

28

Polar Regions

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This chapter should be cited as:

Larsen, J.N., O.A. Anisimov, A. Constable, A.B. Hollowed, N. Maynard, P. Prestrud, T.D. Prowse, and J.M.R. Stone, 2014: Polar regions. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Barros, V.R., C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1567-1612.

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Executive Summary

Additional and stronger scientific evidence has accumulated since the AR4 that reinforces key findings made in the Fourth Assessment Report (AR4).

The impacts of climate change, and the adaptations to it, exhibit strong spatial heterogeneity in the polar regions because of the high diversity of social systems, biophysical regions, and associated drivers of change (*high confidence*). {28.2.2} For example, the tree line has moved northward and upward in many, but not all, Arctic areas (*high confidence*) and significant increases in tall shrubs and grasses have been observed in many places (*very high confidence*). {28.2.3.1.2}

Some marine species will shift their ranges in response to changing ocean and sea ice conditions in the polar regions (*medium confidence*). The response rate and the spatial extent of the shifts will differ by species based on their vulnerability to change and their life history. {28.2.2, 28.3.2} Loss of sea ice in summer and increased ocean temperatures are expected to impact secondary pelagic production in some regions of the Arctic Ocean, with associated changes in the energy pathways within the marine ecosystem (*medium confidence*). These changes are expected to alter the species composition of zooplankton in some regions, with associated impacts on some fish and shellfish populations (*medium confidence*). {28.2.2.1} Also, changes in sea ice and the physical environment to the west of the Antarctic Peninsula are altering phytoplankton stocks and productivity, and krill (*high confidence*). {28.2.2.2}

Climate change is impacting terrestrial and freshwater ecosystems in some areas of Antarctica and the Arctic. This is due to ecological effects resulting from reductions in the duration and extent of ice and snow cover and enhanced permafrost thaw (*very high confidence*), and through changes in the precipitation-evaporation balance (*medium confidence*). {28.2.1, 28.2.3}

The primary concern for polar bears over the foreseeable future is the recent and projected loss of annual sea ice cover, decreased ice duration, and decreased ice thickness (*high confidence*). Of the two subpopulations where data are adequate for assessing abundance effects, it is *very likely* that the recorded population declines are caused by reductions in sea ice extent. {28.2.2.1.2, 28.3.2.2.2}

Rising temperatures, leading to the further thawing of permafrost, and changing precipitation patterns have the potential to affect infrastructure and related services in the Arctic (*high confidence*). {28.3.4.3} Particular concerns are associated with damage to residential buildings resulting from thawing permafrost, including Arctic cities; small, rural settlements; and storage facilities for hazardous materials. {28.2.4-5}

In addition, there is new scientific evidence that has emerged since the AR4.

The physical, biological, and socioeconomic impacts of climate change in the Arctic have to be seen in the context of often interconnected factors that include not only environmental changes caused by drivers other than climate change but also demography, culture, and economic development. Climate change has compounded some of the existing vulnerabilities caused by these other factors (*high confidence*). {28.2.4-5, 28.4} For example, food security for many Indigenous and rural residents in the Arctic is being impacted by climate change, and in combination with globalization and resource development food insecurity is projected to increase in the future (*high confidence*). {28.2.4}

The rapid rate at which climate is changing in the polar regions will impact natural and social systems (*high confidence*) and may exceed the rate at which some of their components can successfully adapt (*low to medium confidence*). {28.2.4, 28.4} The decline of Arctic sea ice in summer is occurring at a rate that exceeds most of the earlier generation model projections (*high confidence*), and evidence of similarly rapid rates of change is emerging in some regions of Antarctica. {WGI AR5 Chapters 4, 5, 9} In the future, trends in polar regions of populations of marine mammals, fish, and birds will be a complex response to multiple stressors and indirect effects (*high confidence*). {28.3.2} Already, accelerated rates of change in permafrost thaw, loss of coastal sea ice, sea level rise, and increased weather intensity are forcing relocation of some Indigenous communities in Alaska (*high confidence*). {28.2.4.2, 28.2.5, 28.3.4}

Shifts in the timing and magnitude of seasonal biomass production could disrupt matched phenologies in the food webs, leading to decreased survival of dependent species (*medium confidence*). If the timing of primary and secondary production is no longer matched to the timing of spawning or egg release, survival could be impacted, with cascading implications to higher trophic levels. This impact would be exacerbated if shifts in timing occur rapidly (*medium confidence*). {28.2.2, 28.3.2} Climate change will increase the vulnerability of terrestrial ecosystems to invasions by non-indigenous species, the majority likely to arrive through direct human assistance (*high confidence*).

