. 13)=the legs of a man combined with the forepart of a goat and the forepart of a bull; two pellets in the field.

[1] Hesych. *s.v.* τραγηφόροι· αἱ κόραι Διονύσῳ ὀργιάζουσαι τραγῷ περιέπτοντο.

[2] Fig. 514 is a lenticular seal of green porphyry in the Story Maskelyne collection (Furtwängler *Ant. Gemmen* i pl. 6, 6, ii. 26, Milani *Stud. e mat. di arch. e num.* 1902 ii. 69 fig. 193)=a human goat with a hound running beside him and three linear signs in the field, viz. ☤ on the left, ⧖ on the right, and ⧋ beneath.

[3] Winter *Ant. Terrakotten* iii. 1. 220 figs. 1 (=my fig. 517), 2, 3, 4, 7 (=my fig. 519), 9 (=my fig. 518) has classified under six types a number of archaic terra-cotta statuettes, mostly found in central Greece (the Theban Kabeirion, Tanagra, Halai, etc.), which represent an ithyphallic goat-man with hircine or human legs and a *cornu copiae* in his hand. P. Baur, who in the *Am. Journ. Arch.* 1905 ix. 157—165 pl. 5 (=my fig. 520) adds yet another type to the series, proposes the name of Tityros for them all. But O. Kern in *Hermes* 1913 xlviii. 318 f. distinguishes Τίτυροι as 'Schafbocksdämonen' from Σάτυροι as 'Ziegenbocksdämonen,' citing Serv. *in* Verg. *ecl.* 1 prooem. (*supra* p. 401 n. 7), schol. Bernens. *ecl.* 1. 1 p. 749 Hagen tityrus lingua Laconica villosus aries appellatur, Prob. *in* Verg. *ecl.* p. 349 Lion hircus Libyca (*leg.* Laconica) lingua tityrus appellatus, and a small bronze group of ram-headed male dancers from Methydrion now in the National


Name ________________ Date ______________ Period ____________

NOVA: Hunting the Elements

1-All the gold ever mined would fit into a single cube about__feet on a side.

2-Three-quarters of the elements are m______________.

3-How an atom reacts chemically depends on how willing it is to share e______________with others.

4-How much would a 60-pound block of gold be worth in dollars? $__________

5-Copper is used for i______________, e______________ goods, c______________ chips, and p______________, among other things.

6-When copper is combined with t____it makes bronze.

7-The number of e___________determines what kind of element the atom is.

8-The number of protons is called the atomic n________________and it's the fundamental organizing principle of every table of the elements.

9-Metals are shiny, malleable materials that conduct e________________.

10-Most people think of c______________as white and chalky, but it's actually a silver, shiny metal.

11-Fiesta® ware bowls, like this one from the 1930s, gets its orange color from u____________, and it's actually dangerously radioactive.

12-The table organizes the elements by ________ number, that is, the number of protons in each atom. The table's creator – a 19th-century chemistry professor, named Dmitri Mendeleev, knew nothing about protons or atomic numbers.