Ocean acidification has the potential to inhibit embryo development and shell formation of some zooplankton and krill in the polar regions, with potentially far-reaching consequences to food webs in these regions (*medium confidence*). Embryos of Antarctic krill have been shown to be vulnerable to increased concentrations of carbon dioxide (CO₂) in the water (*high confidence*). As well, there is increasing evidence that pelagic molluscs (pteropods) are vulnerable to ocean acidification (*medium confidence*). {28.2.2, 28.3.2}

There is increased evidence that climate change will have large effects on Arctic communities, especially where narrowly based economies leave a smaller range of adaptive choices. {28.2.6.1, 28.4} Some commercial activities will become more profitable while others will face decline. Increased economic opportunities are expected with increased navigability in the Arctic Ocean and the expansion of some land- and freshwater-based transportation networks. {28.2.6.1.3, 28.3.4.3} The informal, subsistence-based economy will be impacted (*high confidence*). There is *high confidence* that changing sea ice conditions may result in more difficult access for hunting marine mammals. {28.2.6.1.6} Although Arctic residents have a history of adapting to change, the complex interlinkages among societal, economic, and political factors and climatic stresses represent unprecedented challenges for northern communities, particularly if the rate of change will be faster than the social systems can adapt (*high confidence*). {28.2.5, 28.4}

Impacts on the health and well-being of Arctic residents from climate change are significant and projected to increase—especially for many Indigenous peoples (*high confidence*). {28.2.4} These impacts are expected to vary among the diverse settlements, which range from small, remote, predominantly Indigenous communities to large cities and industrial settlements (*high confidence*), especially those in highly vulnerable locations along ocean and river shorelines. {28.2.4}

28.1. Introduction

Several recent climate impact assessments on polar regions have been undertaken, including the synthesis report on Snow, Water, Ice and Permafrost in the Arctic (AMAP, 2011a), the State of the Arctic Coast 2010 (2011) reports, the Antarctic Climate and the Environment (Turner et al., 2009, 2013), Arctic Resilience Interim Report 2013 (2013), and the findings of the International Polar Year (IPY; Krupnick et al., 2011). These reports draw a consistent pattern of climate-driven environmental, societal, and economic changes in the polar regions in recent decades. In this chapter, we use the scientific literature, including these reports, to consolidate the assessment of the impacts of climate change on polar regions from 2007, advance new scientific evidence of impacts, and identify key gaps in knowledge on current and future impacts. Previous IPCC reports define the Arctic as the area within the Arctic Circle (66°N), and the Antarctic as the continent with surrounding Southern Ocean south of the polar front, which is generally close to 58°S (IPCC, 2007). For the purpose of this report we use the conventional IPCC definitions as a basis, while incorporating a degree of flexibility when describing the polar regions in relation to particular subjects.

Changes in the physical and chemical environments of the polar regions are detailed in the WGI contribution to the AR5. There is evidence that Arctic land surface temperatures have warmed substantially since the mid-20th century, and the future rate of warming is expected to exceed the global rate. Sea ice extent at the summer minimum has decreased significantly in recent decades, and the Arctic Ocean is projected to become nearly ice free in summer within this century. The duration of snow cover extent and snow depth are decreasing in North America while

increasing in Eurasia. Since the late 1970s, permafrost temperatures have increased between 0.5°C and 2°C. In the Southern Hemisphere, the strongest rates of atmospheric warming are occurring in the western Antarctic Peninsula (WAP, between 0.2°C and 0.3°C per decade) and the islands of the Scotia Arc, where there have also been increases in oceanic temperatures and large regional decreases in winter sea ice extent and duration. Warming, although less than WAP, has also occurred in the continental margins near the Bellingshausen Sea, Prydz Bay, and the Ross Sea, with areas of cooling in between. Land regions have experienced glacial recession and changes in the ice and permafrost habitats in the coastal margins. The Southern Ocean continues to warm, with increased freshening at the surface due to precipitation leading to increased stratification. In both polar regions, as a result of acidification, surface waters will become seasonally corrosive to aragonite within decades, with some regions being affected sooner than others (see Box CC-OA; WGI AR5 Chapter 6). Observations and models indicate that the carbon cycle of the Arctic and Southern Oceans will be impacted by climate change and increased carbon dioxide (CO₂).