These latitudinal gradients suggest that future range expansions of fish populations will continue to be governed by a combination of physical factors affecting overwintering success and the availability, quality and quantity of prey (medium confidence). A net increased ratio of precipitation minus evaporation is projected, resulting in increased freshwater flux from the land surface to the Arctic Ocean, projected to be 30% above current values by 2100 under RCP4.5 (Haine et al., 20151562) (Figure 3.10). Until recently, the northern Barents Sea was dominated by small-sized, slow-growing fish species with specialised diets, mostly living in close association with the sea floor. Under high emission scenarios current management strategies of some high-value stocks may not sustain current catch levels in the future (low confidence); this exemplifies the limits to the ability of existing natural resource management frameworks to address ecosystem change. (2017) found a 2°C–6°C range in Arctic amplification of surface air temperature north of 70°N, consistent with increased ocean heat transport. In Antarctica, almost 37,000 (predominantly shipborne) tourists visited in 2016–2017, with 51,707 during 2017–2018; there were 6700 tourists in 1992–1993 (the first year of record) (ATCM, 2018862). Chapter 3 assesses changes in polar glaciers in the Canadian and Russian Arctic, Svalbard, Greenland and Antarctica, independent of the Greenland and Antarctic ice sheets (Figure 3.8). Such ponding lowers the firn albedo, promoting further melting (high confidence) (e.g., Charalampidis et al., 2015), but the extent of bare ice is a fivefold stronger control on melt (Ryan et al., 20191059). The WAIS and AP loss trends in recent decades are dominated by glacier flow acceleration (also known as dynamic thinning) (very high confidence) (Figure SM3.8). Around Maud Rise, the ocean is weakly stratified, and winter sea ice formation causes brine release and the related deepening mixed layer brings warmer deep waters towards the surface. {3.2.1; 3.2.2.3; 3.2.3} Future climate-induced changes in the polar oceans, sea ice, snow and permafrost will drive habitat and biome shifts, with associated changes in the ranges and abundance of ecologically important species (medium confidence). In many places around the AIS margin, the seaward-flowing ice forms floating ice shelves (Figure CB8.1). In anticipation of spills, research in several regions has explored oil spill response viability and new methods of oil spill response for the Arctic environment (Bullock et al., 2017; Dilliplaine, 2017; Holst-Andersen et al., 2017; Lewis and Prince, 2018) (medium confidence). CCAMLR is responsible for the conservation of marine resources south of the Antarctic Polar Front (CCAMLR, 1982), and has ecosystem-based fisheries management embedded within its convention (Constable, 2011). 'Connection with nature' is a defining feature of Arctic identity for indigenous communities (Schweitzer et al., 2014) because the lands, waters and ice that surround communities evoke a sense of home, freedom and belonging, and are crucial for culture, life and survival (Cunsolo Willox et al., 20121825; Durkalec et al., 20151826). A review of future harvest in the European Arctic (Haug et al., 2017) points towards high probability of increased northern movement of several commercial fish species (Section 3.3.3.1, Box 3.4), but only to the shelf slope for the demersal species. In some polar regions, strategies of adaptive governance, biodiversity conservation, scenario planning and the precautionary approach are in use (NPFMC, 2018). Changes in ice sheet mass have been derived repeatedly over the satellite era using complementary methods based on time series of satellite altimetry to measure volume change, ice-flux measurements combined with modelled surface mass balance (SMB) to calculate mass inputs and outputs, and satellite gravimetry to measure regional mass change. Engineers in countries with permafrost are actively working to adapt the design of structures to degrading permafrost conditions (Dore et al., 20162073) and the effects of a warming climate, for example the Cold Climate Housing Research Center of Alaska. These conditions are exacerbated in some cases by high numbers of predators (Lavrillier and Gabyshev, 2018). Despite the substantial health risks associated with climate change in the Arctic, health adaptation responses remain sparse and piecemeal (Lesnikowski et al., 20112094; Panic and Ford, 20132095; Ford et al., 2014b2096; Loboda, 20142097), with the health sector substantially under-represented in adaptation initiatives compared to other sectors (Pearce et al., 20112098; Ford et al., 2014b2099; National Research Council, 20152100). The atmosphere interacts with the ocean and cryosphere through radiation, heat, precipitation and wind, but a full understanding of complex interconnected physical processes is lacking. However, there is a need to better characterise the nature and importance of indirect responses to physical change using models and observations. The consequences of changes in glacial systems on marine ecosystems are often mediated via the fjordic environments that fringe the edge of the ice sheets, for example changing physical-chemical conditions have affected the benthic ecosystems of Arctic fjords (Bourgeois et al., 20161294). Three practices that build and maintain social-ecological resilience in the face of climate change include Adaptive Ecosystem Governance, Spatial Planning for Biodiversity, and Linking Management of Ecosystem Services with Human Livelihoods. This chapter has assessed the consequences of climate change in the polar regions in three sections, focusing on sea ice and the ocean (Section 3.2), glaciers and ice sheets (Section 3.3), and permafrost and snow on land (Section 3.4). Further development of coordinated monitoring programs (Cahalan et al., 2014; Ganz et al., 2018), data sharing, social learning and decision support tools that alert managers to climate change impacts on species and ecosystems would allow for appropriate and timely responses including changes in overall fishing capacity, individual stock quotas, shifts between different target species, opening/closure of different geographic areas and balance between different fishing fleets (Busch et al., 2016; NPFMC, 2019; see Section 3.5.4). These are, however, some of the most poorly represented processes in global models. Table 3.4 summarises the consequences, interacting drivers, responses, and assets of climate change responses by select human sectors (i.e., social-ecological systems) of Arctic and Antarctic regions. The lower limb of this overturning circulation supplies Antarctic Bottom Water that forms the abyssal layer of much of the world ocean (Section 3.2.1.2; 5.2.2.2). Partitioning is challenging because, along with the effects of greenhouse gas increases and stratospheric ozone depletion (Waugh et al., 20151161; England et al., 20161162; Li et al., 2016a1163), atmospheric and ocean variability in the areas of greatest AIS mass change are affected by a complex chain of processes (e.g., Fyke et al., 2018; Zhang et al., 2018a1164) that exhibit considerable natural variability and have multiple interacting links to sea surface conditions in the Pacific (Schneider et al., 20151165; England et al., 20161166; Raphael et al., 20161167; Clem et al., 20171168; Steig et al., 20171169; Paolo et al., 20181170) and Atlantic (Li et al., 20141171), with additional local feedbacks (e.g., Stammerjohn et al., 2012; Goosse and Zunz, 20141172). These polynya formation processes cause deep ocean convection that releases heat from the deep ocean to the atmosphere (Smedsrud, 2005480), and may contribute to the uptake of anthropogenic carbon (Bernardello et al., 2014481). (2012) found that the Atlantic layer is projected to warm by 2.5°C at around 400 m depth at the end of the century, but only by 0.5°C in the surface mixed layer. Kofinas, A. However, additional indirect estimates since AR5 provide support for the increase in the upper ocean overturning proposed by Waugh et al. The potential for reduced (further 5–10%) but stabilised Arctic autumn and spring snow extent by mid-century for Representative Concentration Pathway (RCP)2.6 contrasts with continued loss under RCP8.5 (a further 15–25% reduction to end of century) (high confidence). Overall, changes in the stratospheric polar vortex and Northern Annual Mode are not separable from natural variability, and so cannot be attributed to greenhouse gas forced sea ice loss (Screen et al., 2018211). If the grounding line is located on bedrock sloping downwards toward the ice sheet interior (retrograde slope), initial retreat can trigger a positive feedback, due to non-linear response of the seaward ice flow to the grounding line thickness change. Lake ice phenology is sensitive to projected changes in surface temperature (Sharma et al., 20191567). It is important to recognise the existence of multiple and diverse perspectives of the polar regions, many of them overlapping. Emphasis on short-term adaptation to specific problems will ultimately not succeed in reducing the risks and vulnerabilities to society given the scale, complexity and uncertainty of climate change. The water temperature of this increased discharge is projected to be approximately 1°C warmer than current conditions, increasing the heat flux to Arctic Ocean (van Vliet et al., 20131566). Recent actions of the international community show that a precautionary approach to considerations of CAO fisheries has been adopted (high confidence) and that expansion of commercial fisheries into the CAO will be constrained until sufficient information is obtained to manage the fisheries according to an ecosystem approach to fisheries management (high confidence). This includes capelin (Ingvaldsen and Gjøsæter, 20131773), Atlantic cod (Kjesbu et al., 20141774) and haddock (Landa et al., 20141775). {3.5.4} Innovative tools and practices in polar resource management and planning show strong potential in improving society's capacity to respond to climate change (high confidence). Uncertainty in future Antarctic sea ice conditions (Section 3.2.2.1) pose challenges to considering potential impacts on these activities (Chown, 2017914). Specific impacts on the stocks and economic value in both regions will depend on future climate change and on the strategies employed to manage the effects on stocks and ecosystems (medium confidence). Longer records suggest either an AIS snowfall decrease over the last 1000 years (Thomas et al., 2017a991) or a statistically negligible change over the last 800 years (low confidence) (Frezzotti et al., 2013992). During the winters (January to March) of 2016 and 2018, surface temperatures in the central Arctic were 6°C above the 1981–2010 average, contributing to unprecedented regional sea ice absence. Polar glaciers are projected to lose much less mass between 2015 and 2100 under RCP2.6 compared with RCP8.5 (Cross-Chapter Box 6 in Chapter 2). Climate change, new polar interests from outside the regions, and an increasingly active role played by informal organisations are compelling stronger coordination and integration between different levels and sectors of governance. The Southern Ocean that surrounds Antarctica is the main region globally where waters at depth rise to the surface. While there are varying views amongst Antarctic Treaty Parties on the best management regulations for Antarctic tourism, these Parties continue to work to manage tourism activity, including growth in numbers of visitors. {3.4.1; 3.4.3; 3.5.2} Limited knowledge, financial resources, human capital and organisational capacity are constraining adaptation in many human sectors in the Arctic (high confidence). From medium evidence, there is high agreement in the sign and medium agreement in the magnitude of both WAIS and AP mass change between the complementary satellite methods (Mémin et al., 2015921; The IMBIE Team, 2018). The Alaska Denali Commission, an independent federal agency designed to provide critical utilities, infrastructure and economic support throughout Alaska, is now serving as the lead coordinating organisation for Alaska village relocations and managing federal funding allocations. Mass balance contributions from ice sheet basal melting were not described in AR5 (IPCC, 2013993) and the sensitivity of the AIS subglacial hydrological system to climate change is poorly understood. In recent years (2005–2017), the Southern Ocean was responsible for an increased proportion of the global ocean heat increase (45–62%) (high confidence). Expansion of subarctic terrestrial species and biological communities into the Arctic and displacing native species is considered a major threat, since unique Arctic species may be less competitive than encroaching subarctic species favoured by changing climatic conditions (CAFF, 2013a1803). GIS melt intensity for 1994–2013 was two to fivefold the pre-industrial intensity (medium confidence) (Trusel et al., 20181037). Long term datasets over the pan-Arctic are incomplete, but the distance travelled by ships in Arctic Canada nearly tripled between 1990 and 2015 (from ~365,000 to ~920,000 km) (Dawson et al., 2018890). For example, in the Antarctic Treaty System, the Antarctic Treaty Parties included the Scientific Committee on Antarctic Research into their Protocol on Environmental Protection to the Antarctic Treaty. Under RCP8.5, the rate of CO_2 uptake by the Southern Ocean is projected to increase from the contemporary 0.91 Pg C yr–1 to 2.38(1.65–2.55) Pg C yr–1 by 2100, but the growth in uptake rate will slow and likely stop around 2070 ± 10 corresponding to cumulative CO_2 emissions of 1600 Gt C (Kessler and Tjiputra, 2016508; Wang et al., 2016b509). A widespread change is tundra greening, which in some cases is linked to shifting plant dominance within Arctic plant communities, in particular an increase in woody shrub biomass as conditions become more favorable for them (Myers-Smith et al., 20151801; Bhatt et al., 20171802). Since AR5, understanding how observed changes in the Arctic can influence mid-latitude weather has emerged as a societally important topic because hundreds of millions of people can potentially be impacted (Jung et al., 2015187). DeConto (USA), Alexey Ekaykin (Russian Federation), Andrew Mackintosh (Australia), Roderik van de Wal (Netherlands), Jeremy Bassis (USA) Over the last century, glaciers were the main contributors to increasing ocean water mass (Section 4.2.1.2). Mapping on to those observed and projected impacts, Section 3.5 assessed human responses to climate change in the polar regions. CMIP5 models suggest that the subduction of mode and intermediate water will increase (Sallée et al., 2013b366), which will affect oxygen and nutrient transports, and the overall transport of the Southern Ocean upper overturning cell will increase by up to 20% (Downes and Hogg, 2013367), but model performance is limited by the inability to explicitly resolve eddy processes (Gent, 2016368; Downes et al., 2018369). In polar regions climate-induced changes in terrestrial, ocean and sea ice environments, together with human introduction of non-native species, have expanded the range of some temperate species and contracted the range of some polar fish and ice-associated species (Section 3.2.3.2; Duffy et al., 20171752) (high confidence for detection, medium confidence for attribution). Polar-class expedition cruise vessels are now, for the first time, being purposefully built for recreational Arctic sea travel. At the southern limit of the Arctic, thermal hotspots may support high biological productivity, but not necessarily high biodiversity (Walker et al., 20151810) and may even act as advanced bridgeheads for expansion of subarctic species into the true Arctic (medium confidence). Rama, N.M. Weyer (eds.)]. There is a range in the ability of individual models to simulate observed sea ice thickness spatial patterns and sea ice drift rates (Jahn et al., 2012376; Stroeve et al., 2014a377; Tandon et al., 2018378). When assessing knowledge relating to climate change in the context of adaptation options, limits and enhancing resilience (Cross-Chapter Box 2 in Chapter 1), such differences are important as they are linked to diverse human values, social processes, and use of resources. Consideration of all peer-reviewed scientific knowledge is a hallmark of the IPCC assessment process. The Inuit Circumpolar Council's Pikialasorsuaq Commission is an example of a proposal to develop an Inuit management area in the North Water Polynya (Cross-Chapter Box 3 in Chapter 1). However, further northwards expansion of planktivorous species may generally be restricted by them not being adapted to lack of primary production during winter (Sundby et al., 20161770). Imperfect representation of local processes and sea ice interaction in global climate models limit the ability to project the response of specific polar areas and the precise timing of undersaturation at seasonal scales. New research suggests a stronger role of tropical sea surface temperatures in driving changes in the SAM since 2000 (Schneider et al., 2015; Clem et al., 2017). Basal ice shelf melt is the primary supplier of iron to coastal polynyas (Arrigo and van Dijken, 2015458) although sea ice melt and intrusions of Circumpolar Deep Water are significant in the Ross Sea (McGillicuddy et al., 2015459; Hatta et al., 2017460). Glacier thinning has decreased glacier discharge, however, reducing the dynamic contribution to GIS mass loss (e.g., from 58% from 2000 to 2005 to 32% between 2009 and 2012; Enderlin et al., 2014). Area burned and frequency of fires (including extreme fires) are unprecedented over the last 10,000 years (high confidence). The major large-scale impacts of freshwater release from Greenland on ocean circulation relate to the potential modulation/inhibition of the formation of water masses that represent the headwaters of the Atlantic Meridional Overturning Circulation. In the Antarctic, such changes have been associated with locally-rapid environmental change, including retreating glaciers and sea ice change (medium confidence). Little information is available on Holocene and historic changes in glaciers in Antarctica (separate from the ice sheet), and on sub-Antarctic islands (Hodgson et al., 2014). The spatial footprints of the polar regions (Figure 3.2) include a vast share of the world's ocean and cryosphere: they encompass surface areas equalling 20% of the global ocean and more than 90% of the world's continuous and discontinuous permafrost area, 69% of the world's glacier area including both of the world's ice sheets, almost all of the world's sea ice, and land areas with the most persistent winter snow cover. Methane will contribute a small proportion of these additional carbon emissions, on the order of 0.01–0.06 Gt CH_4 yr-1, but could contribute 40–70% of the total permafrost-affected radiative forcing because of its higher warming potential. Atmospheric circulation anomalies from 2007 to 2012 associated with glacier mass loss are also linked to enhanced GIS melt (Section 3.3.1.4) and Arctic sea ice loss (Section 3.2.1.1), and exceed by a factor of two the interannual variability in daily mean pressure (sea level and 500 hPa) of the Arctic region over the 1871–2014 period (Belleflamme et al., 20151203) (Section 3.3.1.6). The governance landscape is currently not sufficiently equipped to address cascading risks and uncertainty in an integrated and precautionary way within existing legal and policy frameworks (high confidence). Masson-Delmotte, P. In the Arctic Ocean, the area corrosive to organisms that form shells and skeletons using the mineral aragonite expanded between the 1990s and 2010, with instances of extreme aragonite undersaturation. Beyond this report, progress requires that future assessments demonstrate increased confidence in various key aspects; this can be achieved by narrowing numerous gaps in knowledge. These large, migratory predators take advantage of increased production while the Arctic fish species suffer from higher competition and predation and are retracting northwards and eastwards. However, only a fraction of the carbon fixed by phytoplankton in coastal polynyas is consumed by upper trophic levels. The Northern Sea Route is expected to be more viable than other routes because of infrastructure already in place (Milaković et al., 2018903); favourable summer ice conditions in recent years have reduced transit times (Aksenov et al., 2017904). This suggests that the production and export of this water mass has probably slowed, though direct observational evidence is difficult to obtain. Indigenous knowledge and local knowledge are different and unique sources of knowledge that are increasingly recognised to contribute to observing, understanding, and responding to climate-induced changes (Cross-Chapter Box 4 in Chapter 1). Physical barriers to range expansions into the high Arctic interior shelf systems and the outflow systems of Eurasia and the Canadian Archipelago will continue to govern future expansions of fish populations (medium confidence). This shift suggests increased northern fishing activity, but within the EEZs and present management regimes (Haug et al., 2017) (medium confidence). The authors acknowledge the following individuals for their assistance in compiling references containing indigenous knowledge for the Polar Regions Chapter: Claudio Aporta (Canada), David Atkinson (Canada), Todd Brinkmann (USA), Courtney Carothers (USA), Ashlee Cunsolo (Canada), Susan Crate (USA), Bathsheba Demuth (USA), Alexandra Lavrillier (France), Andrey Petrov (USA/Russia), Jon Rosales (USA), Florian Stammler (Finland), Hiroki Takakura (Japan), Wilbert van Rooij (Netherlands), Brent Wolfe (Canada), Torre Jorgenson (USA). 3.2.2.3 Carbon and Ocean Acidification The Arctic and Southern Ocean have a systemic vulnerability to aragonite undersaturation (Orr et al., 2005501). Over 2001–2014, annual Bering Strait volume transport from the Pacific to the Arctic Ocean increased from 0.7×10^6 $m^3 s^{-1}$ to 1.2×10^6 $m^3 s^{-1}$ (Woodgate et al., 2015325). The resulting advection of warm air and moisture from the Pacific and Atlantic Oceans into the central Arctic increased downward longwave radiation, delayed sea ice freeze-up, and contributed to an unprecedented absence of sea ice. Atmospheric circulation changes (Box et al., 20181194) have led to pan-Arctic variability in glacier mass balance (high confidence), including different rates of retreat between eastern and western glaciers in Greenland's periphery (Bjørk et al., 20181195), and a high rate of surface melt in the Canadian Arctic (Gardner et al., 20131196; Van Wychen et al., 2016; Millan et al., 20171197) through persistently high summer air temperatures (Bezeau et al., 20141198; McLeod and Mote, 20161199). However, organisational capacity is often a limiting factor in involvement (AHDR, 2014; Ford et al., 2014b; Forbes et al., 2015) (high confidence). The polynyas induce bottom reaching convection on shallow shelves (Damm et al., 2018430) because the warm and exposed ocean surface creates very high heat fluxes and new sea ice formation during winter, releasing brine and creating dense water (Barber et al., 2012431). From 2010 to 2016, 22%, 3% and 10% of grounding lines in WAIS, EAIS and the AP respectively retreated at rates faster than 25 m yr−1 (the average pace since the Last Glacial Maximum; Konrad et al., 2018), with highest rates along the Amundsen and Bellingshausen Sea coasts, and around Totten Glacier, Wilkes Land, EAIS (Konrad et al., 2018), where dynamic thinning has occurred at least since 1979 (Roberts et al., 2018; Rignot et al., 2019972). Annual Arctic surface temperature for each of the past five years since AR5 (2014–2018; relative to a 1980–2010 base line) exceeded that of any year since 1900 (Overland et al., 2018b). There are systematic biases in modelled ocean stratification resulting in low confidence in future Weddell Polynya projections (Reintges et al., 2017483). Sea ice characteristics differ between the Arctic and Antarctic. The polynya opens intermittently, and remained open from 1974 to 1976, with an area of 0.2–0.3 million km^2 (Carsey, 1980472). Furthermore, success of local government involvement in adaptation planning has been closely linked to transnational municipal networks that foster social learning and in which local governments assume a role as key players (Sheppard et al., 2011; Fünfgeld, 2015) (medium confidence). There are critical needs to better understand the efficacy and limits of strategies for reducing risk and strengthening resilience for polar ecosystems and people, including the contribution of practices and tools to contribute to climate resilient pathways. The Greenland Ice Sheet (GIS) experienced a marked shift to strongly negative mass balance between the early 1990s and mid–2000s (very high confidence) (Shepherd et al., 20121008; Schrama et al., 20141009; Velicogna et al., 20141010; van den Broeke et al., 20161011; Bamber et al., 20181012; King et al., 20181013; Sandberg Sørensen et al., 20181014; WCRP, 20181015). {3.2.1.1; 3.2.4.2; 3.2.4.3; 3.4.3.3.2; 3.5.2.7} Permafrost temperatures have increased to record high levels (very high confidence), but there is medium evidence and low agreement that this warming is currently causing northern permafrost regions to release additional methane and carbon dioxide. These features make the overlying ice sheet vulnerable to dynamical instabilities with the potential to cause rapid ice loss; so-called Marine Ice Sheet and Marine Ice Cliff instabilities, as discussed below. Model projections remain uncertain and affected by the resolution of local ocean physics, which leads to overall medium confidence in the timing of undersaturation and hypercapnia. 3.2.3 Impacts on Marine Ecosystems 3.2.3.1 Arctic Climate change has, and is projected to continue to have, significant implications for Arctic marine ecosystems, with consequences at different trophic levels both in the pelagic, benthic, and sympagic (sea ice related) realms (Figure 3.5). In comparison, the Northwest Passage and Arctic Bridge presently have limited port and marine transportation infrastructure, incomplete soundings and hydrographic charting, challenging sea ice conditions and limited search and rescue capacity; these compound the risks from shipping activity (Stephenson et al., 2013905; Johnston et al., 2017906; Andrews et al., 2018907). Future shipping impacts will be regionally diverse considering the unique geographies, sea ice dynamics, infrastructure and service availability and regulatory regimes that exist across different Arctic nations. Moving toward a dual focus of short- and long-term adaptation involves knowledge co-production, linking knowledge with decision making and implementing ecosystem-based stewardship, which involves the transformation of many existing institutions (high confidence). Thus far, the initiative has supported new regional-to-international networks, and proposals for its expansion. This contrast is maintained by a combination of strong westerly winds and ocean heat loss south of the ACC. Trends in the atmospheric forcing of the Southern Ocean are dominated by a strengthening of westerly winds in recent decades (Swart et al., 2015a332), but there is no evidence that this enhanced wind stress has significantly altered the ACC transport. The remaining ~40% of non-SMB GIS mass loss from 1991 to 2015 has resulted from increased ice discharge due to dynamic thinning (high confidence) (Enderlin et al., 20141062; van den Broeke et al., 20161063; King et al., 20181064) (Figure 3.7). Harvesters of renewable resources are adjusting timing of activities to changes in seasonality and less safe ice travel conditions. Half came from only four glaciers (Jakobshavn Isbræ, Kangerdlugssuaq, Koge Bugt, and Ikertivaq South) (Enderlin et al., 20141066). Greater ship activity in the Southern Ocean may also present a risk for increasing introduction of non-native marine species, with the potential for these species to become invasive with changing environmental conditions (McCarthy et al., 20191785). Satellite measurements of eddy kinetic energy over the last two decades are consistent with this, showing a statistically significant upward trend in eddy energy in the Pacific and Indian Ocean sectors of the Southern Ocean (Hogg et al., 2015338) (medium confidence). These projected increases are due to enhanced snowfall (Krasting et al., 20131534) from a more moisture-rich Arctic atmosphere coupled with winter season temperatures that remain sufficiently low for precipitation to fall as snow. There is medium confidence that the amount of CO_2 drawn into the Southern Ocean from the atmosphere has experienced significant decadal variations since the 1980s. There is high confidence that projected snow cover declines are proportional to the amount of future warming in each model realisation (Thackeray et al., 20161528; Mudryk et al., 20171529). Although manifested locally, these very different future polar environments have the potential to continue/accelerate the global impacts noted above. 3) Choices are available that will influence the nature and magnitude of changes, potentially limiting their regional and global impacts and increasing the effectiveness of adaptation actions. Compared with high greenhouse gas emissions scenarios, projections using low emissions scenarios result in polar regions that will be significantly less altered. Cooperation in the Antarctic also occurs through the the Convention for the Conservation of Antarctic Marine Living Resources. Climate change has contributed to modifying the balance between the interests of state and non-state actors, leading to changing forms of cooperation (Young, 20162146). Expansion of winter sea ice in the Arctic is limited by land, and ice circulates within the central Arctic basin, some of which survives the summer melt season to form multi-year ice. The release of carbon dioxide and methane from the land to the atmosphere further contributes to global warming. In that case they can enjoy sovereign rights beyond the EEZ. For instance, in Canada this effort has included training, information resources, frameworks, general outreach and education and dissemination of information to decision makers (Austin et al., 20152106). For example, several studies have shown that the Convention on the Protection of the Marine Environment of the North East Atlantic, which applies only to the North East Atlantic, and that provides a framework for implementation of the United Nations Convention on the Law of the Sea (UNCLOS) and the Convention on Biological Diversity (CBD), are insufficient to deal with risks when applying a precautionary approach (Jakobsen, 20142157; Hossain, 20152158). In the Arctic, responses to climate change do not only lead to international governance cooperation but also to competition in access to natural resources, especially hydrocarbons. Positive Arctic snow water equivalent changes emerge across the eastern Eurasian Arctic by mid-century for both RCP4.5 and RCP8.5 (Brown et al., 20171532) (medium confidence). A MICI-style behaviour is seen today in Greenland at the termini of Jakobshavn and Helheim glaciers (Parizek et al., 20191349), but calving of these narrow outlets is controlled by a combination of ductile and brittle processes, which might not be representative examples of much wider Antarctic outlet glaciers, like Thwaites. Overall, this assessment finds that unstable retreat and thinning of some Antarctic glaciers, and to a lesser extent Greenland outlet glaciers, may be underway. However, the timescale and future rate of these processes is not well known, casting deep uncertainty on projections of the sea level contributions from the AIS (Cross-Chapter Box 5 in Chapter 1, Section 4.2.3.1). Terrestrial snow cover is a defining characteristic of the Arctic land surface for up to nine months each year, with changes influencing the surface energy budget, ground thermal regime and freshwater budget. (2018)217 suggest that the response of the jet stream to future Antarctic sea ice loss may in fact be less seasonal than the response to Arctic sea ice loss. Engineering adaptation provide proportionally similar cost savings no matter which emission scenario was used. Under RCP8.5, melting ice causes the greatest declining rate of pH and $CaCO_3$ saturation state in the Central Arctic, Canadian Arctic Archipelago and Baffin Bay (Popova et al., 2014504). By 2050, 70% of Arctic infrastructure is located in regions at risk from permafrost thaw and subsidence; adaptation measures taken in advance could reduce costs arising from thaw and other climate change related impacts such as increased flooding, precipitation, and freeze-thaw events by half (medium confidence). The CMIP5 models project with high confidence that thaw depth will increase and areal extent of near-surface permafrost will decrease substantially (Koven et al., 20131535; Slater and Lawrence, 20131536) (Figure 3.10). The IMO has prohibited the use of heavy fuel oil in the Antarctic. Mass gains due to increased snowfall have somewhat offset dynamic-thinning losses (high confidence). There is only low to medium confidence in the current nature of Arctic/mid-latitude weather linkages because conclusions of recent analyses are inconsistent (National Research Council, 2014189; Barnes and Polvani, 2015190; Francis, 2017191). Projected future reductions in summer sea ice (Section 3.2.1.1), increased stratification in summer, shifting currents and fronts and increased ocean temperatures (Section 3.2.2.2) and ocean acidification (Section 3.2.2.3) are all expected to impact the future production and distribution of several marine fish and invertebrates (high confidence). Ocean acidification (Section 3.2.2.3) will affect several key Arctic species (medium confidence). This system contributes fresh water and nutrients to the ocean (Section 3.3.3.3) (Fricker et al., 20071000; Siegert et al., 20071001; Carter and Fricker, 20121002; Horgan et al., 20131003; Le Brocq, 20131004; Flament et al., 20141005; Siegert et al., 20161006), and lubricates glacier sliding (e.g., Dow et al., 2018b). In some cases, relocation of human settlements will be required, necessitating more formal methods of assessing relocation needs and identifying sources of funding to support relocations (Cross-Chapter Box 9) (high confidence). Mesoscale eddies are characterised by horizontal scales of ~10 km in the Arctic, and are important components of the ocean system. Future changes in the strength of this ocean circulation can so far only be projected with limited certainty. These agreements can, if adequately implemented, reduce risks from increased Arctic shipping (medium confidence), however, developing more effective measures is needed as preparedness and response gaps still exist, for example, for the central Arctic Ocean. Data of sufficiently high resolution is limited in the boundary regions of the Arctic Ocean, precluding estimates of eddy variability on a basin-wide scale. On islands adjacent to the AP, glaciers experienced retreat and mass loss during the mid to late 20th century, but since around 2009 there has been a reduction in mass loss rate or a return to slightly positive balance (Navarro et al., 2017; Oliva et al., 2017). This suggests that bias reduction against observed historical metrics (Russell et al., 2018365) in future generations of coupled models (e.g., Coupled Model Intercomparison Project Phase 6 (CMIP6)) should lead to improved confidence in aspects of projected Southern Ocean changes. Cassotta, C. Increasingly, climate change is considered in environmental assessments and proposals for resource planning of polar regions. A comprehensive literature review of 157 discrete cases of Arctic adaptation initiatives by Ford et al. Because of the abundance of marine food resources including seals, whales and fish in and around polynyas, Arctic peoples have hunted regularly in these areas for thousands of years (Barber and Massom, 2007444). {3.2.1.2.4} Both polar oceans have continued to warm in recent years, with the Southern Ocean being disproportionately and increasingly important in global ocean heat increase (high confidence). Although the sign of model changes appear mostly robust, there is low confidence in magnitude due to the large inter-model spread in projections and significant warm biases in historical water mass properties (Sallée et al., 2013a499) and sea surface temperature, which may be up to 3°C too high in the historical runs (Wang et al., 2014500). AIS snowfall increased by 4 ± 1 then 14 ± 1 Gt per decade over the 19th and 20th centuries, of which EAIS contributed 10% (Thomas et al., 2017b990). Longer and improved quantifications of their changes are required, especially where mass losses are greatest, and (relatedly) better attribution of natural versus anthropogenic drivers. Among the risks to societies and economies, aspects of food provision, transport and access to non-renewable resources are of great importance. only products) and mutual respect for cultural differences (Meadow et al., 2015; National Research Council, 2015; Petrov et al., 2016) (high confidence). The increase in sea surface height is ascribed largely to warming-driven steric expansion in the upper ocean, but the mechanism driving such warming is still uncertain (Gille, 2014348). To achieve this, the chapter draws on the body of literature and assessments pertaining to climate-induced dynamics and functioning of the polar regions published since the AR5, which has expanded considerably motivated in large part by growing appreciation of the importance of these regions to planetary systems and to the lives and livelihoods of people across the globe. This is a critical weakness in sustained observations of the global ocean. Further uncertainty derives from increased meltwater from the AIS not being considered in the CMIP5 climate models, despite its potential for significant impact on Southern Ocean dynamics and the global climate, and its potential for positive feedbacks (Bronselaer et al., 2018371). For Antarctica, there is high agreement based on medium evidence that ice shelf retreat or collapse is leading to new marine habitats and to biological colonisation (Gutt et al., 20111302; Fillinger et al., 20131303; Trathan et al., 20131304; Hauquier et al., 20161305; Ingels et al., 20181306). Over recent decades the SAM has exhibited a positive trend during austral summer, indicating a strengthening of the surface westerly winds around Antarctica. On Arctic land, northward range expansions have been recorded in species from all major taxon groups based both on scientific studies and local observations (high confidence) (CAFF, 2013a1789; AMAP, 2017a1790; AMAP, 2017b1791; AMAP, 20181792). A regional process-model study of Alaska projected annual median area burned during the 21st century to be 1.3-1.7 times higher compared with the historical average (Pastick et al., 20171544). There is medium agreement but limited evidence of anthropogenic forcing of AIS mass balance through both SMB and glacier dynamics (low confidence). There is low confidence in projections of Antarctic sea ice because there are multiple anthropogenic forcings (ozone and greenhouse gases) and complicated processes involving the ocean, atmosphere, and adjacent ice sheet (Section 3.2.1.1.). Enabling conditions for the involvement of local communities in climate adaptation planning include investments in human capital, engagement processes for knowledge co-production and systems of adaptive governance. Examples of this include: American mink (Neovison vison) and Nootka lupin (Lupinus nootkatensis) in Arctic western Eurasia, Greenland and Iceland that are already causing severe problems to native fauna and flora (CAFF and PAME, 2017). The increasing imprint of human development, such as flow regulation on major northerly flowing rivers adds complexity to the determination of climate-driven changes. (2013)349 led to AR5 erroneously reporting the upper cell to have slowed (AR5 WGI, Section 3.6.4). There is high confidence that shipping activity during the Arctic summer increased over the past two decades in regions for which there is information, concurrent with reductions in Arctic sea ice extent and the shift to predominantly seasonal ice cover (Pizzolato et al., 2014887; Eguíluz et al., 2016888; Pizzolato et al., 2016889). Similarly, there are knowledge gaps on the extent to which changes in the availability of resources to subsistence harvesters affects food security of households. There is a need to better understand the evolution of polar glaciers and ice sheets, and their influences on global sea level. {3.5.3, 3.5.4} This chapter provides an integrated assessment of climate change across the physical, biological and human dimensions of the polar regions, based on emerging understanding that assessing these dimensions in isolation is not sufficient or forward-looking. The expected overall result of these shifts and limits will be a loss of biodiversity (CAFF, 2013a1807; CAFF, 2013b1808; AMAP, 20181809) (medium confidence). Almost all Antarctic ice shelves provide substantial buttressing (Fürst et al., 20161316) but some are currently thinning at an increasing rate (Khazendar et al., 20161317). In Antarctica, marine-terminating ice margins with the grounding lines thick enough to produce unstable ice cliffs are currently buttressed by ice shelves, with a possible exception of Crane glacier on the Antarctic Peninsula (Section 4.2.3.1.2). Overall, there is low agreement on the exact MICI mechanism and limited evidence of its occurrence in the present or the past. Data sources are as per Table SM3.1. The mean proportion and its 5–95% confidence interval (1.65 times standard deviation of individual estimates) are in the last column. Such practices are most effective when linked closely to the policy process. 1) Climate-induced changes to the polar cryosphere and oceans have global consequences and impacts. Loss of Arctic sea ice continues to add to global radiative forcing and has the potential to influence mid-latitude weather on timescales of weeks to months (Section 3.2.1 Box 3.2), the Southern Ocean takes up a disproportionately high amount of atmospheric heat and carbon (Section 3.2.1), melting polar glaciers and the AIS and GIS contribute to observed and projected sea level rise long into the future (Sections 3.3.1, 3.3.2), and projected widespread disappearance of permafrost has the potential to accelerate global warming through the release of carbon dioxide and methane (Sections 3.4.2, 3.4.3). This is due in part to the high abundance and circumpolar distribution of Antarctic krill, although the abundance and importance of this species varies between different regions of the Southern Ocean (Larsen et al., 2014685; Siegel, 2016686; McCormack et al., 2017687). Range shifts have also been observed in the Bering Sea since 1993, with warm bottom temperatures being associated with range contractions of Arctic species, and range expansions of sub-arctic species, with responses dependent on species specific vulnerably (Alabia et al., 20181771; Stevenson and Lauth, 20181772). Available evidence indicates that the volume of Antarctic Bottom Water in the global ocean has decreased (Purkey and Johnson, 2013353; Desbruyeres et al., 2017354) (medium confidence), thinning at a rate of 8.1 m yr−1 since the 1950s (Azaneu et al., 2013355); recently updated analyses confirm this trend to present day (Figure 5.4). Arctic sea ice variability and impacts on communities includes indigenous knowledge and local knowledge from across the circumpolar Arctic (Cross-Chapter Box 3 in Chapter 1). Furthermore, there is now high confidence that for most of the GIS, increased surface melt has not led to sustained increases in glacier flux on annual timescales because subglacial drainage networks have evolved to drain away the additional water inputs (e.g., Sole et al., 2013; Tedstone et al., 20151068; Stevens et al., 20161069; Nienow et al., 20171070; King et al., 2018). Petzold, B. Some require more refinement while others are well developed. The MISI process might be particularly important in West Antarctica, where most of the ice sheet is grounded on bedrock below sea level (Figure 4.5). Theoretical predictions and high-resolution ocean modelling suggest that the weak sensitivity of the ACC to changes in wind stress is a consequence of eddy saturation (Munday et al., 2013337), whereby the time-mean state of the ocean remains close to a marginal condition for eddy instability and hence additional energy input from stronger winds cascades rapidly into the smaller-scale eddy field. This is further complicated by the northward expansion of the summer ranges of a variety of temperate whale species, documented recently in both the Pacific and Atlantic sides of the Arctic (Brower et al., 20171756; Storrie et al., 20181757) and increasing pressure from anthropogenic activities. {3.5.1, 3.5.2, 3.5.4} Institutional arrangements that provide for strong multiscale linkages with Arctic local communities can benefit from including indigenous knowledge and local knowledge in the formulation of adaptation strategies (high confidence). Between 2003 and 2014, the strength of some currents in the Beaufort Gyre approximately doubled (Armitage et al., 2017323). 3.2.1.3 Ocean Circulation The major elements of Southern Ocean circulation are assessed in Cross-Chapter Box 7 in Chapter 3; Arctic Ocean circulation is considered here. There is low confidence in changes to snow properties such as density and stratigraphy (relevant for understanding the impacts of changes to Arctic snow on ecosystems) which are not resolved directly by climate model simulations, but require detailed snow physics models. Key findings are: The polar regions are losing ice, and their oceans are changing rapidly. In some Arctic areas, such expansions have affected the whole