28.2. Observed Changes and Vulnerability under Multiple Stressors

28.2.1. Hydrology and Freshwater Ecosystems

28.2.1.1. Arctic

Arctic rivers and lakes continue to show pronounced changes to their hydrology and ecology. Previously noted increases in Eurasian Arctic

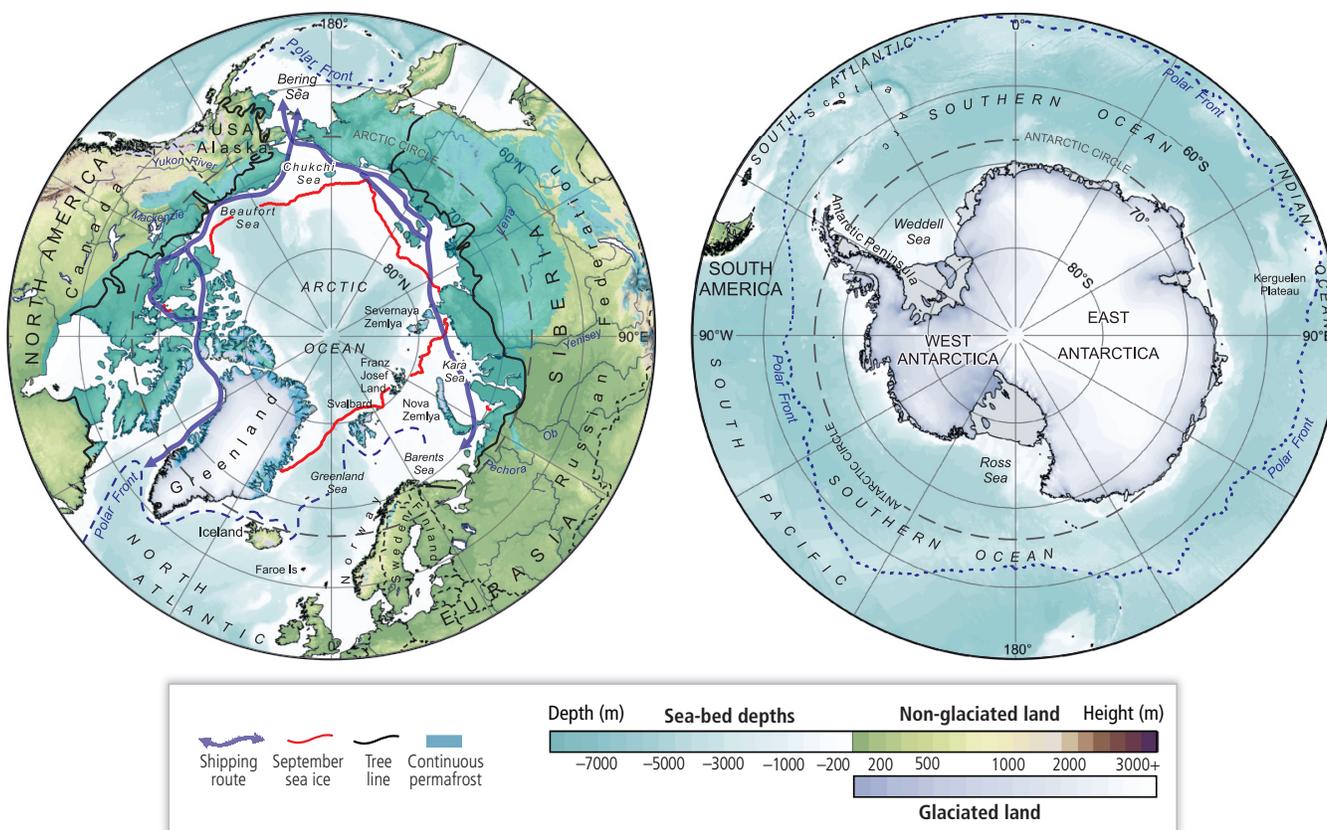


Figure 28-1| Location maps of the north and south polar regions (courtesy of P. Fretwell, British Antarctic Survey).

river flow (1936–1999; Peterson et al., 2002) could not, for a similar period (1951–2000), be attributed with certainty to precipitation changes (Milliman et al., 2008) but has been, including more recent extreme increases (2007), attributed to enhanced poleward atmospheric moisture transport (Zhang et al., 2013). By contrast, decreased flow in high-latitude Canadian rivers (1964–2000; average –10%) does match that for precipitation (Déry and Wood, 2005). Recent data (1977–2007) for 19 circumpolar rivers also indicate an area-weighted average increase of +9.8% (–17.1 to 47.0%; Overeem and Syvitski, 2010) accompanied by shifts in flow timing, with May snowmelt increasing (avg. 66%) but flow in the subsequent month of peak discharge decreasing (~7%). Across the Russian Arctic, dates of spring maximum discharge have also started to occur earlier, particularly in the most recent (1960–2001) period analyzed (average –5 days; range for four regions +0.2 to –7.1 days), but no consistent trend exists for magnitude (average –1%; range +21 to –24%; Shiklomanov et al., 2007). Earlier timing was most pronounced in eastern, colder continental climates, where increases in air temperature have been identified as the dominant control (Tan et al., 2011).

Increases have also occurred in winter low flows for many Eurasian and North American rivers (primarily in the late 20th century; Smith et al., 2007; Walvoord and Striegl, 2007; St. Jacques and Sauchyn, 2009; Ye et al., 2009), the key exceptions being decreases in eastern North America and unchanged flow in small basins of eastern Eurasia (Rennermalm et al., 2010). Most such studies suggest permafrost thaw (WGI AR5 Chapter 4) has increased winter flow, whereas others suggest increases in net winter precipitation minus evapotranspiration (Rawlins et al., 2009a,b; Landerer et al., 2010). Insufficient precipitation stations preclude deciphering the relative importance of these factors (WGI AR5 Section 2.5.1).

The surface-water temperatures of large water bodies has warmed (1985–2009; Schneider and Hook, 2010), particularly for mid- and high latitudes of the Northern Hemisphere, with spatial patterns generally matching those for air temperature. Where water bodies warmed more rapidly than air temperature, decreasing ice cover was suggested as enhancing radiative warming. Paleolimnological evidence indicates that the highest primary productivity was associated with warm, ice-free summer conditions and the lowest with periods of perennial ice (Melles et al., 2007). Increasing water temperatures affect planktonic and benthic biomass and lead to changes in species composition (Christoffersen et al., 2008; Heino et al., 2009; Jansson et al., 2010). Reduced ice cover with higher air temperatures and evaporation are responsible for the late-20th to early-21st century desiccation of some Arctic ponds (Smol and Douglas, 2007).

Changes have occurred in the size and number of permafrost lakes over the last half-century (Hinkel et al., 2007; Marsh et al., 2009), but their patterns and rates of change are not consistent because of differing thawing states, variations in warming, and effects of human activities (Hinkel et al., 2007; Prowse and Brown, 2010a). Thawing permafrost affects the biogeochemistry of water entering lakes and rivers (Frey and McClelland, 2009; Kokelj et al., 2009) and their ecological structure and function (Lantz and Kokelj, 2008; Thompson et al., 2008; Mesquita et al., 2010), such as enhancing eutrophication by a shift from pelagic to benthic-dominated production (Thompson et al., 2012).

The aquatic ecosystem health and biodiversity of northern deltas is dependent on combined changes in the elevation of spring river ice-jam floods and sea level (Lesack and Marsh, 2007, 2010). Diminishing ice shelves (last half-century) have also caused a decline in the number of freshwater epishelf lakes that develop behind them (Veillette et al., 2008; Vincent et al., 2009). Although such biophysical dependencies have been established, temporal trends in such river-delta and epishelf lake impacts and their linkages to changing climate remain to be quantified precisely.

An interplay of freshwater-marine conditions also affects the timing, growth, run size, and distribution of several Arctic freshwater and anadromous fish. Key examples include the timing of marine exit of Yukon River Chinook salmon (*Oncorhynchus tshawytscha*; 1961–2009) varied with air and sea temperatures and sea ice cover (Mundy and Evenson, 2011); the growth of young-of-year Arctic cisco (*Coregonus autumnalis*; 1978–2004) varied in response to lagged sea ice concentration and Mackenzie River discharge, also indicating that decreased sea ice concentration and increased river discharge enhanced marine primary production, leading to more favorable foraging conditions (von Biela et al., 2011); and factors that influence the water level and freshening of rivers, as well as the strength, duration, and directions of prevailing coastal winds, affect survival of anadromous fishes during coastal migration and their subsequent run size (Fechhelm et al., 2007).