fish community, leading to higher competition and predation on smaller sized fish species, while some commercial fisheries have benefited. Over the same period in Antarctic and subantarctic regions, glaciers separate from the ice sheets changed mass by –11 ± 108 Gt yr-1 (low confidence). The role of precipitation biases is not well understood (Thackeray et al., 20161526). Of these, reduced SMB due to an increase in surface melting and runoff recently came to dominate (high confidence) (Andersen et al., 20151019; Fettweis et al., 20171020; van den Broeke et al., 20171021; King et al., 20181022), accounting for 42% of losses for 2000–2005, 64% for 2005–2009 and 68% for 2009–2012 (Enderlin et al., 20141023) (Figure 3.7). The GIS was close to balance in the early years of the 1990s (Hanna et al., 20131024; Khan et al., 20151025), the interior above 2000 m altitude gained mass from 1961 to 1990 (Colgan et al., 20151026) and both coastal and ice sheet sites experienced an increasing precipitation trend from 1890 to 2012 and 1890 to 2000 respectively (Mernild et al., 20151027), but since the early 1990s multiple observations and modelling studies show strong warming and an increase in runoff (very high confidence). The effectiveness of this approach, however, is increasingly challenged as the ranges and populations of species and state of ecosystems are being affected by climate change (Chapin III et al., 20102291; Chapin III et al., 20152292). It has been argued that freshening from glacial melt can enhance basal melting of ice shelves by reducing dense water production and modulating oceanic heat flow into ice shelf cavities (Silvano et al., 20181246). There are a number of mechanisms standardising regulation and governance, such as the International Convention for the Prevention of Pollution from Ships; the International Convention for the Safety of Life at Sea; the International Convention on Standards of Training, and the Certification and Watchkeeping for Seafarers, and the newly implemented International Code for Ships Operating in Polar Waters, or Polar Code (IMO, 2017). The tourism sector relies on a set of regulations that apply to all types of maritime shipping, yet cruise ships intentionally travel off regular shipping corridors and serve a very different purpose than other vessel types, so there is a need for region-specific governance regimes, specialised infrastructure, and focused policy attention (Dawson et al., 2014882; Pashkevich et al., 2015883; Pizzolato et al., 2016884; Johnston et al., 2017885). Similarly, a variety of methods applied to satellite data have found no long-term trend and no statistically significant correlation of ACC position with winds (Gille, 2014343; Chapman, 2017344; Chambers, 2018345). Such connections, however, are only episodic (Cohen et al., 2018201). Several efforts have also been undertaken to provide assessment frameworks and protocols for settlement relocation as an adaptive resource (Bronen, 20152065; Ristroph, 20172066). Summer melting of the Greenland Ice Sheet (GIS) has increased since the 1990s (very high confidence) to a level unprecedented over at least the last 350 years, and two-to-fivefold the pre-industrial level (medium confidence). Fire is projected to increase for the rest of this century across most tundra and boreal regions, while interactions between climate and shifting vegetation will influence future fire intensity and frequency (medium confidence). Consistent results for lower Atlantic Water layer warming were found by Koenigk and Brodeau (2014)485 for RCP2.5 (0.5°C), RCP4.5 (1.0°C) and RCP8.5 (2.0°C). Changes in distribution and abundance of resources. The rate and severity of ecosystem impacts will be spatially heterogeneous and dependent on future emission scenarios. There is medium confidence in an overall freshening trend and low confidence that this is accelerating, given the sparsity of information and significant interannual variability in Antarctic Bottom Water properties at other export locations (Meijers et al., 20161238). The related increase in stratification has the potential to contribute to the warming of the deep Atlantic Water layer, as upward vertical mixing will be reduced (Nummelin et al., 2016492). The anticipated implications of future climate change have become a driver for polar tourism. In practice, however, the full set of challenges has meant more Yamal herders opting out of the traditional collective migration partially or entirely to manage their herds privately. This process maintains the Arctic Ocean halocline (Bauch et al., 2011435), which insulates the sea ice cover from the heat of the underlying Atlantic-derived waters. Relatively few invasive alien species are presently well established in the Arctic, but many are thriving in the subarctic and may expand as a result of climate change (CAFF, 2013a1813; CAFF, 2013b[). In the central basin regions, a statistically significant higher concentration of eddies was sampled in the Canadian Basin compared to the Eurasian Basin between 2003 and 2014; further, a medium correspondence was found between eddy activity in the Beaufort Gyre region and intensified gyre flow (Zhao et al., 2014327; Zhao et al., 2016328). Such export of both extremely cold and dense Antarctic Bottom Water and the lighter mode and intermediate waters (Figure CB7.1) represents important pathways for surface properties to be sequestered from the atmosphere for decades to millennia. Reduction or loss of ice shelf buttressing has dominated AIS dynamic thinning (high confidence). An increase in the ice-free area linked to glacier retreat in Antarctica is expected to increase the area available for new terrestrial ecosystems (Lee et al., 2017a1821). There is growing evidence that ongoing changes in the Arctic, primarily sea ice loss, can potentially influence mid-latitude weather. A systems approach was taken to assess individual and interacting changes within and between these elements to consider consequences, impacts and risks for marine and terrestrial ecosystems and for people. Furthermore, the geographic distribution of publicly available documentation on adaptation initiatives is skewed in the Arctic, with more than three-quarters coming from Canada and USA (Ford et al., 2014a2101; Loboda, 20142102). Many Arctic health adaptation efforts by governments have been groundwork actions, focused increasing awareness of the health impacts of climate change and conducting vulnerability assessments (Lesnikowski et al., 20112103; Panic and Ford, 20132104; Austin et al., 20152105). This section presents the status of practices, tools and strategies currently employed in the Arctic and or Antarctica that can potentially contribute to climate resilient pathways. Given the high amount of residual macronutrients in polynya surface waters, there is evidence that future changes in ice shelf melt rates could increase water column productivity (Gerringa et al., 2015468; Rickard and Behrens, 2016469; Kaufman et al., 2017470), influencing Antarctic coastal ecosystems and increasing the ability of continental shelf waters to sequester atmospheric carbon dioxide (Arrigo and van Dijken, 2015471). At the same time as these northward expansions or shifts, a number of populations of species as different as polar bear and Arctic char show range contraction or population declines (Winfield et al., 20101761; Bromaghin et al., 20151762; Laidre et al., 20181763). In the Canada Basin, projections using RCP8.5 show reductions in mean surface pH from approximately 8.1 in 1986–2005 to 7.7 by 2066–2085, and aragonite saturation from 1.52–0.74 during the same period (Steiner et al., 2014505). Ice shelf collapse has driven dynamic thinning in the northern AP over recent decades (high confidence) (Seehaus et al., 2015973; Wuite et al., 2015974; Friedl et al., 2018975; Rott et al., 2018976). The recent calving of Mertz Glacier Tongue in East Antarctica has altered sea ice and ocean stratification (Fogwill et al., 2016462) such that polynyas there are now twice as productive (Shadwick et al., 2017463). The productivity associated with these polynyas is a critical food source for some of the most abundant top predators in Antarctic waters, including penguins, albatross and seals (Raymond et al., 2014464; Malpress et al., 2017465) (Section 3.2.3.2.4). Changes in the timing, duration and intensity of primary production have occurred in both polar oceans, with marked regional or local variability (high confidence). Better understanding of the sensitivity of Antarctica to marine ice sheet instability is required, and whether recent changes in West Antarctica represent the onset of irreversible change. Management responses will also need to adapt to the effects of future changes in sea ice extent and duration on the spatial distribution of fishing operations (ATCM, 2017; Jabour, 2017) (Section 3.2.4). As ice shelves retreat, the polynyas created in their wake also increase local primary production: the new polynyas created after the collapse of the Larsen A and B ice shelves are as productive as other Antarctic shelf regions, likely increasing organic matter export and altering marine ecosystem evolution (Cape et al., 2013461). It is very likely that projected Arctic warming will result in continued loss of sea ice and snow on land, and reductions in the mass of glaciers. This subset of models also showed large reductions of near-surface permafrost area, averaging a 90% loss (12.7 ± 5.1×106 km2) of permafrost area by 2300 for RCP8.5 and 29% loss (4.1 ± 0.6×106 km2) for RCP4.5, with much of that long-term loss already occurring by 2100. Totten's current behaviour suggests that East Antarctica could become a substantial contributor to future sea level rise, as it has been in the previous warm periods (Aitken et al., 20161325). The ice shelves are thus a key factor controlling AIS dynamics. These past rapid changes have likely been driven by the incursion of Circumpolar Deep Water onto the Antarctic continental shelf (Section 3.3.1.5.1) (Golledge et al., 20141338; Hillenbrand et al., 20171339) and MISI (Jones et al., 2015b1340). During this period, glacier mass loss was largest in the periphery of Greenland (–47 ± 16 Gt yr–1), followed by Arctic Canada North (-39 ± 8 Gt yr–1), Arctic Canada South (–33 ± 9 Gt yr–1), the Russian Arctic (–15 ± 12 Gt yr–1) and Svalbard and Jan Mayen (–9 ± 5 Gt yr–1). Both the WAIS (including Pine Island glacier) and EAIS also experienced rapid thinning and grounding line retreat during the early to mid-Holocene (Jones et al., 2015b1334; Wise et al., 20171335). Glaciers in all other regions including Alaska, Scandinavia and Iceland are assessed in Chapter 2. Changes in the mass of Arctic glaciers for the 'present day' (2006–2015) are assessed using a combination of satellite observations and direct measurements (Figure 3.8; Appendix 2.A, Table 1). In addition to national management, the Joint Norwegian-Russian Fisheries Commission provides cooperative management of the most important fish stocks in the Barents and Norwegian Seas. These changes have the potential to alter biodiversity in polar marine and terrestrial ecosystems (Frenot et al., 20051753; Frederiksen, 20171754; McCarthy et al., 20191755) (medium confidence). Potential Arctic/mid-latitude interactions have a more regional tropospheric pathway in November to December (Honda et al., 2009205; Chen et al., 2016a206; McKenna et al., 2018207), whereas January to March has a more hemispheric stratospheric pathway involving migration of the polar vortex off of its usual centred location on the North Pole (Cohen et al., 2012208; Nakamura et al., 2016209; Zhang et al., 2018b210). Over large sectors of the seasonally ice-free Arctic, summer upper mixed layer temperatures increased at around 0.5°C per decade during 1982–2017, primarily associated with increased absorbed solar radiation accompanying sea ice loss, and the inflow of ocean heat from lower latitude increased since the 2000s (high confidence). Rates of calcification (by which marine organisms form hard skeletons and shells) declined in the Southern Ocean by 3.9 ± 1.3% between 1998 and 2014. These increases in investments are occurring in spite of the limited total savings when comparing shorter travel to increased CO_2 emissions (Lindstad et al., 2016). Commercial shipping mainly uses heavy fuel oil, with associated emissions of sulphur, nitrogen, metals, hydrocarbons, organic compounds, black carbon and fly ash to the atmosphere during combustion (Turner et al., 2017a913). In contrast to the Arctic, the Antarctic continent has seen less uniform temperature changes over the past 30–50 years, with warming over parts of West Antarctica and no significant overall change over East Antarctica (Nicolas and Bromwich, 2014; Jones et al., 2016; Turner et al., 2016), though there is low confidence in these changes given the sparse in situ records and large interannual to interdecadal variability. While winds have strengthened over the Southern Ocean, reanalysis products show no significant shift in the annual mean latitude of zonal wind jets between 1979–2009 (Swart et al., 2015a342). Sommerkorn, S. Laura Gerrish (UK) is thanked for help with figure preparation. Climate-driven environmental changes are affecting local ecosystems and influencing travel, hunting, fishing and gathering practises. Inclusion of MICI in one ice sheet model has improved its ability to match (albeit uncertain) geological sea level targets in the Pliocene (Pollard et al., 20151343) and Last Interglacial (DeConto and Pollard, 20161344), although the MICI solution may not be unique (Aitken et al., 20161345) (Section 4.2.3.1.2). {3.2.1; 3.2.3, 3.2.4} In both polar regions, climate-induced changes in ocean and sea ice, together with human introduction of non-native species, have expanded the range of temperate species and contracted the range of polar fish and ice-associated species (high confidence). In 2009, a new Marine Resources Act entered into force for Norway's EEZ. For stabilised global warming of 1.5°C, an approximately 1% chance of a given September being sea ice free at the end of century is projected; for stabilised warming at a 2°C increase, this rises to 10–35% (high confidence). Reductions in Arctic sea ice extent scale linearly with both global temperatures and cumulative CO_2 emissions in simulations and observations (Notz and Stroeve, 2016379), although aerosols influenced historical sea ice trends (Gagné et al., 2017380). {3.2.1.1} Shipping activity during the Arctic summer increased over the past two decades in regions for which there is information, concurrent with reductions in sea ice extent (high confidence). At the other end of the Arctic zonal range, a temperature increase of only 1°C –2°C in the northernmost subzone may allow the establishment of woody dwarf shrubs, sedges and other species into bare soil areas that may radically change its appearance and ecological functions (Walker et al., 20151811; Myers-Smith et al., 20191812) (medium confidence). Range expansions also include the threat from alien species brought in by humans to become invasive and outcompete native species. Adding to uncertainty in human choice related to climate change is the interaction of climate with other forces for change, such as globalisation and land and sea-use change. And while there has been a general movement to greater urbanisation in the Arctic (AHDR, 2014), that trend is not true for all regions (Heleniak, 2014). Ordinary Least Square (OLS) method is used; units are 1021 J yr-1. Summary of the assessment of practices, tools and strategies that can contribute to climate resilient pathways. There is medium evidence but with low agreement whether the level and timing of increased plant growth and replenishment of soil will compensate these permafrost carbon losses. The consequences of this polar transition extend to the whole planet, and are affecting people in multiple ways Arctic surface air temperature has likely increased by more than double the global average over the last two decades, with feedbacks from loss of sea ice and snow cover contributing to the amplified warming. Fisheries in the polar oceans support regional and global food security and are important for the economies of many countries around the world, but climate change alters Arctic and Antarctic marine habitats, and affects the ability of polar species and ecosystems to withstand or adapt to physical changes. As spring snow and summer sea ice cover decrease, more heat is absorbed at the surface. ASE ice shelf basal melting, grounding line retreat and dynamic thinning have varied with ocean forcing (medium confidence) (Dutrieux et al., 2014977; Paolo et al., 2015978; Christianson et al., 2016979; Jenkins et al., 2018980) but this variability is superimposed on sustained mass losses compatible with the onset of Marine Ice Sheet Instability (MISI) for several major glaciers (medium confidence) (Favier et al., 2014981; Joughin et al., 2014982; Mouginot et al., 2014983; Rignot et al., 2014984; Christianson et al., 2016985). Experimenting, assessing, and continually refining practices while strengthening the links with decision making has the potential to ready society for the expected and unexpected impacts of climate change (high confidence). The Polar Code of 2017 sets new standards for vessels travelling in polar areas to mitigate environmental damage and improve safety (IMO, 2017). An area of response not elaborated in this assessment is geoengineered sea ice remediation to support local-to-regional ecosystem restoration and which may also affect climate via albedo changes. Renewable resource management and biodiversity conservation that seek to maintain resources in historic levels and reduce uncertainty before taking action remains the dominant paradigm in polar regions (Chapin III et al., 20092289; Forbes et al., 20152290). The rest sinks to the seafloor where it is re-mineralised or sequestered (Shadwick et al., 2017466), or is advected off the shelf (Lee et al., 2017b467). In many cases there is limited information on human responses to climate change in the Russian Arctic. {3.4.2; 3.4.3} Projected permafrost thaw and decrease in snow will affect Arctic hydrology and wildfire, with impacts on vegetation and human infrastructure (medium confidence). For instance, projected climate driven changes in ocean properties and hydrography (Section 3.2.2.2) and the abundance of pelagic grazers (Box 3.4) could alter the export of organic matter to the sea floor with associated impacts on the benthos in some Arctic shelf ecosystems (Moore and Stabeno, 2015522; Stasko et al., 2018523) (low confidence). The observed trend of increasing fire is projected to continue for the rest of the century across most of the tundra and boreal region for many climate scenarios, with the boreal region projected to have the greatest increase in total area burned (Balshi et al., 20091538; Kloster et al., 20121539; Wotton et al., 20171540). The polar regions influence the global climate through a number of processes. In the Arctic a number of fish species have changed their spatial distribution substantially over the recent decades (high confidence). Climate change impacts on vertical fluxes and stratification (Sections 3.2.1.2.3, 3.2.2.2) will contribute to changes in bentho-pelagic-sympagic coupling. CMIP5 models show a wide range of mean states and trends in Antarctic sea ice (Turner et al., 2013409; Shu et al., 2015410). However, this information will be important in enabling CCAMLR fisheries management to respond to the effects of climate change on krill and krill predators in the future. Commercial fisheries management responses to climate change impacts in the Southern Ocean may need to address the displacement of fishing effort due to poleward shifts in species distribution (Pecl et al., 2017) (Box 3.4) (low confidence). This chapter incorporates published indigenous knowledge and local knowledge for assessing climate change impacts and responses. These tools facilitate the assessment of Arctic oil-spill response capability, ice detection in low visibility, improved management of sea ice and icebergs, and numerical modelling of icing and snow as risk mitigation. At present health adaptation to climate change is generally under-represented in policies, planning, and programming (AHDR, 20142092). All of these routes offer significant trade benefits because they provide substantial distance savings compared to traditional routes via the Suez or Panama Canals. In the future, the ability to manage, respond, and adapt to climate-related health challenges will be a defining issue for the health sector in the Arctic (Ford et al., 20102126; Durkalec et al., 20152127) (medium confidence). Table 3.4: Response of key human sectors /systems to climate change in polar regions. The most recent examples of terrestrial vertebrates expanding northwards include a whole range of mammals in Yakutia, Russia (Safronov, 20161793), moose (Alces alces) into the Arctic region of both northern continents (Tape et al., 20161795) and North American beaver (Castor canadensis) in Alaska (Tape et al., 20181794). Negative-NAO wind patterns increased GIS melt observed in a 40-year runoff signal (Ahlstrom et al., 20171184), and an increase in melting beginning in the mid-1800s closely followed the onset of industrial era Arctic warming and emerged beyond the range of natural variability in the last few decades (Graeter et al., 20181185; Trusel et al., 20181186) (Section 3.3.1.4). The post-1990s period experienced the warmest GIS near-surface summer air temperatures of 1840–2010 (+1.1˚C) (statistically highly significant) (Box, 2013), and ice core analysis found the 2000–2010 decade to be the warmest for around 2000 years (Vinther et al., 20091031; Masson-Delmotte et al., 20121032), and possibly around 7000 years (Lecavalier et al., 20171033). Increased surface melt on Arctic glaciers has led to a positive feedback from lowered surface albedo, causing further melt (Box et al., 20121204), and in Svalbard, mean glacier albedo has reduced between 1979 and 2015 (Möller and Möller, 20171205). The potential for reduced but stabilised Arctic autumn and spring snow extent by mid-century for RCP2.6 contrasts with continued loss under RCP8.5, and the area with near-surface permafrost is projected to decrease less by 2100 under RCP2.6 than under RCP8.5 (Section 3.4.2). 3.2.1 Observed Changes in Sea Ice and Ocean 3.2.1.1 Sea Ice Sea ice reflects a high proportion of incoming solar radiation back to space, provides thermal insulation between the ocean and atmosphere, influences thermohaline circulation, and provides habitat for ice-associated species. There is high confidence that demand for Arctic cruise tourism will continue to grow over the coming decade (Johnston et al., 2017866). Runoff into the Arctic Ocean increased for Eurasian and North American rivers by 3.3 ± 1.6% and 2.0 ± 1.8% respectively (1976–2017; medium confidence). A discussion of the relocation of Alaska's coastal villages is found in Cross-Chapter Box 9. The ocean heat transport increases in all Arctic gateways, but is dominated by the Barents Sea, and when winter sea ice disappears here the heat loss cannot increase further and the excess ocean heat continues into the Arctic Basin (Koenigk and Brodeau, 2014490). The surface mixed layer of the Arctic Ocean is expected to freshen in future because an intensified hydrological cycle will increase river runoff (Haine et al., 2015491) (medium confidence). In some CMIP5 models, phases of Weddell polynya activity appear for decades or centuries at a time, and then cease for a similar period (Reintges et al., 2017482). GIS mass balance is characterised by large interannual variability (e.g., van den Broeke et al., 2017) but from 2005 to 2016, GIS was the largest terrestrial contributor to global sea level rise (WCRP, 20181017). A geodetic reconstruction of past ice sheet elevations indicates a GIS mass change of –75.1 ± 29.4 Gt yr–1 from 1900 to 1983, –73.8 ± 40.5 Gt yr–1 from 1983 to 2003, and –186.4 ± 18.9 Gt yr–1 from 2003 to 2010, with the losses consistently concentrated along the northwest and southeast coasts, and more locally in the southwest and on the large west coast Jakobshavn Glacier, though intensifying and spreading to the remainder of the coastal ice sheet in the latest period (Kjeldsen et al., 20151018). For the Southern Ocean, there is limited evidence for stratification changes in the post-AR5 period, and low confidence in how stratification changes are affecting sea ice and basal ice shelf melt. First, physical and ecosystem changes in the polar regions have socioeconomic impacts that extend across the globe. Recent evidence suggests that the ACC and its associated fronts and thermal gradients may be more permeable to biological dispersal than previously thought, with storm-forced surface waves and ocean eddies enhancing oceanographic connectivity for drift particles in surface layers of the Southern Ocean (Fraser et al., 20171783; Fraser et al., 20181784) (low confidence), but it is unclear whether this will be an increasingly important pathway under climate change. Considering indigenous knowledge and local knowledge facilitates cooperation in the development, identification, and decision making processes for responding to climate change in communities across the Arctic, and better understanding of the challenges facing Indigenous peoples. About 20% of Arctic land permafrost is vulnerable to abrupt permafrost thaw and ground subsidence, which is expected to increase small lake area by over 50% by 2100 for RCP8.5 (medium confidence). This extended positive phase of the SAM is unprecedented in at least 600 years, according to palaeoclimate reconstructions (Abram et al., 2014; Dätwyler et al., 2017) and is associated with cooler conditions over the continent. Consequently, climate change is inducing structural change over large spatial scales, leading to a borealisation ('Atlantification') of the European Arctic biological communities (Fossheim et al., 20151779; Kortsch et al., 20151780; Frainer et al., 20171781) (medium confidence). There is evidence based on population genetics that the ecosystem off Northeast Greenland could also become populated by a larger proportion of boreal species with ocean warming. Those described are well represented in the literature and have shown sufficient utility to merit further use (ARR, 2016; AMAP, 2017a; AMAP, 2017b; AMAP, 2018) (high confidence). There has been a rise in geopolitical debate regarding national and international level regulations and policies, and maritime infrastructure to support Arctic shipping development (Heininen and Finger, 2017; AMAP, 2018; Drewniak et al., 2018; Nilsson and Christensen, 2019). Climate change and its consequences for the marine environment are a central issue for this Convention because it challenges ways to regulate and manage fisheries and designate and manage Marine Protected Areas. Human responses to climate change in the Arctic and Antarctica are shaped by their unique physical, ecological, social, cultural and political conditions. Several factors explain the lack of outmigration, including an unwillingness to move, attachment to place, people's inability to relocate, the effectiveness of alternative ways of achieving acceptable outcomes and methods of buffering through subsidies (Huntington et al., 20182070) (medium confidence). Polynyas are projected to change in different ways depending on regional ice conditions and ice formation processes. Mass changes of glaciers in these regions between 2006 and 2015 (–90 ± 860 Gt yr–1) have low confidence as they are based on a single data compilation with large uncertainties in the Antarctic region (Zemp et al., 2019) (Figure 3.8). This causes heat loss to the atmosphere above 200 W m^{-2} (Campbell et al., 2019479). Commercially and ecologically important fish stocks like Atlantic cod, haddock and mackerel have expanded their spatial distributions northwards many hundreds of kilometres, and increased their abundance. This significant summer warming since the early 1990s increased GIS melt event duration (Mernild et al., 20171034) and intensity to levels exceptional over at least 350 years (Trusel et al., 20181035), and melt frequency to levels unprecedented for at least 470 years (Graeter et al., 20181036). Knowledge co-production involving Indigenous peoples comes with its own set of challenges (Armitage et al., 2011; Robards et al., 2018). The Arctic 5 and several other nations subsequently agreed to a treaty (the Central Arctic Ocean Fisheries Agreement) that imposed a 16-year moratorium on commercial fishing in the CAO. Although there is high agreement amongst models, contemporary biases in the fluxes of CO_2 in CMIP5 models in the Southern Ocean (Mongwe et al., 2018510) suggest medium confidence levels for these projections. Mechanisms for Arctic amplification are still debated, but include: reduced summer albedo due to sea ice and snow cover loss, the increase of total water vapour content in the Arctic atmosphere, changes in total cloudiness in summer, additional heat generated by newly formed sea ice across more extensive open water areas in the autumn, northward transport of heat and moisture and the lower rate of heat loss to space from the Arctic relative to the subtropics (Serreze and Barry, 2011; Pithan and Mauritsen, 2014; Goosse et al., 2018; Stuecker et al., 2018) (SM3.1.1). Response options exist that can ameliorate the impacts of polar change, build resilience and allow time for effective mitigation measures. These multiple perspectives encompass the polar regions as a source of resources, a key part of the global climate system, a place for preserving intact ecosystems, a place for international cooperation and, importantly, a homeland. Increased wind power input to the Arctic Ocean system can in principle be compensated by the production of eddy kinetic energy; analysis of observations in the Beaufort Gyre region suggest this is about as likely as not (Meneghello et al., 2017326). Concurrently, it assesses the local, regional and global consequences and impacts of individual and interacting polar system changes, and it assesses response options to reduce risk and build resilience in the polar regions. . The Polar Code, however, currently excludes fishing vessels and vessels on government service, thereby excluding many shipping activities, particularly in the Antarctic region (IMO, 2017). Also in Western Canada, the commercial fishery for Arctic char (Salvenius alpinus) in Cambridge Bay is co-managed by local Inuit organisations and Fisheries and Oceans Canada (DFO, 2014). Snow cover also interacts with vegetation, influences biogeochemical activity and affects habitats and species, with consequences for ecosystem services. The ability of models to simulate the processes controlling MISI has improved since AR5 (Pattyn, 20181342), but significant discrepancies in projections remain (Section 4.2.3.2) due to poor understanding of mechanisms and lack of observational data on bed topography, isostatic rebound rates, etc. Total ASE ice discharge increased by 77% since the 1970s (Mouginot et al., 2014953), primarily from acceleration of Pine Island Glacier that began around 1945, Smith, Pope and Kohler glaciers around 1980, and Thwaites Glacier around 2000 (Mouginot et al., 2014954; Konrad et al., 2017955; Smith et al., 2017c956). This halt in the increase in the uptake rate of CO_2 is linked to the combined feedbacks from well-understood reductions in buffering capacity and warming, as well as the increased upwelling rate of carbon-rich Circumpolar Deep Water (Hauck and Volker, 2015509) (Cross-Chapter Box 7 in Chapter 3). Even as the overall regional water cycle intensifies, including increased precipitation, evapotranspiration, and river discharge to the Arctic Ocean, decreases in snow and permafrost may lead to soil drying (medium confidence). Chapter 4 assesses the sea level impacts from observed and projected changes in ice sheets (Section 3.3.1) and polar glaciers (Section 3.3.2), including uncertainties related to marine ice sheets (Cross-Chapter Box 8 in Chapter 3). For instance, there is evidence of latitudinal partitioning between the four dominant mid-water species (Polar cod, saffron cod (Eleginus gracilis), capelin, and Pacific herring (Clupea pallasii)) in the Chuckchi and Northern Bering Sea, with Polar cod being most abundant to the north (De Robertis et al., 2017). There are critical gaps in knowledge concerning interactions between the atmosphere and specific elements of the polar ocean and cryosphere. In several cases, drivers of change interacting with climate change are regionally specific and not easily captured. Nicolai, A. While advancements have been made, the practice of knowledge co-production would benefit from further experimentation and innovation in methodologies and better training of researchers (van der Hel, 2016; Vlasova and Volkov, 2016; Berkes, 2017) (medium confidence). The current pan-Arctic trend of urbanisation (AHDR, 20142071), suggests that climate change responses related to infrastructure in towns and cities of the North will require significant adaptation in designs and increases in spending (Streletskiy et al., 20122072). The disappearance of ice shelves may allow the formation of ice cliffs, which may be inherently unstable if they are tall enough (subaerial cliff height between 100 and 285 m) to generate stresses that exceed the strength of the ice (Parizek et al., 20191327). Projected mass reductions for polar glaciers between 2015 and 2100 range from 16 ± 7% for RCP2.6 to 33 ± 11% for RCP8.5 (medium confidence). The Polar Code does not enhance enforcement capabilities or include environmental protection provisions to address a number of particular polar region-specific risks such as black carbon, ballast water and heavy fuel oil transport and use in the Arctic (Anderson, 2012; Sakhuja, 2014; IMO, 2017). This was caused by a wide range of model sensitivity in permafrost area to air temperature change, resulting in a large range of projected near-surface permafrost loss by 2100: 2–66% for RCP2.6 (24 ± 16%; likely range), 15–87% under RCP4.5 and 30–99% (69 ± 20%; likely range) under RCP8.5. A more recent analysis of near-surface permafrost trends from a subset of models that self-identified as structurally representing the permafrost region had a significantly smaller range of estimated present day near-surface permafrost area (13.1–19.3 x 106 km2; mean ± SD, 14.1 ± 3.5 x 106 km2) (McGuire et al., 20181537). Internal variability (Polvani and Smith, 2013412; Zunz et al., 2013413), and model sensitivity to warming (Rosenblum and Eisenman, 2017414) are also important sources of uncertainty. Adaptation at the local-scale is broad, ranging from community freezers to increase food security, to community-based monitoring programs to detect and respond to climate health events, to Elders mentoring youth in cultural activities to promote mental health when people are 'stuck' in the communities due to unsafe travel conditions (Pearce et al., 20102111; Brubaker et al., 20112112; Harper et al., 20122113; Brubaker et al., 20132114; Douglas et al., 20142115; Austin et al., 20152116; Bunce et al., 20162117; Cunsolo et al., 20172118) (high confidence). The seasonal cycles of pH and aragonite saturation will be attenuated (Kwiatkowski and Orr, 2018517) (Section 5.2.2.3), however when the mean state changes are combined with the changes in seasonality, the onset of undersaturation is brought forward by 10–20 years (Table SM3.5). This chapter assesses the state of physical, biological and social knowledge concerning the Arctic and Antarctic ocean and cryosphere, how they are affected by climate change, and how they will evolve in future. Relatedly, knowledge gaps exist concerning how fisheries target levels will change alongside environmental change and how to incorporate this into decision making. Assessing these impacts requires consideration of complex interconnected processes, many of which are incompletely observed. Changes in the ice sheet thickness can redistribute subglacial water, affecting drainage pathways and ice flow (Fricker et al., 20161007), but hydrological observations are very scarce. EAIS and WAIS snowfall increases offset 20th century sea-level rise by 7.7 ± 4.0 mm and 2.8 ± 1.7 mm respectively (Medley and Thomas, 2018989) (medium confidence). Rapid mass loss due to glacier flow acceleration in the Amundsen Sea Embayment (ASE) of West Antarctica and in Wilkes Land, East Antarctica, may indicate the beginning of Marine Ice Sheet Instability (MISI), but observational data are not yet sufficient to determine whether these changes mark the beginning of irreversible retreat. Understanding of precipitation in the polar regions is critically limited by sparse observations, and there is a lack of understanding of the processes that drive regional variability in wetting/drying and greening/browning of the Arctic land surface. In Antarctic marine systems, there is evidence of recent climate-related range shifts in the southwest Atlantic and West Antarctic Peninsula for penguin species (Pygoscelis papua and P. High-latitude warming is projected to drive earlier river ice break-up in spring due to both decreasing ice strength, and earlier onset of peak discharge (Cooley and Pavelsky, 20161572). Due to accessibility and convenience, these tourism operations are mostly based around the few ice-free areas of Antarctica, concentrated on the AP (Pertierra et al., 2017863). The role of cross-scale boundary organisations in climate change adaptation planning, and how central government initiatives can ultimately translate into 'hybrid' forms of adaptation at the local level that allow for actions that are sensitive to local communities has proven important in Norway (Dannevig and Aall, 2015). At the national level, Norway, Sweden and Finland have engaged in the European Climate Adaptation Platform (Climate-ADAPT), a partnership that aims to support Europe in adapting to climate change by helping users to access and share data and information on expected climate change in Europe, current and future vulnerability of regions and sectors, national and transnational adaptation strategies and actions, adaptation case studies and potential adaptation options, and tools that support adaptation planning. New information strengthens findings reported in WGII AR5 of ecologically and commercially important fish stocks having extended their habitats markedly to the north and east, concomitant to increased sea temperature and retreating sea ice. However, most terrestrial frozen water is stored in Antarctic and Greenland ice sheets, and future changes in their dynamics and mass balance will cause sea level rise over the 21st century and beyond (Section 4.2.3). Arctic forcing on the atmosphere from loss of sea ice and terrestrial snow is increasing, but the potential for Arctic/mid-latitude weather linkages varies for different jet stream patterns (Grotjahn et al., 2016192; Messori et al., 2016193; Overland and Wang, 2018a194). The future dynamic response of the AIS to warming will largely be determined by changes in ice shelves, because their thinning or collapse will reduce their buttressing capacity, leading to an acceleration of the grounded ice and to thinning of the ice margin. Opportunities for tourism vessels in the Arctic to contribute to international research activities ('ships of opportunity') may improve sovereignty claims in some regions, contribute to science and enhance education of the public (Stewart et al., 20132037; Arctic Council, 2015a2038; Stewart et al., 20152039; de la Barre et al., 2016). These costs do not include costs related to flooding and other stressors associated with warming or additional costs of commercial and industrial operations. In summary, both ocean forcing and surface melt affect ice shelf mechanical stability (high confidence), but the precise importance of the different mechanisms remains poorly understood and observed. Despite this complex ecosystem-based approach to fisheries management, it may not be possible to prevent projected declines of some high value species at high rates of global warming (Ianelli et al., 2016). In the Arctic, the status of Permanent Participants has enabled the effective participation of Indigenous Peoples in the work of the Council (Pincus and Ali, 20162145). As fire activity increases, flammable vegetation, such as the black spruce forest that dominates boreal Alaska, is projected to decline as it is replaced by low-flammability deciduous forest (Johnstone et al., 20111541; Pastick et al., 20171542). Current impacts associated with the observed increase in Arctic shipping include a higher rate of reported accidents per km travelled compared to southern waters (CCA, 2016), increases in vessel noise propagation (Halliday et al., 2017894) and air pollution (Marelle et al., 2016895). Arctic processes, such as discharge of freshwater from the Greenland Ice Sheet, have the potential to impact on the formation of the headwaters of the Atlantic Meridional Overturning Circulation (Section 6.7.1), and can impact on the structure and function of the marine ecosystem with implications for commercially-harvested species (Sections 3.2.3, 3.2.4). However, inverse analyses suggest that such overturning experiences significant inter-decadal variability in response to wind forcing, with reductions in 2000–2010 relative to 1990–2000 (DeVries et al., 2017352). Efforts were initiated with stakeholders in Arctic Canada to identify strategies that would lower risks (Pizzolato et al., 20162033); a next step to lower risks and build resilience is to further develop those strategies (AMAP, 2017a2034; AMAP, 2017b2035; AMAP, 20182036). However, ice loss from the AIS has continued to accelerate, driven primarily by increased melting of the underside of floating ice shelves, which has caused glaciers to flow faster. While the drivers of historical decadal variability are known with medium confidence, there is currently limited evidence and low agreement concerning causes of the strong recent decrease (2016–2018), and low confidence in the ability of current-generation climate models to reproduce and explain the observations. Approximately four million people currently reside in the Arctic with about three quarters residing in urban areas, and approximately 10% being Indigenous (AHDR, 2014). This upwelling and sinking constitutes a two-limbed overturning circulation, by which much of the global deep ocean is renewed. The Southern Ocean overturning circulation plays a strong role in mediating climate change via the transfer of heat and carbon (including that of anthropogenic origin) with the atmosphere (Sections 3.2.1.2; 5.2.2.2); it also has an impact on sea ice extent and concentration, with implications for climate via albedo (Section 3.2.1.1). Reductions in Arctic snow cover duration are projected by the CMIP5 multi-model ensemble due to later snow onset in the autumn and earlier snow melt in spring (Brown et al., 20171527) driven by increased surface temperature over essentially all Arctic land areas (Hartmann et al., 2013). Delayed freeze-up of sea ice in subarctic seas (Chukchi, Barents and Kara) acts as a positive feedback allowing warmer temperatures to progress further toward the North Pole (Kim et al., 2017). Fjords that have been studied in the subpolar western AP are hotspots of abundance and biodiversity of benthic macro-organisms (Grange and Smith, 20131314) and there is evidence that glacier retreat in these environments can impact the structure and function of benthic communities (Moon et al., 20151315; Sahade et al., 20151316) (low confidence). There is high confidence that the input of ice shelf meltwater has increased in the Amundsen and Bellingshausen Seas since the 1990s, but low confidence in trends in other sectors (Paolo et al., 20151233). Freshwater injected from the AIS affect water mass circulation and transformation, though sea ice dominates upper ocean properties away from the Antarctic ice shelves (Abernathey et al., 20161234; Haumann et al., 20161235). While in some cases Indigenous people are negatively impacted by sectoral activities such as mining and oil and gas development (Nymand and Fondahl, 2014), in other cases they benefit financially (Shadian, 2014), setting up dilemmas and potential internal conflicts (Huskey, 2018; Southcott and Natcher, 2018) (high confidence). A number of recent events in the Arctic indicate new extremes in the Arctic climate system. There is inadequate knowledge concerning carbon dioxide and methane emissions from land and sub-sea permafrost. There are clear regional gaps in knowledge of polar ecosystems and biodiversity, and insufficient population estimates/trends for many key species. Since AR5, however, substantial contrary evidence has emerged. From 2000 to 2016, dynamic thinning of 89% of GIS outlet glaciers accounted for –682 ± 31 Gt mass change, of which 92% came from the northwest and southeast GIS (King et al., 20181065). Similar displacements may take place within zones of the Arctic when low- and mid-Arctic species expand northward. As temperatures increase in the Arctic, permafrost soils in northern regions store less carbon. It is virtually certain that the Antarctic Peninsula (AP) and West Antarctic Ice Sheet (WAIS) combined have cumulatively lost mass since widespread measurements began in 1992, and that the rate of loss has increased since around the year 2006 and continued post-AR5 (Martín-Español et al., 2016915; Zwally et al., 2017916; Bamber et al., 2018917; Gardner et al., 2018918; The IMBIE Team, 2018; Rignot et al., 2019919), extending and reinforcing previous findings (IPCC, 2013920) (Figure 3.7, Table 3.3, SM3.3.1.1). Shortening windows of operation for use of ice roads; construction of all-season roads Weak regional and national economies, other disasters that divert resources, disinterest by southern-based law makers Marine Transportation Open seas allowing for more vessels; greater constraints in use of ice roads Increased shipping, tourism, more private vessels. The Antarctic continent is surrounded by sea ice which interacts with adjacent ice shelves; winter season expansion is limited by the influence of the Antarctic Circumpolar Current (ACC). Ship traffic has already increased and is projected to become more feasible in the coming decades as further reductions in sea ice cover make Arctic routes more accessible. Consistent with AR5, it is likely that Antarctic ozone depletion has been the dominant driver of the positive trend in the SAM during austral summer from the late 1970s to the late 1990s (Schneider et al., 2015; Waugh et al., 2015; Karpechko et al., 2018), the period during which ozone depletion was increasing. There is limited evidence that freshening occurred between 2003 and 2015 in North East Greenland fjords and coastal waters (Sejr et al., 20171230). Rather than treating regional impacts of climate change and their governance in isolation (i.e., purely with a regional lens), the need to cooperate in a global multi-regulatory fashion across several levels of governance is increasingly realised (Stokke, 20092141; Cassotta et al., 20162142) (medium confidence). For example, retrofitting and redesigning of infrastructure in order to handle increased precipitation and warmer temperatures can reduce climate-related costs by 50%, from USD 5.5 to 2.9 billion under RCP8.5 by 2100. Okem, J. Around half of the AIS bed melts (Siegert et al., 2017994), producing ~65 Gt yr–1 of water (Pattyn, 2010995) (low confidence), some of which refreezes (Bell, 2008996) and some accumulates in subglacial lakes with a total volume of 10s of 1000s of km3 (Popov and Masolov, 2007997; Lipenkov et al., 2016998; Siegert, 2017999). Transit times across the Northern Sea Route have shortened due to lighter ice conditions, and while long-term, pan-Arctic datasets are incomplete, the distance travelled by ships in Arctic Canada nearly tripled during 1990–2015 (high confidence). Authors: Robert M. Of even greater importance is novel evidence of distinct distributional changes at the community level (Fossheim et al., 20151776; Kortsch et al., 20151777; Frainer et al., 20171778) (Box 3.4 Figure 1). A comparative risk assessment for spills has been developed for the Arctic waters (Robinson et al., 2017) and Statoil has developed and uses risk assessment decision-support tools for environmental management, together with environmental monitoring (Utvik and Jahre-Nilsen, 2016). Extreme climatic conditions, remoteness from densely populated regions, limited human mobility, short seasons of biological productivity, high costs in monitoring and research, sovereignty claims to lands and waters by southern-based governments, a rich diversity of indigenous cultures and institutional arrangements that in some cases recognise indigenous rights and support regional and international cooperation in governance are among the many factors that impede and or facilitate adaptation. Importantly, health adaptation is occurring at the local scale in the Arctic (Ford et al., 2014a2109; Ford et al., 2014b2110). Also noted are anticipated future conditions and level of certainty and other drivers of change that may interact with