28.2.1.2. Antarctic

Biota of Antarctic freshwater systems (lakes, ponds, short streams, and seasonally wetted areas) are dominated by benthic microbial communities of cyanobacteria and green algae in a simple food web. Mosses occur in some continental lakes with higher plants absent. Planktonic ecosystems are typically depauperate and include small algae, bacteria, and colorless flagellates, with few metazoans and no fish (Quesada and Velázquez, 2012). Recent compilations of single-year data sets have reinforced previous conclusions on the changing freshwater habitats in Antarctica (Verleyen et al., 2012). In regions where the climate has warmed, the physical impacts on aquatic ecosystems include loss of ice and perennial snow cover, increasing periods of seasonal open water, increased water column temperatures, and changes in water column stratification. In some areas, a negative water balance has occurred as a result of increased temperature and changes in wind strength driving enhanced evaporation and sublimation and leading to increased salinity in lakes in recent decades (Hodgson et al., 2006a). In other areas, especially glacial forelands, increased temperatures have led to greater volumes of seasonal meltwater in streams and lakes together with increased nutrient fluxes (*high confidence*). In both cases, the balance between precipitation and evaporation can have detectable effects on lake ecosystems (*medium confidence*) through changes in water body volume and lake chemistry (Lyons et al., 2006; Quesada et al., 2006). Non-dilute lakes with a low lake depth to surface area ratio are most susceptible to interannual and inter-decadal variability in the water balance, as measured by changes in specific conductance (*high confidence*; Verleyen et al., 2012). Warming in the northwestern Antarctic Peninsula region has resulted in permafrost degradation in the last approximately 50 years, impacting surface geomorphology and hydrology (Bockheim et al., 2013) with the potential to increase soil biomass.

28.2.2. Oceanography and Marine Ecosystems

28.2.2.1. Arctic

28.2.2.1.1. Marine plankton, fish, and other invertebrates

WGI documented the expected physical and chemical changes that will occur in Arctic marine ecosystems (WGI AR5 Chapters 4, 6, 11). Naturally occurring interannual, decadal, and multi-decadal variations in climate will continue to influence the Arctic Ocean and its neighboring high-latitude seas (Chapter 5). In recent years (2007–2012), ocean conditions in the Bering Sea have been cold (Stabeno et al., 2012a), while the Barents Sea has been warm (Lind and Ingvaldsen, 2012).

In this section, we build on previous reviews of observed species responses to climate (Wassman et al., 2011) to summarize the current evidence of the impact of physical and chemical changes in marine systems on the phenology, spatial distribution, and production of Arctic marine species. For each type of response, the implications for phytoplankton, zooplankton, fish, and shellfish are discussed. The implications of these changes on marine ecosystem structure and function will be the result of the synergistic effects of all three types of biological responses.

Phenological response

The timing of spring phytoplankton blooms is a function of seasonal light, hydrographic conditions, and the timing of sea ice breakup (Wassman, 2011). In addition to the open water phytoplankton bloom, potentially large ice algal blooms can form under the sea ice (Arrigo, 2012). During the period 1997–2009, a trend toward earlier phytoplankton blooms was detected in approximately 11% of the area of the Arctic Ocean (Kahru et al., 2011). This advanced timing of annual phytoplankton blooms coincided with decreased sea ice concentration in early summer. Brown and Arrigo (2013) studied the timing and intensity of spring blooms in the Bering Sea from 1997 to 2010 and found that in northern regions sea ice consistently retreated in late spring and was associated with ice-edge blooms, whereas in the southern regions the timing of sea ice retreat varied, with ice-edge blooms associated with late ice retreat, and open water blooms associated with early ice retreat. Given the short time series and limited studies, there is *medium confidence* that climate variability and change has altered the timing and the duration of phytoplankton production.

The life cycles of calanoid copepods in the Arctic Ocean and Barents Sea are timed to utilize ice algal and phytoplankton blooms (Falk-Petersen et al., 2009; Søreide et al., 2010; Darnis et al., 2012). Based on a synthesis of existing data, Hunt, Jr. et al. (2011) hypothesized that, in the southeastern Bering Sea, ocean conditions and the timing of sea ice retreat influences the species composition of dominant zooplankton, with lipid-rich copepods being more abundant in cold years.