climate and affect outcomes. Overturning circulation in the Southern Ocean is a key factor that controls heat and carbon exchanges with the atmosphere, and hence global climate, however there are no direct measures of this and only sparse indirect indicators of how it may be changing. It is very likely that both the Southern Ocean and the Arctic Ocean will experience year-round conditions of surface water undersaturation for mineral forms of calcium carbonate by 2100 under RCP8.5; under RCP2.6 the extent of undersaturated waters are reduced markedly. Model simulations show that a temporary temperature overshoot of a warming target has no lasting impact on ice cover (Armour et al., 2011406; Ridley et al., 2012407; Li et al., 2013408). Glacier acceleration of up to 25% also affected the Getz Ice Shelf margin from 2007 to 2014 (Chuter et al., 2017958). Under the same scenario, aragonite undersaturation is projected to occur in the bottom waters over the entire Kara Sea shelf by 2040 and over most of the Barents and East Greenland shelves by 2070 due to the accumulation of anthropogenic CO_2 (Wallhead et al., 2017507). Between the 1990s and 2017, tidewater glaciers have exhibited regional patterns in glacier dynamics; glaciers in Arctic Canada have largely decelerated, while glaciers in Svalbard and the Russian Arctic have accelerated (Van Wychen et al., 2016; Strozzi et al., 2017). Connectivity is reduced by the influence of chaotic internal natural variability and other tropical and oceanic forcing. To date, 14 non-native terrestrial species have colonised the Antarctic Treaty area (excluding sub-Antarctic islands) (Hughes et al., 20151818), while the number in the sub-Antarctic is much higher (on the order of 200 species) (Frenot et al., 20051819) (low confidence). {3.4.1; 3.4.3} Climate-related changes to Arctic hydrology, wildfire and abrupt thaw are occurring (high confidence), with impacts on vegetation and water and food security. A new initiative to operationalise One Health concepts and approaches under the AC's Sustainable Development Working Group has gained momentum since 2015 (Ruscio et al., 20152124). This is supported by eddy-resolving models, which also show a marked regional variability (Patara et al., 2016339), and there is evidence that local hotspots in eddy energy, especially downstream of major topographic features including the Drake Passage, Kerguelen Plateau, Campbell Plateau and the East Pacific Rise, may dominate the regional fields (Thompson and Naveira Garabato, 2014340). Working Group I (WGI) of the IPCC's 5th Assessment Report (AR5) assessed that there was medium confidence that the mean position of the ACC had moved southwards in response to a contraction of the Southern Ocean circumpolar winds. (2014b) found that adaptation is primarily local and motivated by reducing risks and their related vulnerabilities (high confidence). On the AP, snowfall began to increase in the 1930s, accelerated in the 1990s (Thomas et al., 2015986; Goodwin et al., 2016987), and now offsets sea-level rise by 6.2 ± 1.7 mm per century (Medley and Thomas, 2018988). On Arctic land, projections indicate a loss of globally unique biodiversity as some high Arctic species will be outcompeted by more temperate species and very limited refugia exist (medium confidence). It has been shown recently (Barletta et al., 20181323) that the Amundsen Sea Embayment (ASE) experiences unexpectedly fast bedrock uplift (up to 41 mm yr-1, due to mantle viscosity much lower than the global average) as an adjustment to reduced ice mass loading, which could help stabilise grounding line retreat. One of the largest outlets of the East Antarctic Ice Sheet (EAIS), Totten glacier, has also been retreating and thinning in recent decades (Li et al., 2015b1324). Differences in sensitivity and the scope for adaptation to projected levels of ocean acidification exist across a broad range of marine species groups. Melbourne-Thomas, M.M.C. Muelbert, G. In contrast to fire, there has not yet been a comprehensive circumpolar projection of how abrupt thaw rates may change in the future, but one component of abrupt thaw, change in abrupt thaw lake area, has been projected to increase to increase by 53% under RCP8.5 (Walter Anthony et al., 20181550) above the 1.4 x 106 km2 of small lakes and ponds that currently exist in the permafrost region (Muster et al., 20171551). Some of the differences in projected changes have been found to be correlated with biases in the various models' ability to simulate the historical state of the Southern Ocean, such as mixed layer depth (Sallée et al., 2013a363) and westerly wind jet latitude (Bracegirdle et al., 2013364). Annual tundra area burned in Alaska is projected to double under RCP6.0 from a historic rate of 270 km2 yr-1 to 500–610 km2 yr-1 over the 21st century (Hu et al., 20151548). Important advances have also been made since AR5 in (i) identifying key variables to detect and attribute change in Southern Ocean ecosystems, as part of long-term circumpolar modelling designs (Constable et al., 2016696), and (ii) refining methods for using sea ice projections from global climate models in ecological studies and ecosystem models for the Southern Ocean (Cavanagh et al., 2017697). Sea ice production is greatest in Ross and Weddell sea polynyas and around East Antarctica (Drucker et al., 2011451; Nihashi and Ohshima, 2015452; Tamura et al., 2016453) (high confidence). Projected snow water equivalent increases across the North American Arctic are only modest, emerge later in the century, and only under RCP8.5 (Brown et al., 20171533). This brief synopsis considers the chapter findings across sections, and draws out three key assessment points that inform global responses to polar ocean and cryosphere change. Other non-environmental factors which influence Arctic shipping are natural resource development, regional trade, geopolitics, commodity prices, global economic and social trends, national priorities, tourism demand, ship building technologies and insurance costs (Lasserre and Pelletier, 2011891; Têtu et al., 2015892; Johnston et al., 2017893). Antarctic krill (Euphausia superba) play a central role in Southern Ocean foodwebs as grazers and as prey items for fish, squid, marine mammals and seabirds (Schmidt and Atkinson, 2016683; Trathan and Hill, 2016684) (SM3.2.6). These newly-revealed habitats have allowed new phytoplankton blooms to be produced resulting in new marine zooplankton and seabed communities (Gutt et al., 20111307; Fillinger et al., 20131308; Trathan et al., 20131309; Hauquier et al., 20161310) (Section 3.2.3.2.1), and have resulted in enhanced carbon uptake by coastal marine ecosystems (medium confidence), although quantitative estimates of biological carbon uptake are highly variable (Trathan et al., 20131311; Barnes et al., 20181312). Across the Arctic, increased surface melt and subsequent ice-layer formation via refreezing within snow and firn also reduces the ability of glaciers to store meltwater, increasing runoff (Zdanowicz et al., 20121206; Gascon et al., 2013a1207; Gascon et al., 2013b1208; Noël et al., 20171209; Noël et al., 20181210). For instance, all initiatives of the Fifth National Communications of Annex I parties to the UNFCCC affect health vulnerability, however, only 15% of initiatives had an explicit human health component described (Lesnikowski et al., 20112093). Changes due to offshore development and transportation Subsistence (marine and terrestrial) Changes in species distribution and abundance (not all negative); impediments to access of harvesting areas; safety; changes in seasonality; reduced harvesting success and process of food production (processing, food storage; quality); threats to culture and food security Change in gear, timing of hunting, species switching; mobilisation to be involved in political action Systems of adaptive co-management that allow for species switching, changes in harvesting methods and timing, secure harvesting rights Less access to some areas, more in others. Disruptions to cultural and subsistence hunting activities from increased shipping (Huntington et al., 2015896; Olsen et al., 2019897) compound climate-related impacts to people (Sections 3.4.3.3.2, 3.4.3.3.3). It is projected that shipping activity will continue to rise across the Arctic as northern routes become increasingly accessible (Stephenson et al., 2011898; Stephenson et al., 2013899; Barnhart et al., 2015900; Melia et al., 2016901), although mitigating economic and operational factors remain uncertain and could influence future traffic volume (Zhang et al., 2016902). Along with growing number of visitors, this is expected to increase in the establishment probability of terrestrial alien species (Chown et al., 20121822; Hughes et al., 20151823) (medium confidence). The Arctic is home to over four million people, with large regional variation in population distribution and demographics (Heleniak, 20141824). Over the last two decades, Arctic surface air temperature has increased at more than double the global average (high confidence) (Notz and Stroeve, 2016; Richter-Menge et al., 2017). Five Arctic States, known as 'Arctic 5' (Canada, Denmark, Norway, Russia and the United States) have sovereign rights for exploring and exploiting resources within their 200 nautical mile Exclusive Economic Zones (EEZs) in the High Arctic and manage their resources within their own regulatory measures. Projections to mid-century are primarily dependent on natural variability and model dependent uncertainties rather than the choice of forcing scenario (Hodson et al., 20131530). Black carbon emissions from shipping activity within the Arctic are projected to increase (Arctic Council, 2017911) and are more easily deposited at the surface in the region compared with emissions from lower latitudes (Sand et al., 2013912). Despite this, alien species and their propagules continue to be introduced to the Antarctic continent and sub-Antarctic islands (Hughes et al., 20151817). Practices are shown with the potential extent of their contribution to resilience building, considering also seven general strategies (Biggs et al., 20122207; Quinlan et al., 20162208; Cross-Chapter Box 2 in Chapter 1). Compared to a decade ago, there are more cruises on offer, ships travel further in a single season, larger vessels with more passenger berths are in operation, more purpose-built polar cruise vessels are being constructed, and private pleasure craft are appearing in the Arctic more frequently (Lasserre and Têtu, 2015859; Johnston et al., 2017860; Dawson et al., 2018861). These changes are altering biodiversity in polar marine ecosystems (medium confidence) {3.2.3; Box 3.4}. Industry has responded to the increase in shipping activity by investing in development of shipping designs for travel in mixed-ice environments (Stephenson et al., 2011; Stephenson et al., 2013). Model deficiencies are related to stratification (Sallée et al., 2013a418), freshening by ice shelf melt water (Bintanja et al., 2015419), atmospheric processes including clouds (Schneider and Reusch, 2015420; Hyder et al., 2018421), and wind and ocean driven processes (Purich et al., 2016a422; Purich et al., 2016b423; Schroeter et al., 2017424; Purich et al., 2018a425; Zhang et al., 2018a426). Meredith (UK), Robert Hallberg (US), Alessandro Tagliabue (UK), Andrew Meijers (UK/Australia), Jamie Oliver (UK), Andrew Hogg (Australia) Horizontal circulation and movement of fronts The Southern Ocean is disproportionately important in global climate and ecological systems, being the major connection linking the Atlantic, Pacific and Indian Oceans in the global circulation. For example, for stabilised global warming of 1.5°C, a sea ice-free Arctic in September is projected to occur significantly less frequently than at 2°C (1% c.f. 10–35%) (Section 3.2.2). Industry self-regulation supplements these requirements, coordinated by the International Association of Antarctica Tour Operators, which has worked with Antarctic Treaty Consultative Parties to manage changes in operations and their impact on ice-free areas (ATCM, 20162040). Reducing and avoiding the impacts of climate change on infrastructure will require special attention to engineering, land use planning, maintenance operations, local culture and private and public budgeting (AMAP, 2017a2054; AMAP, 2017b2055; AMAP, 20182056). In the Arctic, there are also risks and opportunities related to employment, health and well-being, and the commodification of culture (Stewart et al., 2013874; Stewart et al., 2015875). Thus the potential of MICI to impact the future sea level remains very uncertain (Edwards et al., 20191330). Woody shrubs and trees are projected to expand, covering 24–52% of the current tundra region by 2050. Over the ice shelf regions, where dense waters sink and flood the global ocean abyss, the role of glacial freshwater input is clearer. An increase in stratification caused by release of freshwater from the AIS was invoked as a mechanism to suppress vertical heat flux and permit an increase in sea ice extent (Bintanja et al., 20131239; Bronselaer et al., 20181240; Purich et al., 20181241), though some studies conclude that glacial freshwater input is insufficient to cause a significant sea ice expansion (Swart and Fyfe, 20131242; Pauling et al., 20171243) (Section 3.2.1.1). The Arctic is no exception to this global trend. The most pronounced recent range expansion into the Arctic may be that of the summer feeding distribution of the temperate Atlantic mackerel (Scomber scombrus) in the Nordic Seas. Mitigation approaches include banning heavy fuel oil as already implemented in Antarctica and the waters around Svalbard, and the use of new technology like scrubbers. {Box 3.1; 3.2.1.1} The Arctic and Southern Oceans are continuing to remove carbon dioxide from the atmosphere and to acidify (high confidence). Thus, for continental Antarctica, existing climatic barriers to alien species establishment will weaken as warming continues across the region (medium confidence). Zhai, M. During 1970–2017, the Southern Ocean south of 30°S accounted for 35–43% of the global ocean heat gain in the upper 2000 m (high confidence), despite occupying ~25% of the global ocean area. Section 4.2 assesses the sea level impacts from observed and projected changes in ice sheets. Evidence exists for an anthropogenic role in the atmospheric circulation (NAO) changes that have driven GIS mass loss (Section 3.3.1.5.2) (medium confidence), although this awaits formal attribution testing (e.g., Easterling et al., 2016). High-altitude GIS sites NEEM and Summit warmed by, respectively, 2.7°C ± 0.33°C over the past 30 years (Orsi et al., 20171028) and by 2.7°C ± 0.3°C from 1982 to 2011 (McGrath et al., 20131029), while satellite thermometry showed statistically significant widespread surface warming over northern GIS from 2000 to 2012 (Hall et al., 20131030). More restrictions with regulations related to species at risk. The Southern Annular Mode (SAM), Pacific South American mode (by which tropical Pacific convective heating signals are transmitted to high southern latitudes) and zonal-wave 3 are the dominant large-scale atmospheric circulation drivers of Antarctic surface climate and sea ice changes (SM3.1.3). Alongside the mean state changes, Southern Ocean aragonite saturation is also affected by the seasonal cycle of carbonate as well as by the impact of reduced buffering capacity (SM3.2.4) on the seasonal cycle of CO_2 (Sasse et al., 201511v; McNeil and Sasse, 2016512). A statistical approach projected a fourfold increase in the 30-year probability of fire occurrence in the forest-tundra boundary by 2100 (Young et al., 20171549). These events were caused by a split of the tropospheric polar vortex into two cells, which facilitated the intrusion of subarctic storms (Overland and Wang, 2016). While there is evidence of an increase in the frequency of weak polar vortex events (Screen et al., 2018202), studies do not show increases in the number of mid-latitude cold events in observations or model projections (Ayarzaguena and Screen, 2016203; Trenary et al., 2016204). A scenario-based approach to identify management strategies that are effective under changing climate conditions is being explored for the Barents Sea (Planque et al., 2019). Due to vegetation-climate interactions, there is only medium confidence in projections of future area burned. These recent findings do not preclude more local changes in frontal position, but it is now assessed as unlikely that there has been a statistically significant net southward movement of the mean ACC position over the past 20 years. The upwelling waters in the overturning bring heat to the Antarctic shelf seas, with consequences for ice shelves, marine-terminating glaciers and the stability of the Antarctic Ice Sheet (AIS) (Section 3.3.1). to constrain the models. Biodiversity projections are limited by key uncertainties regarding the potential for organisms to adapt to habitat change and the resilience of foodweb structures. This 'Arctic squeeze' is a combined effect of the fact that the area of the globe increasingly shrinks when moving poleward and that there is nowhere further north on land to go for terrestrial biota at the northern coast. In parallel with these expansions, pathogens and pests are also spreading north (CAFF, 2013a1796; Taylor et al., 20151797; Forde et al., 2016b1798; Burke et al., 2017b1799; Kafle et al., 20181800). Recent work has characterised the nature of habitat change for Southern Ocean biota at regional and circumpolar scales (Constable et al., 2014688; Gutt et al., 2015689; Constable et al., 2016690; Hunt et al., 2016691; Gutt et al., 2018692), and the direct responses of biota to these changes (Constable et al., 2014693) (summarised in Figure 3.6). Only around half of the 1960–2014 surface melt ran off, most of the rest being retained in firn and snow (Steger et al., 20171045), particularly in recently observed firn aquifers in south and west Greenland (Humphrey et al., 20121046; Forster et al., 20131047; Munneke et al., 20141048; Poinar et al., 20171049) that cover up to 5% of GIS (Miège et al., 20161050; Steger et al., 20171051) and stored around one fifth of the meltwater increase since the late 1990s (Noël et al., 2017) (medium confidence). One Health approaches seek to link human, animal, and environmental health, using interdisciplinary and participatory methods that can draw on indigenous knowledge and local knowledge (Dudley et al., 20152125). Increases in Arctic marine transportation create impacts and risks for ecosystems and people, such as an increased likelihood of accidents, the introduction of invasive species, oil spills, waste discharges, detrimental impacts on animals, habitat and subsistence activities (Sections 3.2.4.3, 3.4.3.3.2). New shipping routes through the Arctic offer cost savings because they are shorter than traditional passages via the Suez or Panama Canals. Alegría, M. Responding to climate change in polar regions will be more effective if attention to reducing immediate risks (short-term adaptation) is concurrent with long-term planning that builds resilience to address expected and unexpected impacts (high confidence). The loss of ice shelves and retreat of coastal glaciers around the AP in the last 50 years has exposed at least 2.4 × 104 km2 of new open water. The reduced survival rate of sea ice in the Transpolar Drift interrupts the transport of sediment-laden ice produced from Siberian shelf polynyas (Krumpen et al., 2019438), with consequences for the associated biogeochemical matter and gas fluxes (Damm et al., 2018439) (medium confidence). Several factors are important in successful knowledge co-production, including use of social-ecological frameworks, engagement of a broad set actors with diverse epistemological orientations, a 'team science' approach to studies, strong leadership, attention to process (vs. Scenario planning, adaptive management and similar efforts will contribute to the resilience and conservation of these social-ecological systems (medium confidence). Dynamic thinning losses were –112 ± 12 Gt yr–1 for 2003–2013, largely from the ASE (Figure SM3.8) (Martín-Español et al., 2016951), which contributed –102 ± 10 Gt yr–1 from 2003 to 2011 (Sutterley et al., 2014952). Ice shelves in contact with bathymetric features on the sea floor or confined within embayments provide back stress (buttressing) that impedes the seaward flow of the upstream ice and thereby stabilises the ice sheet. Uncertainty in sea ice projections reduces confidence in projections of Antarctic Ice Sheet surface mass balance because sea ice affects Antarctic temperature and precipitation trends (Bracegirdle et al., 2015427), and impacts projected changes in the Southern Hemisphere westerly jet (Bracegirdle et al., 2018428; England et al., 2018429) with implications for the Southern Ocean overturning circulation (Cross-Chapter Box 7 in Chapter 3). Industry growth also points to the need for operators, governments, destination communities and others to identify and evaluate adaptation strategies, such as disaster relief management plans, updated navigation technologies for vessels, codes of conduct for visitors and improved maps (Pizzolato et al., 20162030) and to respond to perceptions of tourism by residents of local destinations (Kaján, 20142031; Stokke and Haukeland, 20172032). Bare ice produced ~78% of runoff from 1960 to 2014, and its extent is expected to increase non-linearly as snow cover retreats to higher, flatter areas of ice sheet (Steger et al., 20171060). States can individually or cooperatively pursue the establishment of Special Areas and Particularly Sensitive Sea Areas at the IMO with a view to protect ecologically unique or vulnerable and economically or culturally important areas in national and international waters from risks and impacts of shipping, including through routing, discharge and equipment measures. Arctic sea ice extent continues to decline in all months of the year (very high confidence); the strongest reductions in September (very likely –12.8 ± 2.3% per decade; 1979–2018) are unprecedented in at least 1000 years (medium confidence). These trends and extremes provide medium evidence with high agreement of the contemporary coupled atmosphere-cryosphere system moving well outside the 20th century envelope. From Greenland, the 2012–2016 ice losses (–247 ± 15 Gt yr-1) were similar to those from 2002 to 2011 (–263 ± 21 Gt yr-1) and extremely likely greater than from 1992 to 2001 (–8 ± 82 Gt yr-1). Uncertainties denote the 90% confidence interval accounting for the reduction in the degrees of freedom implied by temporal correlations of residuals, as per Section 5.2. Values in curved brackets are percentages of heat gain by the Southern Ocean relative to the global ocean. Due to these uncertainties, low confidence is therefore ascribed to the CMIP5-based model projections of future Southern Ocean circulation and water masses. The observational era is not sufficiently long to rule out this behaviour. By end of century, however, differences between scenarios emerge. Glacier retreat, causing glaciers to shift from being marine-terminating to land-terminating, can reduce the productivity in coastal areas off Greenland with potentially large ecological implications, also negatively affecting production of commercially harvested fish (Meire et al., 20171299). Palaeo evidence also suggests that the GIS has contributed substantially to sea level rise during past warm intervals (Cross-Chapter Box 8 in Chapter 3). {2.2.3, 3.3.2} There is limited evidence and high agreement that recent Antarctic Ice Sheet (AIS) mass losses could be irreversible over decades to millennia. In the Barents Sea, major expansions in distribution over the recent years to decades have been well documented for both individual species and whole biological communities (high confidence). {3.5.3} The capacity of governance systems in polar regions to respond to climate change has strengthened recently, but the development of these systems is not sufficiently rapid or robust to address the challenges and risks to societies posed by projected changes (high confidence). Dynamical considerations and numerical simulations indicate that, if further increases in the westerly winds are sustained, then it is very likely that the eddy field will continue to grow in intensity (Morrison and Hogg, 2013358; Munday et al., 2013359), with potential consequences for the upper-ocean overturning circulation and transport of tracers (Abernathey and Ferreira, 2015360) (including heat, carbon, oxygen and nutrients), and likely that the mean

position and strength of the ACC will remain only weakly sensitive to winds. There is an emerging body of literature on this topic (e.g., Berdahl et al., 2014; Desch et al., 2017; Field et al., 2018), which at present is too limited to allow assessing dimensions of feasibility, benefits and risks, and governance. During 2007–2016, continuous-zone permafrost temperatures in the Arctic and Antarctic increased by 0.39 ± 0.15°C and 0.37 ± 0.10°C respectively. Limited evidence of past MICI in Antarctica is provided by deep iceberg plough marks on the sea-floor (Wise et al., 20171341). While the occurrence of regime shifts in polar systems is both documented and anticipated, there is little or no understanding of their preconditions or of indicators that would help pre-empt them. However, since AR5 it has been argued that several Greenland outlet glaciers (Petermann, Kangerdlugssuaq, Jakobshavn Isbræ, Helheim, Zachariæ Isstrøm) and North-East Greenland Ice Stream may contribute more than expected to future sea level rise (Mouginot et al., 20151347). Current evidence of invasions by shell-crushing crabs on the Antarctic continental slope and shelf remains equivocal (Griffiths et al., 20131786; Aronson et al., 20151787; Smith et al., 2017d1788). There is high confidence through a growing body of literature that variability of tropical sea surface temperatures can influence Antarctic temperature changes (Li et al., 2014; Turner et al., 2016; Clem et al., 2017; Smith and Polvani, 2017) and the Southern Hemisphere mid-latitude circulation (Li et al., 2015a; Raphael et al., 2016; Turney et al., 2017; Evtushevsky et al., 2018; Yuan et al., 2018). However, with decreasing ice cover and potential interest in expanding fisheries, the Inuvialuit subsistence fishers of the western Canadian Arctic developed a new proactive ecosystem-based Fisheries Management Framework (Ayles et al., 2016). Interactions across scales are also dependent on the extent to which various stakeholders are perceived as legitimate in their perceptions and recommendations, an issue related to the use of local knowledge and indigenous knowledge in governance (Cross-Chapter Box 4 in Chapter 1) (AHDR, 2014; Ford et al., 2014b; Forbes et al., 2015) (high confidence). At a more regional level, Alaska's 'Climate Action for Alaska' was reconstituted in 2017 and is now actively linking local concerns with state-level policies and funding, as well as setting targets for future reductions in the state's carbon emission. In the few Arctic regions where data is sufficient to assess trends in biodiversity, the ecosystem level responses appear to be products of multiple interacting physical, chemical and biological processes (Frederiksen, 2017521) (medium confidence). Permafrost thaw and decrease in snow on land are projected to drive habitat and biome shifts, affecting ranges and abundance of ecologically important species, and driving changes in wildfire, vegetation and human infrastructure (Sections 3.4.2, 3.4.3). The fisheries of the southeastern Bering Sea are managed through a complex suite of regulations that includes catch shares (Ono et al., 2017), habitat protections, restrictions on forage fish, bycatch constraints (DiCosimo et al., 2015) and community development quotas. It is challenging to measure the Southern Ocean overturning directly, and misinterpretation of Waugh et al. This is consistent with CMIP5 model projections of increased discharge from Arctic watersheds (van Vliet et al., 20131563; Gelfan et al., 20161564; MacDonald et al., 20181565). {3.2.1.2.1} Climate-induced changes in seasonal sea ice extent and thickness and ocean stratification are altering marine primary production (high confidence), with impacts on ecosystems (medium confidence). Circumpolar- or global-scale models represent permafrost degradation in response to warming scenarios as increases in thaw depth only. This includes the CCAMLR Ecosystem Monitoring Program, which aims to monitor important land-based predators of krill to detect the effects of the krill fishery on the ecosystem. Continued loss of Arctic multi-year sea ice will affect ice-related and pelagic primary production (high confidence), with impacts for whole ice-associated, seafloor and open ocean ecosystems. Arctic land areas are almost always completely snow covered in winter, so the transition seasons of autumn and spring are key when characterising variability and change. Specifically, climate change is projected to alter the distribution and properties of Arctic marine habitats with associated implications for species composition, production and ecosystem structure and function (Frainer et al., 2017518; Kaartvedt and Titelman, 2018519; Moore et al., 2018520). Ice shelves buttress 90% of AIS outflow (Depoorter et al., 2013959; Rignot et al., 2014960; Fürst et al., 2016961; Reese et al., 2018962), and ice shelf thinning increased in WAIS by 70% in the decade to 2012, averaged 8% thickness loss from 1994 to 2012 in the ASE (Paolo et al., 2015963), and explains the post-2009 onset of rapid dynamic thinning on the southern-AP Bellingshausen Sea coast (Wouters et al., 2015964; Hogg et al., 2017965; Martin-Español et al., 2017966) (Figure SM3.8). Improved mechanistic understanding of the observed changes and trends in Antarctic sea ice is required, notably the decadal increase and very recent rapid retreat. Considerations include socioeconomic and political implications related to safety (marine and local accidents), security (trafficking, terrorism and local issues), and environmental and cultural sustainability (invasive species, release of biocides, chemicals and other waste, marine mammal strikes, fuel spills, air and underwater noise pollution and impacts to subsistence hunting) (Arctic Council, 2015a908; Halliday et al., 2017909; Hauser et al., 2018910). {3.5.2, 3.5.4, Cross-Chapter Box 9} It is extremely likely that the rapid ice loss from the Greenland and Antarctic ice sheets during the early 21st century has increased into the near present day, adding to the ice sheet contribution to global sea level rise. In some cases, spatial shifts in distribution have also been influenced by fluctuations in population abundance linked to climate-induced impacts on reproductive success (Section 3.2.3). Considerable literature exists on the potential for sea ice loss in the Barents and Kara Seas to drive cold episodes in eastern Asia (Kim et al., 2014196; Kretschmer et al., 2016197), while sea ice anomalies in the Chukchi Sea and areas west of Greenland are associated with cold events in eastern North America (Kug et al., 2015198; Ballinger et al., 2018199; Overland and Wang, 2018a200). In response, GIS meltwater production and runoff increased (Hanna et al., 20121038; Box, 2013; Fettweis et al., 20131039; Tedstone et al., 20151040; van den Broeke et al., 20161041; Fettweis et al., 20171042), resulting in 1994–2013 runoff being 33% higher the 20th century mean and 50% higher than the 18th century (Trusel et al., 20181043), and 80% higher in a western-GIS marginal river catchment in 2003–2014 relative to 1976–2002 (Ahlstrom et al., 20171044). In addition to global carbon emission mitigation, hardening and redesigning of infrastructure can reduce costs of future climate-related impacts. Models indicate that under anthropogenic climate change, surface freshening caused by increased precipitation reduces the occurrence of the Weddell polynya (de Lavergne et al., 2014). The timescales and likelihood of such effects are assessed separately in Chapter 6 (Section 6.7). Accumulation and percolation of surface melt and rain water also impact ice shelves by lowering albedo, deepening surface crevasses, and causing flexural stresses that can lead to hydrofracturing and ice shelf collapse (Macayeal and Sergienko, 20131319). Changes in coastal ecosystems affecting fisheries productivity Implementation of adaptive management practices to assess stocks, change allocations as needed, and address issues of equity Implementation of adaptive management that is closely linked to monitoring, research, and public participation in decisions Displacement of fishing effort will impact fishing operations in the eastern Bering Sea and Barents Sea as well as the Convention for the Conservation of Antarctic Marine Living Resources area Changes in human preference, demand and markets, changes in gear, changes in policies affecting property rights. 8 Reviews | 1335 Downloads 62 Resources Read More Activity, Assessment | Grades 9-12 Read More Handout, Lesson Plan | Grades 6-12 Read More Activity, Handout, Lesson Plan | Grades 9-12 Read More Activity | Grades 6-12 Read More Assessment, Handout, Presentation | Grades 6-8 Read More Climate change in the Arctic and Antarctic affect people outside of the polar regions in two key ways. About 4400 people reside in Antarctic in the summer and about 1100 in the winter, predominantly based at research stations of which approximately 40 are occupied year-round (The World Factbook, 2016). Site-specific management tools are in place. In the US Arctic, an adaptive management approach has been introduced that utilises future ecological scenarios to develop strategies for mitigating the future risks and impacts of climate change (NPFMC, 2018). For Antarctica, freshwater input to the ocean from the ice sheet is divided approximately equally between melting of calved icebergs and of ice shelves in situ (Depoorter et al., 20131231; Rignot et al., 20141232). Further back in time during the early to mid- Holocene, pre-historic glacial deposits, ice core records, and numerical modelling evidence shows that many Arctic glaciers were at various stages similar to or smaller than present (Gilbert et al., 20171190; Zekollari et al., 20171191), experienced greater melt rates (Lecavalier et al., 20171192), or may have disappeared altogether (Solomina et al., 20151193) (medium confidence). Herders' responses to climate change have varied by region and respective herding practices, and in some cases are constrained by limited access to pastures (Klokov, 2012; Forbes et al., 2016; Uboni et al., 2016; Mallory and Boyce, 2017). Projections demonstrate a similar distribution of heat storage to historical observations, notably focused in deep pools north of the Subantarctic Front (e.g., Armour et al., 2016495). Increased Arctic shipping has significant socioeconomic and political implications for global trade, northern nations and economies strongly linked to traditional shipping corridors, while also increasing environmental risk in the Arctic. For Nenets of the Yamal, Russia, resilience in herding has been facilitated through herders' own agency and, to some extent, the willingness of the gas industry to observe non-binding guidelines that provide for herders' continued use of traditional migrations routes (Forbes et al., 2015). Global environmental and climate regimes that are implemented and managed through regional regimes (such as the Kyoto Protocol or the Paris Agreement) are also relevant for the Antarctic Treaty and its Protocol on Environmental Protection, which requires, amongst other issues, a minimisation of adverse environmental impacts. At present, the Greenland Ice Sheet (GIS) and polar glaciers are contributing more to sea level rise than the Antarctic Ice Sheet (AIS). The limited available information on marine fish from other Arctic shelf regions reveals a latitudinal cline in the abundance of commercially harvestable fish species. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [H.-O. Projected changes to polynyas are important because the spring phytoplankton bloom starts early as the ocean is often well-ventilated and nutrient rich, so the entire biological range from phytoplankton to seabirds to marine mammals thrive in polynya waters (high confidence) (Stirling, 1997440; Arrigo and van Dijken, 2004441; Karnovsky et al., 2009442). The large-scale impacts of Antarctic Bottom Water changes include a potential modulation to the strength of the Atlantic Meridional Overturning Circulation (e.g., Patara and Böning, 2014; see also Section 5.2.2.2.1). In all these regions, restrictions affecting the movement of reindeer to pastures are expected to negatively interact with the effects of climate and affect the future sustainability of herding systems (high confidence). The growth of the polar tourism market is, in part, a response to climate change, as travellers seek 'last-chance' opportunities, which, in turn, is creating new challenges in governance (Section 3.2.4.2). Furthermore, circumpolar efforts are also underway, including a circumpolar working group with experts from public health to assess climate-sensitive infectious diseases, and to identify initiatives that reduce the risks of disease (Parkinson et al., 20142108). The amplification of nutrient fluxes caused by enhanced upwelling at calving fronts (Meire et al., 20171295), combined with high carbon/nutrient burial and recycling rates (Wehrmann et al., 20131296; Smith et al., 20151297), plays an important role in sustaining high productivity of the Arctic fjord ecosystems of Greenland and Svalbard (Lydersen et al., 20141298). Interannual sea ice variability in the models is larger than observations (Zunz et al., 2013411), which may mask disparity between models and observations. Ongoing climate change induced reductions in suitable habitat for Arctic sea ice affiliated endemic marine mammals is an escalating threat (Section 3.2.3.1) (high confidence). In the US portion of the Chukchi and Beaufort Seas EEZ, fishing is prohibited until sufficient information is obtained to sustainably manage the resource (Wilson and Ormseth, 2009). These situations raise issues of environmental justice and human rights (Bronen, 20172059), and illustrate the limits of incremental adaptation when transformation change is needed (Kates et al., 20122060). This range expansion was linked both to a pronounced increase in stock size and warming of the ocean (Berge et al., 20151767; Olafsdottir et al., 20191768) (high confidence). There are, however, biases in salinity of ~1 across the Arctic Basin for the present day climate (Ilicak et al., 2016493) in forced global ice-ocean models with configurations comparable to CMIP5, suggesting limited predictive skill for the Arctic freshwater cycle. It is extremely likely that the 2002–2011 and 2012–2016 ice losses were greater than in the 1992–2001 period (Bamber et al., 20181016) (Table 3.3, Figure 3.7, SM3.3.1.3). Even though it remains difficult to project the amount of ice loss from Antarctica after the second half of the 21st century, it is expected to contribute significantly to future sea level rise. While many of these perspectives are equally relevant for both polar regions, only the Arctic has a population for whom the region is a permanent home: approximately four million people reside there, of whom 10% are indigenous. This intricate regulatory framework has inherent risks and benefits to fishers and industry by limiting flexibility (Anderson et al., 2017b). Also shown is the current level of their application in polar regions and key conditions facilitating implementation. {3.2.4; 3.5.2; 3.5.4} Widespread disappearance of Arctic near-surface permafrost is projected to occur this century as a result of warming (very high confidence), with important consequences for global climate. There is high confidence that biodiversity supported by ice-free areas, particularly those on the AP, are vulnerable to the introduction of terrestrial alien species via tourists and scientists (Chown et al., 2012876; Huiskes et al., 2014877; Hughes et al., 2015878; Duffy et al., 2017879; Lee et al., 2017a880) (Box 3.3) as well as to the direct impacts of humans (Pertierra et al., 2017881). Andrews et al. The social and cultural differences are an especially noteworthy factor in assessing polar responses. The International Maritime Organization (IMO) has responsibility for the safety and security of shipping and the prevention of marine and atmospheric pollution by ships, including in the Arctic and Antarctic. Hence, long-term retreat on every retrograde sloped bed is not necessarily unstoppable (Gomez et al., 20151322). While the annual mean value of transport is stable in the instrumental period (Chidichimo et al., 2014333; Koenig et al., 2014334; Donohue et al., 2016335) it is difficult to resolve changes in barotropic transport; overall there is medium confidence that ACC transport is only weakly sensitive to changes in winds. To address these challenges, the North Pacific Fishery Management Council recently adopted a Fishery Ecosystem Plan that includes a multi-model climate change action module (Punt et al., 2016; Holsman et al., 2017; Zador et al., 2017; Holsman et al., 2019). {3.4.1; 3.4.2; 3.4.3; 3.5.2}. The anticipated near- and long-term growth of Arctic tourism, especially with small vessels (yachts) (Johnston et al., 2017), points to a deficiency in current regulations and policies to address human safety, environmental risks and cultural impacts. The Canadian government's actions on climate change have been among the most extensive of the Arctic nations, including funding of ArcticNet, a Network of Centres of Excellence, and consideration of climate change by The Northern Contaminants and Nutrition North Canada programs. The way states and institutions manage international cooperation on environmental governance is changing in response to climate change in the polar regions. In other regions such as western Canada, by contrast, black spruce could be replaced by the even more flammable jack pine, creating regional-scale feedbacks that increase the spread of fire on the landscape (Héon et al., 20141543). In contrast, where warm water intrusions drive melting within ice shelf cavities, a significant entrained heat flux to the surface can exist and increase stratification and potentially reduce sea ice extent (Jourdain et al., 20171244; Merino et al., 20181245). This offers the opportunity, for the first time in a global report, to trace cause and consequence of climate change from polar ocean and cryosphere systems to biological and social impacts, and relate them to responses to reduce risks and enhance adaptation options and resilience. However, there is only medium confidence in the magnitude of these changes due to at least a five-fold range of estimated present day near-surface permafrost area (25 x 106 km2) by these models. Fisheries in the Southern Ocean are relatively mobile and are potentially able to respond to range shifts in target species, which is in contrast to small-scale coastal fisheries in other regions. In some cases supraglacial (i.e., flowing on the glacier surface) rivers might diminish destabilising impact of surface melt by removing meltwater before it ponds on the ice shelf surface (Bell et al., 20171320). Networks of protected areas, participatory scenario analysis, decision support systems, community-based ecological monitoring that draws on local and indigenous knowledge, and self assessments of community resilience contribute to strategic plans for sustaining biodiversity and limit risk to human livelihoods and wellbeing. 3.2.2.2 Physical Oceanography Consistent with the projected sea ice decline, there is high confidence that the Arctic Ocean will warm significantly towards the end of this century at the surface and in the deeper layers. While management in some polar fisheries is among the most developed, scientists are exploring modifications to existing precautionary, ecosystem-based management approaches to increase the scope for adaptation to climate change impacts on marine ecosystems and fisheries. Projected range expansion of subarctic marine species will increase pressure for high-Arctic species (medium confidence), with regionally variable impacts. This has implications for people's livelihoods, cultural practices, economies and self-determination. For the RCP8.5 scenario, the entire Arctic and Southern Ocean surface waters will very likely be typified by year-around conditions corrosive for aragonite minerals for 2090–2100 (Figure 3.4) (Hauri et al., 2015502; Sasse et al., 2015503), whilst under RCP2.6 the extent of undersaturated waters are reduced markedly. These differences have strong implications for natural resource management, economic sectors and Arctic cultures (Section 3.5.2). Reduced mass loss has been linked to increased winter snow accumulation and decreased summer melt at these locations, associated with recent deepening of the circumpolar pressure trough (Oliva et al., 2017). Freshwater release also affects local circulation within fjords through two principle mechanisms; subglacial release from tidewater glaciers enhances buoyancy driven circulation, whereas runoff from land-terminating glaciers contributes to surface layer freshening and estuarine circulation (Straneo and Cenedese, 20151229). From Antarctica, the 2012–2016 losses (–199 ± 26 Gt yr-1) were extremely likely greater than those from 2002 to 2011 (–82 ± 27 Gt yr-1) and likely greater than from 1992 to 2001 (–51 ± 73 Gt yr-1). For Greenland and Svalbard, there is limited evidence with high agreement that the retreat of marine-terminating glaciers will alter food supply to higher trophic levels of marine food webs (Meire et al., 20171292; Milner et al., 20171293). Knowledge on how to translate existing theoretical understandings of social-ecological resilience into decision making and governance is limited. However, both Russian and Canadian legislation provide the possibility for stricter shipping provisions in ice-covered waters. The Arctic 5 officially adopted the precautionary approach to fishing in 2015 by signing the Oslo Declaration concerning the prevention of unregulated fishing in the CAO. Changes in permafrost influence global climate through emissions of carbon dioxide and methane released from the microbial breakdown of organic carbon, or the release of trapped methane. Arctic Coastal Polynyas Arctic polynyas (areas of open water surrounded by sea ice) are important because they ventilate the Arctic Ocean. The considerable Coupled Model Intercomparison Project Phase 5 (CMIP5) inter-model variations in Southern Ocean time-mean circulation projections reported in WGI AR5 (Meijers et al., 2012361; Downes and Hogg, 2013362) remain largely unchanged. Attribution studies show the important role of anthropogenic increases in greenhouse gases in driving observed Arctic surface temperature increases (Fyfe et al., 2013; Najafi et al., 2015), so there is high confidence in projections of further Arctic warming (Overland et al., 2018a). {3.2.2; 3.3.2; 3.4.2, Cross-Chapter Box 6 in Chapter 2} Both polar oceans will be increasingly affected by CO_2 uptake, causing conditions corrosive for calcium carbonate shell-producing organisms (high confidence), with associated impacts on marine organisms and ecosystems (medium confidence). The practices listed below are not inclusive of the many resilience-building efforts underway in the polar regions. (2018)2170, CCAMLR Report on the 37th Meeting of the Commission, CCAMLR (2018)). The discrepancy between these studies and those assessed in WGI AR5 appears to be caused by issues associated with using a fixed sea surface height contour as a proxy for frontal position in the presence of strongly eddying fields (Chapman, 2014346) and large-scale increases in sea surface height consistent with mean global trends in sea level rise (Gille, 2014347). In both polar regions, cooperative approaches to regional governance have been developed to allow for the participation of non-state actors. During the historical period, regional trends of Antarctic sea ice are not captured by the models, particularly the decrease in the Bellingshausen Sea and the expansion in the Ross Sea (Hobbs et al., 2015415). Table 3.4 summarises the consequences, interacting drivers, responses and assets for responding to climate change by social-ecological subsystems (i.e., sectors) of Arctic and Antarctic regions. Relatedly, there is a paucity of studies analysing differences in the trajectories of polar cryosphere and ocean systems between low and very low greenhouse gas emission scenarios. (2019)1782 show that Atlantic cod, beaked redfish (Sebastes mentella), and deep-sea shrimp (Pandalus borealis) recently found on the Northeast Greenland shelf originate from the quite distant Barents Sea, and suggested that pelagic offspring were dispersed via advection across the Fram Strait. While transnational networks can be a catalyst for action and promoting innovation, there remain outstanding challenges in measuring the effectiveness of these networks (Fünfgeld, 2015). Adaptation through formal institutions by Indigenous people is enabled through self-government, land claims and co-management institutions (Baird et al., 2016; Huet et al., 2017). Greater levels of Arctic ship-based transportation and tourism have socioeconomic and political implications for global trade, northern nations, and economies linked to traditional shipping corridors; they will also exacerbate region specific risks for marine ecosystems and coastal communities if further action to develop and adequately implement regulations does not keep pace with increased shipping (high confidence). Poleward ocean heat transport contributes to Arctic Ocean warming (medium confidence). Also, over the recent decade a northward shift in benthic species, with subsequent changes in community composition has been detected in both the northern Bering Sea (Grebmeier, 20121758), off Western Greenland (Renaud et al., 20151759) and the Barents Sea (Kortsch et al., 20121760) (medium confidence). Partitioning between natural and human drivers of atmospheric and ocean circulation changes remains very uncertain. In Alaska, reindeer herding is primarily free range, where herders must manage herd movements in the event of icing events and the potential loss of reindeer because the movements of caribou herds (wild reindeer), both of which are partially driven by climate. Snow and lake ice cover has declined, with June snow extent decreasing 13.4 ± 5.4% per decade (1967–2018) (high confidence). The different physical settings have also led to the evolution of unique marine and terrestrial biology in each polar region and shape effects, impacts and adaptation of polar ecosystems. By contrast, the Antarctic population changes seasonally between approximately 1100 and 4400, based predominantly at research stations. Conversely, on the sub-Antarctic Kerguelen Islands, increased glacier mass loss (Verfaillie et al., 2015) may be due to reduced snow accumulation rather than increased air temperature as a result of southward migration of storm tracks (Favier et al., 2016). Projections of all glaciers, including those in polar regions, are covered in Cross-Chapter Box 6 in Chapter 2. The early to middle part of the Holocene coincided with substantial decreases in net precipitation that may be due to weakening jet stream winds related to Arctic temperatures (Routson et al., 2019188). Emerging evidence suggests, however, that internal variability, including links between the Arctic and lower latitude, strongly influences the ability of models to simulate observed reductions in Arctic sea ice extent (Swart et al., 2015b383; Ding et al., 2018384). The uncertainty in sea ice sensitivity (ice extent loss per unit of warming) is quite large (Niederdrenk and Notz, 2018381) and the model sensitivity is too low in most CMIP5 models (Rosenblum and Eisenman, 2017382). Some of the critical ones, which are priorities for future initiatives, are outlined here. Limitations of government budgets, other disasters that may take priority for spending, deficiencies in policies for addressing mitigation and relocation Responses to climate change at or across local, regional and national levels occur directly and indirectly through a broad range of governance activities, such as land and sea use planning and regulations, economic development strategies, tax incentives for use of alternative energy technologies, permitting processes, resource management and national security. Most CMIP5 models capture the seasonal changes in surface heat and freshwater fluxes for the present day climate, and show that the excess summer solar heating is used to melt sea ice, in a positive ice albedo feedback (Ding et al., 2016484). The tightly coupled relationship of northern local communities and their environment provide an opportunity to better understand climate change and its effects, support adaptation and limit unintended consequences. Seven general strategies for building resilience have been recognised: i) maintain diversity and redundancy, ii) manage connectivity, iii) manage slow variables and feedbacks, iv) foster an understanding of social-ecological systems as complex adaptive systems, v) encourage learning and experimentation, vi) broaden participation, and vii) promote polycentric governance systems (Biggs et al., 2012; Quinlan et al., 2016) (Cross-Chapter Box 2 in Chapter 1). Without further action leading to adequate implementation of well-developed management plans and region-specific regulations, anticipated future increases in Arctic shipping will pose a greater risk to people and ecosystems (high confidence). Hollowed, G. Adaptation at the individual, household, and community levels may be seriously restricted by conditions where there is poverty (high confidence) Changes in cost of fuel, land use affecting access, food preferences, harvesting rights; international agreements to protect vulnerable species Reindeer Herding Rain-on-snow events causing high mortality of herds; shrubification of tundra pasture lowering forage quality Changes in movement patterns of herders; policies to ensure free-range movements; supplemental feeding. Flexibility in movement to respond to changes in pastures, secure land use rights and adaptive management. Continued, and in some areas, greater, international cooperation on shipping governance can facilitate addressing emerging climate change issues (Arctic Council, 2015a; ARR, 2016; PEW Charitable Trust, 2016; Chénier et al., 2017; IMO, 2017) (high confidence). Whether unstable WAIS retreat has begun or is imminent remains a critical uncertainty (Cross-Chapter Box 8 in Chapter 3). It is not clear, however, if the changes observed recently are a linear response to increased ocean forcing (Section 3.3.1.2), or an indication that MISI has commenced (Roberts et al., 20181326). Impacts will vary between regions, depending on the degree of climate change and the effectiveness of human responses. This has consequences for where, when, and how many fish can be captured. The mean flow circumnavigates Antarctica as the world's largest ocean current, the Antarctic Circumpolar Current (ACC), transporting approximately 173.3 ± 10.7 ×106 m3 s–1 (Donohue et al., 2016331) of water eastward in a geostrophic balance set up by the contrasting properties of waters around Antarctica and those inside the subtropical gyres to the north of ACC. An analysis of the costs of total damages from climate change to public infrastructure in Alaska show the financial benefits of proactive adaptation (Melvin et al., 20172074) (Figure 3.12). Here, the most vulnerable species and communities may be in the species-poor, but unique, northernmost sub-zone of the Arctic because species cannot migrate northward as southern species encroach (CAVM Team, 20031804; Walker et al., 20161805; AMAP, 20181806). The declaration established a moratorium to limit potential expansion of CAO commercial fishing until sufficient information, also on climate change impacts, is available to manage it sustainably. Annual retreat rates of tidewater glaciers in Svalbard and the Russian Arctic for 2000–2010, have increased by a factor 2 and 2.5 respectively, between 1992 and 2000 (Carr et al., 2017). Melting ice sheets and glaciers in the polar regions cause sea levels to rise, affecting coastal regions and their large populations and economies. Comparing 26 different CMIP5 simulations for RCP4.5, Burgard and Notz (2017) found that ocean heat transport changes explain the Arctic Ocean multi-model mean warming, but that differences between models are compensated by changes in surface fluxes. This has consequences for climate, ecosystems and fisheries; however, lack of understanding and poor model performance translates to very limited predictive skill. Trends in snow water equivalent over Arctic land are inadequately known, reducing confidence in assessments of snow's role in the water cycle and in insulating the underlying permafrost. Several regional and national-level initiatives on food security (ICC, 2012), as well as research reporting high levels of household food insecurity (Kofinas et al., 20162119; Watts et al., 20172120) have prompted greater concerns for climate change (Loring et al., 20132121; Beaumier et al., 20152122; Islam and Berkes, 20162123). Secondary production and upper food web processes are typically adapted to the early availability of energy to the system with arrival of higher trophic species (Asselin et al., 2011443). Grounding line retreat, an indicator of thinning, has been observed with high confidence (Rignot et al., 2014967; Christie et al., 2016968; Hogg et al., 2017969; Konrad et al., 2018970; Roberts et al., 2018971). There is also evidence that marine-terminating glaciers are important feeding areas for marine mammals and seabirds at Greenland (Laidre et al., 20161300) and Svalbard (Lydersen et al., 20141301). Pulse disturbances are not included in the permafrost projections described above, and there is high confidence that fire and abrupt thaw will accelerate change in permafrost relative to climate effects alone, if the rates of these disturbances increase. Limited evidence is available to confirm the importance of MICI. {3.2.2.1; 3.2.3; 3.2.3.1; Box 3.4; 3.4.2; 3.4.3} The projected effects of climate-induced stressors on polar marine ecosystems present risks for commercial and subsistence fisheries with implications for regional economies, cultures and the global supply of fish, shellfish, and Antarctic krill (high confidence). This variability, combined with the indirect nature of observational estimates, means that there is low confidence in assessments of long-term changes in upper cell overturning. Winter (January to March) near-surface temperature anomalies of +6°C (relative to 1981–2010) were recorded in the central Arctic during both 2016 and 2018, nearly double the previous record anomalies (Overland and Wang, 2018a). Acceleration due to surging (an internal dynamic instability) of a few key glaciers has dominated dynamic ice discharge on time-scales of years to decades (Van Wychen et al., 2014; Dunse et al., 2015). The recent acceleration and surge behaviour of polythermal glaciers in Svalbard and the Russian Arctic is caused by destabilisation of the marine termini due to increased surface melt, and changes in basal temperature, lubrication and weakening of subglacial sediments (Dunse et al., 2015; Sevestre et al., 2018; Willis et al., 2018) or terminus thinning and response to warmer ocean temperatures (McMillan et al., 2014a) (low confidence). In the Ross Sea, grounding lines may have retreated several hundred kilometers inland and then re-advanced to their present-day positions due to bedrock uplift after ice mass removal (Kingslake et al., 20181336), thus supporting the stabilising role of glacial isostatic adjustment on ice sheets (Barletta et al., 20181337). A niche market known as 'last chance tourism' has emerged whereby tourists explicitly seek to experience vanishing landscapes or seascapes, and natural and social heritage in the Arctic and Antarctic, before they disappear (Lemelin et al., 2010; Lamers et al., 2013867). In addition to the Protocol, mandatory measures have been agreed to manage aspects of tourism activity. However, there is medium confidence for the response of specific locations, due to the need for improved resolution of the local circulation, interactions with sea ice, and other processes that modulate the rate of acidification. Changes in Arctic sea ice have potential to influence mid-latitude weather on timescales of weeks to months (low to medium confidence). Future impacts for linked human systems depend on the level of mitigation and especially the responsiveness of precautionary management approaches (medium confidence). Responses addressing changes in the abundance and distribution of fish resources (Section 3.2.4.1) differ by region. In contrast to the Southern Ocean (Cross-Chapter Box 7 in Chapter 3), there is comparatively little knowledge on changing Arctic frontal positions and current cores since AR5. (2013). Important differences in the trajectories of loss emerge from 2050 onwards, depending on mitigation measures taken (high confidence). In turn, this thinning can initiate grounding line retreat (Konrad et al., 20181321). Increased ocean heat transport into the Barents Sea beyond 2020 appears as a probable mechanism with continued warming (Koenigk and Brodeau, 2014486; Årthun et al., 2019487). Projections of changes in Southern Ocean circulation are discussed in Cross-Chapter Box 7 in Chapter 3. As a result, there is low confidence in the ability to assess the magnitude by which abrupt thaw across the entire landscape will affect regional permafrost, even though this mechanism for rapid change appears critically important for projecting future change (Kokelj et al., 20171552). Climate model simulations project a warmer and wetter Arctic (Krasting et al., 20131553), with increased specific humidity due to enhanced evaporation (Laîné et al., 20141554), and moisture flux convergence increases into the Arctic (Skific and Francis, 20131555). There is increasing awareness of the influence of a changing climate on freshwater systems across the Arctic, and associated impacts on hydrological, biogeophysical and ecological processes (Prowse et al., 20151456; Walvoord and Kurylyk, 20161457), and northern populations (Takakura, 20181458) (Section 3.4.3.3.1). Changing insurance premiums Human Health Threats to food security, potential threats to physical and psychological well being Greater focus on food security research; programs that address fundamental health issues Human and financial resources to support public programs in hinterland regions; cultural awareness of health issues as related to climate change Greater likelihood of illnesses, food insecurity, cost of health care A reduction (of increase) in public resources to support health services to rural community populations, research that links ecological change to human health Coastal settlements (see Cross-Chapter Box 9) Change in extent of sea ice with more storm surges, thawing of permafrost, and coastal erosion Maintenance of erosion mitigation; relocation planning, some but incomplete allocation for funding Local leadership and community initiatives to initiate and drive processes, responsive agencies, established processes for assessments and planning, geographic options Increasing number of communities needing relocation, rising costs for mitigating erosion issues. Acidification of the polar oceans will progress more slowly and affect much smaller areas under RCP2.6 compared with RCP8.5 (Section 3.2.2). In addition to dramatic Arctic summer sea ice loss over the past 15 years, all Arctic winter sea ice maxima of the last 4 years were at record low levels relative to 1979–2014 (Overland, 2018). Increased cold-season precipitation is projected across the Arctic by CMIP5 models (Lique et al., 20161556) due to increased moisture flux convergence from outside the Arctic (Zhang et al., 20121557) and enhanced moisture availability from reduced sea ice cover (Bintanja and Selten, 20141558) (high confidence). In spite of these adaptations, many groups are making decisions without adequate knowledge to forecast near- and long-term conditions, and without the funding, skills and institutional support to engage fully in planning processes (high confidence). Increases in polar cruise tourism pose risks and opportunities related to development, education, safety (including search and rescue), security within communities and environmental sustainability (Johnston et al., 2012a868; Johnston et al., 2012b869; Stewart et al., 2013870; Dawson et al., 2014871; Lasserre and Têtu, 2015872; Stewart et al., 2015873). Arctic amplification of anthropogenic warming (e.g., Serreze et al., 2009) affects atmospheric circulation (Francis and Vavrus, 20151181; Mann et al., 20171182) and has reduced sea ice extent (Section 3.2.1.1.1), feeding back to exacerbate both warming and NAO changes (Screen and Simmonds, 20101183) that impact GIS mass balance. Arctic and boreal permafrost region soils contain 1460–1600 Gt organic carbon (medium confidence). The combined sea level rise contribution from both ice sheets for 2012–2016 was 1.2 ± 0.1 mm yr-1, a 29% increase on the 2002–2011 contribution and a ~700% increase on the 1992–2001 period. This extent is not well reproduced in climate models, however, with biases of –6% to 13% (Ryan et al., 20191061). The following sections assess the extent to which these practices operationalise resilience-building through knowledge co-production, the linking of knowledge with decision making, and implementation of resilience-based ecosystem management, considering also their application level and key facilitating conditions; a summary is presented in Table 3.5. The co-production of knowledge and transdisciplinary research are currently contributing to the understanding of polar climate change through the use of a diversity of cultural, geographic, and disciplinary perspectives that provide a holistic framing of problems and possible solutions (Miller and Wyborn, 2018; Robards et al., 2018) (high confidence). Three aspects of knowledge co-production are highlighted below. Reduced Arctic sea ice cover allows greater access to offshore petroleum resources and ports supporting resource extraction on land. Antarctic ice loss is dominated by acceleration, retreat and rapid thinning of major West Antarctic Ice Sheet (WAIS) outlet glaciers (very high confidence), driven by melting of ice shelves by warm ocean waters (high confidence). There is a large spread in the timing of when the Arctic may become ice free in the summer, and for how long during the season (Massonnet et al., 2012386; Stroeve et al., 2012a387; Overland and Wang, 2013388) as a result of natural climate variability (Notz, 2015389; Swart et al., 2015b390; Screen and Deser, 2019391), scenario uncertainty (Stroeve et al., 2012a392; Liu et al., 2013393), and model uncertainties related to sea ice dynamics (Rampal et al., 2011394; Tandon et al., 2018395) and thermodynamics (Massonnet et al., 2018396). This will challenge adaptation responses regionally and worldwide. This is consistent with longer-term analyses that find only minimal changes in ACC transport since the last glaciation (McCave et al., 2013336). It has also been shown that Greenland was nearly ice free for extensive episodic periods during the Pleistocene, suggesting a sensitivity to deglaciation under climates similar to or slightly warmer than present (Schaefer et al., 20161348). As integral parts of the Earth system, the polar regions interact with the rest of the world through shared ocean, atmosphere, ecological and social systems; notably, they are key components of the global climate system. Part of the scientific disagreement is due to irregular connections in the Arctic to mid-latitude linkage pathways, both within and between years (Overland and Wang, 2018b195). Recent implementation of Inuit-led marine management areas acknowledge the Inuit knowledge of polynyas, and recognise the potential for development of fisheries and other resources in polynya systems, provided these activities minimise harm on the environment and wildlife. Mackintosh, J. Important differences in the physical setting of the two polar regions—the Arctic, an ocean surrounded by land, the Antarctic, a continent surrounded by an ocean—structure the nature and magnitude of interactions of cryosphere and ocean systems and their global linkages. From 1997 to 2016 the total area occupied by this large stock expanded from 0.4 to 2.5 million km2 and the centre-of-gravity of distribution shifted westward by 1650 km and northward by 400 km (Olafsdottir et al., 2019), far into Icelandic and Greenland waters and even up to Svalbard (Berge et al., 20151764; Jansen et al., 20161765; Nøttestad et al., 20161766). Private pleasure craft remain almost completely unregulated, and will pose unique risks in the future (Johnston et al., 2017886). The same logic has more recently been applied by some herders in the wake of recent rain-on-snow events (Section 3.4.3.2.2) (Forbes et al., 2016). Poloczanska, K. Satellite data indicate a general strengthening of the surface geostrophic currents in the Arctic basin (Armitage et al., 2017324). While not exclusively 'polar', Alaska attracts the highest number of cruise passengers annually at just over one million; Svalbard attracts 40,000–50,000; Greenland 20,000–30,000; and Arctic Canada 3,500–5,000 (Johnston et al., 2017858). Cooperation of the member states of the Arctic Council resulted in the 2011 Agreement on Cooperation on Aeronautical and Maritime Search and Rescue in the Arctic and in the 2013 Agreement on Cooperation on Marine Oil Pollution Preparedness and Response in the Arctic. Subsidence due to thawing permafrost and river and delta erosion makes other rural communities of Alaska and Russia vulnerable, potentially requiring relocation in the future (Bronen, 20152057; Romero Manrique et al., 20182058). For most Arctic Indigenous peoples, human responses to climate change are viewed as a matter of cultural survival (Greaves, 2016) (Cross-Chapter Box 3 in Chapter 1). From 1980 to 2012, the salinity of Antarctic Bottom Water reduced by an amount equivalent to 73 ± 26 Gt y–1 of freshwater added, around half the estimated increase in freshwater input by Antarctic glacial discharge up to that time (Purkey and Johnson, 20131236). Institutional barriers presently limit their efficacy. Antarctic Bottom Water becomes coherently warmer by up to 0.3°C by 2100 across the model ensemble under RCP8.5 (Heuzé et al., 2015496). Rapid disintegration of ice shelves in the Canadian and Russian Arctic continues and has led to acceleration and thinning in tributary-glacier basins (high confidence) (Willis et al., 2015; Copland and Mueller, 2017). It is very unlikely that this new trend from states to refer to Article 76 will lead to future (military) conflicts (Berkman and Vylegzhanin, 20132160; Kullerud et al., 20132161; Stokke, 20132162; Verschuuren, 20132163), although the issue cannot be totally dismissed (Kraska, 20112164; Åtland, 20132165; Huebert, 20132166; Cassotta et al., 20152167; Barret, 20162168; Cassotta et al., 20162169). In the Antarctic, cooperation in general does occur via UNCLOS, the Convention for the Safety of Life at Sea and the Convention for the Prevention of Pollution from Ships and the Polar Code. Based on these recent events, there is medium confidence in the drivers of Weddell Polynya formation; it forms over deep water and appears connected to sea ice divergence created by ocean eddies (Holland, 2001475) or strong winds (Campbell et al., 2019476; Francis et al., 2019477; Wilson et al., 2019478). Under RCP4.5 and RCP8.5 further range expansions of mackerel are projected in Greenland waters (Jansen et al., 20161769) (medium confidence). In response to climate change (i.e., icing events and early spring runoffs blocking migration), the only way of avoiding high deer mortality is to change migration routes or take deer to other pastures. Approximately half the observed sea ice loss is attributable to increased atmospheric greenhouse gas concentrations (medium confidence). The upper ocean also becomes considerably fresher (salinity decrease of approximately 0.1) (Sallée et al., 2013b497) with an overall increase in stratification and a shallowing of mixed layers (Sallée et al., 2013a498). {3.3.1} Mass loss from Arctic glaciers (–212 ± 29 Gt yr-1) during 2006–2015 contributed to sea level rise at a similar rate (0.6 ± 0.1 mm yr-1) to the GIS (high confidence). Using RCP8.5, Vavrus et al. At the same time, the global appetite for maritime trade and commerce through the Arctic (including community re-supply, mining and resource development, tourism, fisheries, cargo, research, and military and icebreaking, etc.) is increasing as the region becomes more accessible because of reduced sea ice cover. These interactions necessitate that responses to climate change consider cumulative effects as well as context-specific pathways for building resilience (Nymand and Fondahl, 2014; ARR, 2016). The sections below assess human responses to climate change in polar regions by examining various sectors of human-environment activity (i.e., social-ecological subsystems), reviewing their respective systems of governance related to climate change, and considering possible resilience pathways. Ekaykin, A. The cost savings of retrofitting and redesigning infrastructure is even higher than the savings from carbon mitigation, where impact costs are estimated at USD 4.2 billion under RCP4.5 by 2100. In Alaska, the Arctic Investigations Program responds to infectious disease via advancing molecular diagnostics, integrating data from electronic health records and environmental observing networks, as well as improving access to in-home water and sanitation services. Sector /System Consequence of climate change Documented responses Key assets and strategies of adaptive and transformative capacity Anticipated future conditions/level of certainty Other forces for change that may interact with climate and affect outcomes Commercial Fisheries Consequences are multi-dimensional, including impacts to abundance and distribution of different target species differently, by region. Increased risk of hazardous waste and oil spills and accidents requiring search and rescue. Strong international cooperation leading to agreed-upon and enforced policies that maintain standards for safety; well-developed response plans with readiness by agents in some regions Continued increases in shipping traffic with increased risks of accidents Political conflict in other areas that impeded acceptance of policies for safety requirements, timing, and movements. Antarctic coastal polynyas are biological hot-spots that support high rates of primary production (Ainley et al., 2015454; Arrigo et al., 2015455) due to a combination of both high light (Park et al., 2017456) and high nutrient levels, especially iron (Gerringa et al., 2015457). {3.2.1.1; Box 3.2} It is very likely that Antarctic sea ice cover exhibits no significant trend over the period of satellite observations (1979–2018). Historical simulations from CMIP5 models tend to underestimate observed reductions in spring snow cover extent due to uncertainty in the parameterisation of snow processes (Essery, 20131518; Thackeray et al., 20141519), challenges in simulating snow-albedo feedback (Qu and Hall, 20141520; Fletcher et al., 20151521; Li et al., 2016b1522), unrealistic temperature sensitivity (Brutel-Vuilmet et al., 20131523; Mudryk et al., 20171524), and biases in climatological spring snow cover (Thackeray et al., 20161525). Acidification of both polar oceans will have progressed; this, and changing marine habitats associated with ocean warming, are projected to impact marine ecosystems (Sections 3.2.2, 3.2.3). Several elements for successful climate change adaptation planning at the local level have previously been identified: formal analytical models need to be relevant to the concerns and needs of stakeholders, experts should be made sensitive to community perspectives, information should be packaged and communicated in ways that are accessible to non-experts and processes of engagement that foster creative problem solving be used. Municipalities and industry are addressing infrastructure failures associated with flooding and thawing permafrost, and coastal communities and cooperating agencies are in some cases planning for relocation (high confidence). Species distribution models for terrestrial invasive species indicate that climate does not currently constitute a barrier for the establishment of invasive species on all subantarctic islands, and that the AP region will be the most vulnerable location on the Antarctic continent to invasive species establishment under RCP8.5 (Duffy et al., 20171820). 3.2.2 Projected Changes in Sea Ice and Ocean 3.2.2.1 Sea Ice The multi-model ensemble of historical simulations from CMIP5 models identify declines in total Arctic sea ice extent and thickness (Sections 3.2.1.1.1; 3.2.1.1.2; Figure 3.3) which agree with observations (Massonnet et al., 2012372; Stroeve et al., 2012a373; Stroeve et al., 2014a374; Stroeve and Notz, 2015375). Ice sheet changes over earlier periods have also been reconstructed from firn/ice core and geological evidence (SM3.3.1). Based on four CMIP5 models, the Barents Sea is projected to become ice-free during winter beyond 2050 under RCP8.5 (Onarheim and Årthun, 2017488), to which the main response is an increased ocean-to-atmosphere heat flux and related surface warming (Smedsrud et al., 2013489). Arctic sea ice has thinned, concurrent with a shift to younger ice: since 1979, the areal proportion of thick ice at least 5 years old has declined by approximately 90% (very high confidence). This weaker amplified warming compared to the Arctic is due to deep ocean mixing and ocean heat uptake over the Southern Ocean (Collins et al., 2013). In other cases, cultural resources in the form of historic infrastructure are being threatened and require mitigation (Radosavljevic et al., 20152061). CMIP5 models project continued declines in Arctic sea ice through the end of the century (Figure 3.3) (Notz and Stroeve, 2016385) (high confidence). Collectively, these very different future polar environments pose strong challenges to sustainable use of natural resources, infrastructure, cultures and lives and livelihoods. This self-sustaining process is known as Marine Ice Sheet Instability (MISI). Pritchard, and E.A.G. Schuur, 2019: Polar Regions. Together these conditions make for complexity and uncertainty in human decision making, be it at the household and community levels to the international level. About a third of the Antarctic Ice Sheet (AIS) is 'marine ice sheet', i.e., rests on bedrock below sea level (Figure 4.5), with most of the ice sheet margin terminating directly in the ocean. This warming was highly unusual over the last 1000 years but not unprecedented, and along with subsequent cooling is within the bounds of the large natural decadal-scale climate variability in this region (Mulvaney et al., 20121177; Turner et al., 20161178). Limited evidence from geological records and ice sheet modelling suggests that parts of AIS experienced rapid (i.e., on centennial time-scale) retreat likely due to ice sheet instability processes between 20,000 and 9,000 years ago (Golledge et al., 20141331; Weber et al., 20141332; Small et al., 20191333). On the shallow Siberian shelves, the ocean surface waters are dominated by river runoff which is rich with sediments (Damm et al., 2018432), which end up both in the dense bottom water and in new sea ice (Bauch et al., 2012433; Janout et al., 2015434). For each of the five years since the IPCC 5th Asessment Report (AR5) (2014–2018), Arctic annual surface air temperature exceeded that of any year since 1900. Such movements can in principle have profound effects on marine ecosystems via, e.g., changing habitat ranges for different species (e.g., Cristofari et al., 2018; Meijers et al., 2019341) (Section 3.2.3.2). Multi-year, large magnitude extreme positive Arctic temperatures and sea ice minimums (Section 3.2.1.1) since AR5 provide high agreement and medium evidence of contemporary conditions well outside the envelope of previous experience (1900–2017) (AMAP, 2017d; Walsh et al., 2017). Today, thinning and retreat of ice shelves is associated primarily with ocean driven basal melt that, in turn, promotes iceberg calving (Section 3.3.1.2). Intense ice growth within these polynyas contributes to the production of Antarctic Bottom Water, the densest and most voluminous water mass in the global ocean (Jacobs, 2004447; Nicholls et al., 2008448; Orsi and Wiederwohl, 2009449; Ohshima et al., 2013450). 203-320. The reason to have private herds is one of adaptive advantage; smaller, privately owned herds are nimbler in the face of rapid changes in land cover and the expansion of infrastructure (Forbes, 2013). Detailed assessment of atmospheric processes was outside the remit of this chapter, however such gaps limit understanding of ongoing and future trajectories of the polar regions and their climate systems. Limited evidence with high agreement from individual glaciers suggests that regional variability in glacier mass changes may be linked to changes in the large-scale Southern Hemisphere atmospheric circulation (Section 3.3.1.5.2). Lake ice models project an earlier spring break-up of between 10–25 days by mid-century (compared with 1961–1990), and up to a 15-day delay in the freeze-up for lakes in the North American Arctic, with more extreme reductions for coastal regions (Brown and Duguay, 20111568; Dibike et al., 20111569; Prowse et al., 20111570) (medium confidence). Newly available habitat on coastlines may also provide breeding or haul out sites for land-based predators such as penguins and seals (Trathan et al., 20131313) (low confidence). Nevertheless, CCAMLR has not agreed to any climate change program and at its most recent meeting, there was again no agreement to do so (Brooks et al. Derksen, A. Ongoing GIS mass loss over recent years has resulted from a combined increase in dynamic thinning and a decrease in SMB. Together, these impact access to (and food availability within) herding, hunting, fishing, forage and gathering areas, affecting the livelihood, health and cultural identity of residents including Indigenous peoples (high confidence). A similar polynya appeared in spring 2017, with a smaller area in 2016, but did not occur in 2018 (Campbell et al., 2019473; Jena et al., 2019474). While there has been discussion of future 'climigration' in rural Alaska (Bronen and Chapin, 20132067; Matthews and Potts, 20182068), a study of Alaska rural villages threated by climate change showed no outmigration response (Hamilton et al., 20162069). The Protocol on Environmental Protection to the Antarctic Treaty restricts the introduction of non-native species to Antarctica as do the management authorities of sub-Antarctic islands (De Villiers et al., 2006). For stabilised global warming of 1.5°C, sea ice in September is likely to be present at end of century with an approximately 1% chance of individual ice-free years (Notz and Stroeve, 2016399; Sanderson et al., 2017400; Jahn, 2018401; Sigmond et al., 2018402); after 10 years of stabilised warming at a 2°C increase, more frequent occurrence of an ice-free summer Arctic is expected (around 10-35%) (Mahlstein and Knutti, 2012403; Jahn et al., 2016404; Notz and Stroeve, 2016405). This leads to an amplification of the seasonal variability of pCO_2 (Hauck and Völker, 2015513; McNeil and Sasse, 2016514; Landschützer et al., 2018515) and the hydrogen ion concentration that accelerates the onset of hypercapnia (i.e., high pCO_2 levels; $pCO_2 > 1000$ µatm) to nearly 2 decades (~2085) ahead of anthropogenic CO_2 forcing (McNeil and Sasse, 2016516). Recent AP warming and consequent ice shelf collapses have evidence of a link to anthropogenic ozone and greenhouse gas forcing via the SAM (e.g., Marshall, 2004; Shindell, 20041173; Arblaster and Meehl, 20061174; Marshall et al., 20061175; Abram et al., 20141176) and to anthropogenic Atlantic sea surface warming via the Atlantic Multidecadal Oscillation (e.g., Li et al., 2014). Here, they become transformed into cold, dense waters that sink back to the deep ocean, storing significant amounts of human-produced heat and dissolved carbon for decades to centuries or longer, and helping to slow the rate of global warming in the atmosphere. Pörtner, D.C. Roberts, V. The ensemble mean across multiple models show a decrease in total Antarctic sea ice extent during the satellite era, in contrast to the lack of any observed trend (Figure 3.3; Section 3.2.1.1.1). A shoaling of the aragonite saturation horizon of approximately 1200 m, a large increase in area extent of undersaturated surface waters, and a pH change in the surface water of –0.19 are projected using the SRES A1B scenario (broadly comparable to RCP6.0) in the Nordic Sea from 2000 to 2065 (Skogen et al., 2014506). Increases in precipitation extremes are also projected over northern watersheds (Kharin et al., 20131559; Sillmann et al., 20131560), while rain on snow events are expected to increase (Hansen et al., 20141561). Iceberg calving rates in Svalbard are linked to ocean temperatures which control rates of submarine melt (Luckman et al., 2015; Vallot et al., 2018) (medium confidence). Level of participation by country and the extent to which national level efforts are linked with regional and local adaptation varies. In Fennoscandia, husbandry practices of reindeer by some (mostly Sami) include supplemental feeding, which provide a buffer for unfavourable conditions. Simultaneous with rising sea temperatures and retreating sea ice, these Arctic fishes are being replaced by boreal, fast-growing, large-bodied generalist fish moving in from the south. Finland's national adaptation strategy outlines various anticipatory and reactive measures for numerous sectors, including health (Gagnon-Lebrun and Agrawala, 20072107). 3.2.4 Impacts on Social-Ecological Systems 3.2.4.1 Fisheries 3.2.4.2 Tourism Reductions in sea ice have facilitated an increase in marine and cruise tourism opportunities across the Arctic related to an increase in accessibility (Dawson et al., 2014856; Johnston et al., 2017857) (high confidence). Meredith, M., M. Authors: Michael P. Continued economic viability and cultural tradition. Increased frequency of extreme events and changing forage quality adding to vulnerabilities of reindeer and herders (medium confidence) Change in market value of meat; overgrazing; land use policies affecting access to pasture and migration routes, property rights Tourism (Arctic and Antarctic) Warmer conditions, more open water, public perception of 'last chance' opportunities Increased visitation, (quantity and quality) increase in off-season tourism to polar regions Policies to ensure safety, cultural integrity, ecological health, adequate quarantine procedures Increased risk of introduction of alien species and direct effects of tourists on wildlife Travel costs. Human responses to climate change in the polar regions occur in a fragmented governance landscape. More broadly over the AP and coastal WAIS where dynamic mass losses are concentrated, natural variability in atmospheric and ocean forcing appear to dominate observed mass balance (medium confidence) (Smith and Polvani, 20171179; Jenkins et al., 20181180). Shifting tourism market, more enterprises Non-Renewable Resource Extraction (Arctic only) Reduced sea ice and glaciers offering some new opportunities for development; changes in hydrology (spring runoff), thawing permafrost, and temperature affect production levels, ice roads, flooding events, and infrastructure Some shifts in practices, greater interest in offshore and on-land development opportunities in some regions Modification of practices and use of climate change scenario analysis Increased cost of operations in areas of permafrost thawing; more accessible areas in open waters and receding glaciers Changes in policies affecting extent of sea and land use area, new extraction technologies (e.g., fracking), changes in markets (e.g., price of barrel of oil) Infrastructure -urban and rural human settlements, year-round Thawing permafrost affecting stability of ground; coastal erosion Damaged and loss of infrastructure, increase in operating costs Resources for assessments, mitigation, and where needed, relocation Increasing cost to maintain infrastructure and greater demand for technological solutions to mitigate issues. However, Indigenous people are not homogenous in their perspectives. {3.3.1; Cross-Chapter Box 8 in Chapter 3; 4.2.3.1.2} The polar regions will be profoundly different in future compared with today, and the degree and nature of that difference will depend strongly on the rate and magnitude of global climatic change. Under RCP2.6 and RCP4.5, Arctic snow cover duration stabilises at 5–10% reduction (compared to a 1986–2005 reference period); under RCP8.5, snow cover duration declines reach –15 to –25% (Brown et al., 20171531) (Figure 3.10) (high confidence). When combined with the Arctic regions covered in Chapter 2 (Alaska, the Yukon territory of Canada, Iceland and Scandinavia), Arctic glaciers as a whole lost mass at a rate of –213 ± 29 Gt yr–1, a sea level contribution of 0.59 ± 0.08 mm yr–1 (high confidence). Adaptive management that combines annual measures and within-season provisions informed by assessments of future ecosystem trends reduces the risks of negative climate change impacts on polar fisheries (medium confidence). These findings indicate that overlapping changes in key ocean and sea ice habitat characteristics (temperature, sea ice cover, iceberg scour, mixed layer depth, aragonite undersaturation; Sections 3.2.1, 3.2.2) will be important in determining future states of Southern Ocean ecosystems (Constable et al., 2014694; Gutt et al., 2015695) (medium confidence). Internal climate variability results in an uncertainty of approximately 20 years in the timing of seasonally ice-free conditions (Notz, 2015397; Jahn, 2018398), but the clear link between summer sea ice extent and cumulative CO_2 emissions provides a basis for when consistent ice-free conditions may be expected (high confidence). Tignor, E. There are four potential Arctic international trade routes: the Northwest Passage, the Northern Sea Route, the Arctic Bridge and the Transpolar Sea Route. In some places, notably the Indian-Australian sector, Antarctic Bottom Water freshening may be accelerating (Menezes et al., 20171237). Projected shifts will include further habitat contraction and changes in abundance for polar species, including marine mammals, birds, fish, and Antarctic krill (medium confidence). Alaskan coastal communities are not the only settlements potentially requiring relocation. Regions of the Arctic differ widely in population, ranging from 94% of Iceland's population living in urban environments to 68% of Nunavut's population living in rural areas. Further reductions in sea ice are projected for Arctic shelf seas which have already lost ice in recent decades (Barnhart et al., 2015436; Onarheim et al., 2018437) so polynyas will cease to exist where seasonal sea ice disappears or evolve to become part of the marginal sea ice zone due to changes in ice dynamics (i.e., the North Water polynya and the Circumpolar Flaw Lead); new or enlarged polynyas could result in regions where thinner ice becomes more effectively advected offshore, or where marine terminating glaciers increase land ice fluxes to the marine system (medium confidence). Conservation of biodiversity is described as an integral part of its sustainable fisheries management and it is mandatory to apply "an ecosystem approach, taking into account habitats and biodiversity" (Gullestad et al., 2017). Projections Projections of future trends in the Southern Ocean are dominated by the potential for a continued strengthening of the westerly winds (Bracegirdle et al., 2013356), as well as a combination of warming and increased freshwater input from both increased net precipitation and changes in sea ice export (Downes and Hogg, 2013357). CMIP5 projections (Figure 3.3) indicate that observed Southern Ocean warming trends will continue under RCP4.5 and RCP8.5 scenarios, leading to 1°C–3°C warming by 2100 mostly in the upper ocean (Sallée et al., 2013a494). The high seas region of the CAO is per definition outside of any nation's EEZ. Antarctic Coastal Polynyas The Antarctic continent is surrounded by coastal polynyas, which form from the combined effects of winds and landfast ice in the lee of coastal features that protrude into the westward coastal current (Nihashi and Ohshima, 2015445; Tamura et al., 2016446). England et al. As a result, progressively more ice will flow into the ocean (Figure CB8.1a). There is a very wide spread of model responses in the Weddell Sea (Hobbs et al., 2015416; Ivanova et al., 2016417), a region with complex ocean-sea ice interactions that many models do not replicate (de Lavergne et al., 2014). Since AR5, there is growing observational and modelling evidence that accelerated retreat may be underway in several major Amundsen Sea outlets, including Thwaites, Pine Island, Smith, and Kohler glaciers (e.g., Rignot et al., 2014) supporting the MISI hypothesis, although observed grounding line retreat on retrograde slope is not definitive proof that MISI is underway. Addressing the risks of climate change impacts in polar regions also requires linking levels of governance and sector governance across local to global scales, considering impacts and human adaptation (Stokke, 20092149; Berkman and Vylegzhanin, 20102150; Tuori, 20112151; Young, 20112152; Koivurova, 20132153; Prior, 20132154; Shibata, 20152155; Young, 20162156) (high confidence). In the Arctic, changes in primary production have affected regional species composition, spatial distribution, and abundance of many marine species, impacting ecosystem structure (medium confidence). Alien species are a major driver of terrestrial biodiversity change also in the Antarctic region (Frenot et al., 20051814; Chown et al., 20121815; McClelland et al., 20171816). This evidence, however, does not provide a complete assessment of the rates and magnitudes of past glacier mass loss. Fire also appears to be expanding as a novel disturbance into tundra and forest-tundra boundary regions previously protected by a cool, moist climate (Jones et al., 20091545; Hu et al., 20101546; Hu et al., 20151547) (medium confidence). Mintenbeck, A. There has been an overall greening of the tundra biome, but also browning in some regions of tundra and boreal forest, and changes in the abundance and distribution of animals including reindeer and salmon (high confidence). While such changes and modifications occur in both the Arctic and Antarctic, the role of states has remained present in all the regimes and sectors of human responses (Young, 20162147; Jabour, 20172148). The choices that enable these differences influence the rate and magnitude of polar change, their consequences and impacts at regional and global scales, the effectiveness of adaptation and opportunities for climate resilient pathways (Section 3.5.4). This act applies to all wild living marine resources, and states that its purpose is to ensure sustainable and economically profitable management of resources. Overall during this period, Arctic glaciers caused a similar amount of sea level rise to the GIS (Section 3.3.1.3), but their rate of mass loss per unit area was larger (Bolch et al., 20131187). There is limited evidence (high agreement) that the current rate of glacier mass loss is larger than at any time during the past 4000 years (Fisher et al., 20121188; Zdanowicz et al., 20121189). By 2100, near-surface permafrost area will decrease by 2–66% for RCP2.6 and 30–99% for RCP8.5. This is projected to release 10s to 100s of billions of tons (Gt C), up to as much as 240 Gt C, of permafrost carbon as carbon dioxide and methane to the atmosphere with the potential to accelerate climate change. The onset and persistence of MISI is dependent on several factors in addition to overall bed slope, including the details of the bed geometry and conditions, ice shelf pinning points, lateral shear from the walls, self-gravitation effects on local sea level and isostatic adjustment. Tourism activities in the Antarctic are conducted in accordance with the Protocol on Environmental Protection to the Antarctic Treaty, which establishes general environmental principles, environmental assessment requirements, a scheme of establishing protected areas and restrictions on waste disposal. It acts to oxygenate the ocean interior and sequesters nutrients that ultimately end up supporting a significant fraction of primary production in the rest of the world ocean (Section 5.2.2.2). Ottersen, H. In the Canadian sector of the Beaufort Sea, commercial fisheries are currently only small-scale and locally operated. Snow depth on sea ice is essentially unmeasured, limiting mass balance estimates and ice thickness retrievals. The formation and export of Antarctic Bottom Water is predicted to continue decreasing (Heuzé et al., 2015370) due to warming and freshening of surface source waters near the continent. In some cases, regimes allow for a substantial level of participation by specific groups of the civil society (Jabour, 20172143; Keil and Knecht, 20172144). The predominant shipborne activities in Antarctica are fishing, logistic support to land-based stations, and marine research vessels operating for both non-governmental and governmental sectors. Mass balance (Gt yr-1) of the West Antarctic Ice Sheet (WAIS), Antarctic Peninsula (AP), East Antarctic Ice Sheet (EAIS), the combined Antarctic Ice Sheets (AIS) and the Greenland Ice Sheet (GIS) and the total sea level contribution (mm yr-1). AIS mass changes are dominated by changes in snowfall and glacier flow. At a basin/circumpolar scale, there is high confidence in these projections due to our robust understanding of the driving mechanisms. Responsibility for funding has been a key issue in the relocation process (Iverson, 20132062) as well as the overall role of government and local communities in relocation