There is ample evidence that the timing of spawning and hatching of some fish and shellfish is aligned to match larval emergence with seasonal increases in prey availability (Gjosaeter et al., 2009; Vikebø et al., 2010; Bouchard and Fortier, 2011; Drinkwater et al., 2011). These regional phenological adjustments to local conditions occurred over

many generations (Ormseth and Norcross, 2009; Geffen et al., 2011; Kristiansen et al., 2011). There is *medium to high confidence* that climate-induced disruptions in this synchrony can result in increased larval or juvenile mortality or changes in the condition factor of fish and shellfish species in the Arctic marine ecosystems.

Observed spatial shifts

Spatial heterogeneity in primary production has been observed (Lee et al., 2010; Grebmeier, 2012). Simulation modeling studies show that spatial differences in the abundance of four species of copepod can be explained by regional differences in the duration of the growing season and temperature (Ji et al., 2012). Retrospective studies based on surveys from 1952 to 2005 in the Barents Sea revealed that changes in the species composition, abundance, and distribution of euphausiids were related to climate-related changes in oceanographic conditions (Zhukova et al., 2009).

Retrospective analysis of observed shifts in the spatial distribution of fish and shellfish species along latitudinal and depth gradients showed observed spatial shifts were consistent with expected responses of species to climate change (Simpson et al., 2011; Poloczanska et al., 2013; see also Box CC-MB). Retrospective studies from the Bering Sea, Barents Sea, and the northeast Atlantic Ocean and Icelandic waters showed that fish shift their spatial distribution in response to climate variability (i.e., interannual, decadal, or multi-decadal changes in ocean temperature; Mueter and Litzow, 2008; Sundby and Nakken, 2008; Hátún et al., 2009; Valdimarsson et al., 2012; Kotwicki and Lauth, 2013). There are limits to the movement potential of some species. Vulnerability assessments indicate that the movement of some sub-Arctic fish and shellfish species into the Arctic Ocean may be impeded by the presence of water temperatures on the shelves that fall below their thermal tolerances (Hollowed et al., 2013; Hunt, Jr. et al., 2013). Coupled biophysical models have reproduced the observed spatial dynamics of some the species in the Bering and Barents Seas, and are being used to explain the role of climate variability and change on the distribution and abundance of some species (Huse and Ellingsen, 2008; Parada et al., 2010). In summary, there is *medium to high confidence* based on observations and modeling that some fish and shellfish have shifted their distribution in response to climate impacts on the spatial distribution and volume of suitable habitat.

Observed variations in production

Seasonal patterns in light, sea ice cover, freshwater input, stratification, and nutrient exchange act in concert to produce temporal cycles of ice algal and phytoplankton production in Arctic marine ecosystems (Perrette et al., 2011; Wassmann, 2011; Tremblay et al., 2012). Satellite observations and model estimates for the period 1988–2007 showed that phytoplankton productivity increased in the Arctic Ocean in response to a downward trend in the extent of summer sea ice (Zhang et al., 2010). Satellite data provided evidence of a 20% increase in annual net primary production in the Arctic Ocean between 1998 and 2009 in response to extended ice-free periods (Arrigo and van Dijken, 2011). Regional trends in primary production will differ in response to the

amount of open water area in summer (Arrigo and van Dijken, 2011). Other studies showed gross primary production increased with increasing air temperature in the Arctic Basin and Eurasian shelves (Slagstad et al., 2011). A recent 5-year study (2004–2008) in the Canada Basin showed that smaller phytoplankton densities were higher than larger phytoplankton densities in years when sea surface temperatures (SSTs) were warmer, the water column was more stratified, and nutrients were more depleted during the Arctic summer (Li et al., 2009; Morán et al., 2010). Additional observations will help to resolve observed differences between *in situ* and satellite-derived estimates of primary production (Matrai et al., 2013). In conclusion, based on recent observations and modeling, there is *medium to high confidence* that primary production has increased in the Arctic Ocean in response to changes in climate and its impact on the duration and areal extent of ice-free periods in summer.

Regional differences in zooplankton production have been observed. During a period of ocean warming (1984–2010), Dalpadado et al. (2012) observed an increase in the biomass of lipid-rich euphausiids in the Barents Sea and relatively stable levels of biomass and production of *Calanus finmarchicus*. In the Bering Sea, observations over the most recent decade in the southeast Bering Sea showed *C. marshallae* were more abundant in cold than in warm years (Coyle et al., 2011).