planning (Marino, 20122063; Romero Manrique et al., 20182064). The Greenland Ice Sheet (GIS) has limited direct access to the ocean through relatively narrow subglacial troughs (Morlighem et al., 20171346), and most of the bedrock at the ice sheet margin is above sea level (Figure 4.5). Currently, there is no formal mechanism for choosing which data are needed in a management procedure for krill or how to include such data. Dynamic thinning in the ASE and western AP accounted for 88% of the –36 ± 15 Gt yr–1 increase in AIS mass loss from 2008 to 2015 (Gardner et al., 2018957). The stipulation of the total quota for the various joint fish stocks is a key element, as is more long-term precautionary harvesting strategies, better allowing for responses to climate change (medium confidence). Second, physical changes in the Arctic and Antarctic influence processes that are important for global climate and sea level. The Weddell Polynya The Weddell Polynya is a large area of open water within the winter ice pack of the Weddell Sea close to the Maud Rise seamount (at approximately 65ºS, 3ºE), and has importance on a global scale for deep water ventilation. The horizontal circulation in the circumpolar Southern Ocean is comprised of an eastward-flowing mean current concentrated in a series of sinuous, braided jets exhibiting strong meandering variability and shedding small-scale transient eddies (Figure CB7.1). New water masses are produced that sink back into the ocean interior. While potential aquifer storage is equivalent to about a quarter of annual GIS melt production (Koenig et al., 20141053; van den Broeke et al., 20161054) and aquifers have spread to higher altitudes (Steger et al., 20171055), their potential to buffer runoff has been reduced by firn densification (Polashenski et al., 20141056), diversion of water to the bed via crevasses (Poinar et al., 20171058), and the formation of ice layers that prevent drainage and promote surface ponding on the firn (Charalampidis et al., 2016) (high confidence). With ice retreating and thinning, and improved access to natural resources, coastal states are increasingly recurring to the option to invoke Article 76 of the UNCLOS (Art. 76 UNCLOS; Verschuuren, 20132159) and seek to demonstrate with scientific data, submitted to the Commission on the Limits of Continental Shelf, and within a set timeline, that their continental shelf is extended. Many ships travelling these waters will therefore continue to pose risks to the environment and to themselves, as they are not regulated under the Polar Code (high confidence). An exception is that the Beaufort Gyre expanded to the northwest between 2003 and 2014, contemporaneous with changes in its freshwater accumulation and alterations in wind forcing, resulting in increased proximity to the Chukchi Plateau and Mendeleev Ridge (Armitage et al., 2017329; Regan et al., 2019330) (Section 3.2.1.2.2). Polar regions support several of the world's largest commercial fisheries. Canada's Northwest Passage (southern route), which only saw occasional cruise ship transits in the early 2000s is now reliably accessible during the summer cruising season, and as a result has experienced a doubling and quadrupling of cruise and pleasure craft activity over the past decade (Johnston et al., 2017864; Dawson et al., 2018865). 2) Across many aspects, the polar regions of the future will appear significantly different from those of today By the end of this century, Arctic sea ice and snow on land are projected to be diminished compared with today, as are the masses of the AIS and GIS and the polar glaciers (Sections 3.2.2, 3.3.2; 3.4.2). Waugh (2014)350 and Ting and Holzer (2017)351 suggest that over the 1990s–2000s water mass ages changed in a manner consistent with an increase in upwelling and overturning. Mean maximum ice thickness is projected to decrease by 10–50 cm over the same period (Brown and Duguay, 20111571). Despite established cooperation in international polar region governance, several authors have come to the conclusion that the current international legal framework is inadequate when applying a precautionary approach at the regional level (medium confidence). The effects of current and projected levels of acidification have been examined for a broad suite of species groups (bivalves, cephalopods, echinoderms, crustaceans, corals and fishes) and these studies reveal species-specific differences in sensitivity, as well as differences in the scope for, and energetic cost of, adaptation (Luckman et al., 2014524; Howes et al., 2015525; Falkenberg et al., 2018526). 3.2.3.2 3.2.3.2 Southern Ocean Marine ecosystem dynamics in the Antarctic region are dominated by the ACC and its frontal systems (Cross-Chapter Box 7 in Chapter 3), subpolar gyres, polar seasonality, the annual advance and retreat of sea ice (Section 3.2.1.1) and the supply of limiting micronutrients for productivity (most commonly iron) (Section 5.2.2.5). This ice cliff failure can lead to ice sheet retreat via a process called marine ice cliff instability (MICI; Figure CB8.1b), that has been hypothesised to cause partial collapse of the West Antarctic Ice Sheet (WAIS) within a few centuries (Pollard et al., 20151328; DeConto and Pollard, 20161329). Implications to world demands on natural resources, innovation and development of technologies, population trends and economic growth are likely to affect all systems, as is the Paris Agreement (AMAP, 2017b2128). This chapter therefore takes a systems approach that emphasises the interactions of cryosphere and ocean changes and their diverse consequences and impacts to assess key issues of climatic change for the polar regions, the planet and its people (Figure 3.1). antarctica) and for Antarctic krill (Euphausia superba), but mesozooplankton communities do not appear to have changed or shifted in response to ocean warming (Section 3.2.3.2). Complex interplay between hydrology and hydraulics in controlling spring flooding and ice jam events complicate projections of these events (Prowse et al., 20101573; Prowse et al., 20111574). Overturning circulation and water mass formation The Southern Ocean is the key region globally for the upwelling of interior ocean waters to the surface, enabling waters that were last ventilated in the pre-industrial era to interact with the industrial-era atmosphere and the cryosphere. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. To view the Supplementary Material for Chapter 3 click on the image below There has been a southward shift in the distribution of Antarctic krill in the South Atlantic, the main area for the krill fishery (medium confidence). 3.2.4.3 Transportation The Arctic is reliant on marine transportation for the import of food, fuel and other goods. Only a few studies have focused on the potential impact of Antarctic sea ice changes on the mid-latitude circulation (Kidston et al., 2011212; Raphael et al., 2011213; Bader et al., 2013214; Smith et al., 2017b215; England et al., 2018216); these find that any impacts on the jet stream are strongly dependent on the season and model examined. Geopolitical complexities also confound responses. 3.2.1.2 Ocean Properties Ocean heat content trend (0–2000 m depth) during 2005–2017 and 1970–2017 for the global ocean and Southern Ocean. There is limited understanding concerning the resources that are needed for successful adaptation responses and about the effectiveness of institutions in supporting adaptation. Comparing 20 CMIP5 simulations for RCP8.5, Nummelin et al.

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