There is strong evidence that climate variability impacts the year-class strength of Arctic marine fish and shellfish through its influence on predation risk; the quality, quantity, and availability of prey; and reproductive success (Mueter et al., 2007; Bakun 2010; Drinkwater et al., 2010). Regional differences in the species responses to climate change will be a function of the exposure of the species to changing environmental conditions, the sensitivity of the species to these changes (Beaugrand and Kirby, 2010), and the abilities of species to adapt to changing conditions (Pörtner and Peck, 2010; Donelson et al., 2011). There is *high confidence* that shifts in ocean conditions have impacted the abundance of fish and shellfish in Arctic regions. Observed trends in the abundance of commercial fish and shellfish may also be influenced by historical patterns of exploitation (Vert-pre et al., 2013).

28.2.2.1.2. Marine mammals, polar bears, and seabirds

Studies on responses of Arctic and subarctic marine mammals to climate change are limited and vary according to insight into their habitat requirements and trophic relationships (Laidre et al., 2008). Many Arctic and sub-Arctic marine mammals are highly specialized, have long life spans, and are poorly adapted to rapid environmental change (Moore and Huntington, 2008), and changes may be delayed until significant sea ice loss has occurred (Freitas et al., 2008; Laidre et al., 2008).

Climate change effects on Arctic and sub-Arctic marine mammal species will vary by life history, distribution, and habitat specificity (*high confidence*). Climate change will improve conditions for a few species, have minor negative effects for others, and some will suffer major negative effects (Laidre et al., 2008; Ragen et al., 2008). Climate change resilience will vary and some ice-obligate species should survive in regions with sufficient ice and some may adapt to ice-free conditions (Moore and Huntington, 2008). Less ice-dependent species may be more

adaptable but an increase in seasonally migrant species could increase competition (Moore and Huntington, 2008).

Climate change vulnerability was associated with feeding specialization, ice dependence, and ice reliance for prey access and predator avoidance (Laidre et al., 2008). There is *medium agreement* on which species' life histories are most vulnerable. Hooded seals (*Cystophora cristata*) and narwhal (*Monodon monoceros*) were identified as most at risk and ringed seals (*Pusa hispida*) and bearded seals (*Erignathus barbatus*) as least sensitive (Laidre et al., 2008). Kovacs et al. (2010) shared concern for hooded seals and narwhal but had concerns for ringed seals and bearded seals. Narwhal may have limited ability to respond to habitat alteration (Williams et al., 2011). Species that spend only part of the year in the Arctic (e.g., gray whale (*Eschrichtius robustus*), killer whale (*Orcinus orca*)) may benefit from reduced ice (Laidre et al., 2008; Moore, 2008; Higdon and Ferguson, 2009; Matthews et al., 2011; Ferguson et al., 2012). Killer whale expansion into the Arctic could cause a trophic cascade (Higdon and Ferguson, 2009), although there is *limited evidence* at this time.

There is *limited evidence* although *medium agreement* that generalists and pelagic feeding species may benefit from increased marine productivity from reduced ice while benthic feeding species near continental shelf habitats may do poorly (Bluhm and Gradinger, 2008). There is *limited evidence* but *high agreement* that dietary or habitat specialists will do poorly with reduced ice. Reduction of summer/autumn ice was the primary extrinsic factor affecting Pacific walrus (*Odobenus rosmarus*), with predictions of distribution changes, reduced calf recruitment, and longer term predictions of high extinction probability (Cooper et al., 2006; MacCracken, 2012). Summer ice retreat may make migration to such habitats energetically unprofitable for ringed seals (Freitas et al., 2008). Ice loss threatens Baltic ringed seals (Kovacs and Lydersen, 2008). In Hudson Bay, earlier spring break-up and changes in snow cover over lairs have reduced ringed seal recruitment (Ferguson et al., 2005). Changes in snowfall over the 21st century were projected to reduce ringed seal habitat for lairs by 70% (Hezel et al., 2012). Similarly, harp seal (*Pagophilus groenlandicus*) breeding habitat was affected by changing ice conditions that could reduce pup survival (Bajzak et al., 2011). Although there is *limited evidence*, there are concerns that climate change may cause indirect effects on Arctic marine mammals' health (e.g., pathogen transmission, food web changes, toxic chemical exposure, shipping, and development; Burek et al., 2008).

Empirical studies provide direct insight into the mechanisms of climate change impact on polar bears (*Ursus maritimus*) but modeling allows predictive capacity (Amstrup et al., 2010; Hunter et al., 2010; Durner et al., 2011; Castro de la Guardia et al., 2013).

Polar bears are highly specialized and use annual ice over the continental shelves as their preferred habitat (Durner et al., 2009; Miller et al., 2012). The recent and projected loss of annual ice over continental shelves, decreased ice duration, decreased ice thickness, and habitat fragmentation are causing reduced food intake, increased energy expenditure, and increased fasting in polar bears (*high confidence*; Stirling and Parkinson, 2006; Regehr et al., 2007; Durner et al., 2009; Amstrup et al., 2010; Hunter et al., 2010; Derocher et al., 2011; Rode et al., 2012; Sahanatien and Derocher, 2012; Castro de la Guardia et al., 2013).

Subpopulation response varies geographically. Only 2 of the 19 subpopulations—Western Hudson Bay (Regehr et al., 2007) and the southern Beaufort Sea (Regehr et al., 2010; Rode et al., 2010a)—have data series adequate for clear identification of abundance effects related to climate change. Many other subpopulations show characteristics associated with decline but some remain stable. Declining ice is causing lower body condition, reduced individual growth rates, lower fasting endurance, lower reproductive rates, and lower survival (*high confidence*; Regehr et al., 2007, 2010; Rode et al., 2010a, 2012; Molnar et al., 2011). Condition is a precursor to demographic change (*very high confidence*; Hunter et al., 2010; Regehr et al., 2010; Rode et al., 2010a; Robinson et al., 2011). The decline in the subpopulation in Western Hudson Bay by 21% between 1987 and 2004 was related to climate change (*medium confidence*; Regehr et al., 2007). Replacement of multi-year ice by annual ice could increase polar bear habitat (*low confidence*; Derocher et al., 2004). Increasing the distance to multi-year ice and terrestrial refugia at maximal melt may result in drowning, cub mortality, and increased energetic costs (Monnett and Gleason, 2006; Durner et al., 2011; Pagano et al., 2012). There is *robust evidence* of changes in sea ice conditions changing polar bear distribution including den areas (*high confidence*; Fischbach et al., 2007; Schliebe et al., 2008; Gleason and Rode, 2009; Towns et al., 2010; Derocher et al., 2011). The number of human-bear interactions is projected to increase with warming (*high confidence*; Stirling and Parkinson, 2006; Towns et al., 2009).

Use of terrestrial resources by polar bears was suggested as adaptive (Dyck et al., 2007, 2008; Dyck and Romberg, 2007; Armstrong et al., 2008; Dyck and Kebreab, 2009; Rockwell and Gormezano, 2009; Smith et al., 2010). Polar bears cannot adapt to terrestrial foods (Stirling et al., 2008b; Amstrup et al., 2009; Rode et al., 2010b; Slater et al., 2010), and will most likely not be able to adapt to climate change and reduced sea ice extent (*very high confidence*). Changing ice conditions are linked to cannibalism (Amstrup et al., 2006), altered feeding (Cherry et al., 2009), unusual hunting behavior (Stirling et al., 2008a), and diet change (Iverson et al., 2006; Thiemann et al., 2008) (*medium confidence*).

Upwelling or subsurface convergence areas found in frontal zones and eddies, and the marginal ice zone, are associated with high marine productivity important to Arctic seabirds (e.g., Irons et al., 2008). Long-term or permanent shifts in convergence areas and the marginal ice-edge zone induced by climate change may cause mismatch between the timing of breeding and the peak in food availability, and thus potentially have strong negative impacts on seabird populations (*medium confidence*; Gaston et al., 2005, 2009; Moline et al., 2008; Grémillet and Boulinier, 2009).

The contrasting results from the relatively few studies of impacts of climate change on Arctic seabirds demonstrate that future impacts will be highly variable between species and between populations of the same species (*medium confidence*). Retreating sea ice and increasing SSTs have favored some species and disadvantaged others (Gaston et al., 2005; Byrd et al., 2008; Irons et al., 2008; Karnovsky et al., 2010; Fredriksen et al., 2013). Some species of seabirds respond to a wide range of sea surface temperatures via plasticity of their foraging behavior, allowing them to maintain their fitness levels (Grémillet et al., 2012). Phenological changes and changes in productivity of some breeding colonies have been observed (Byrd et al., 2008; Gaston and

Woo, 2008; Moe et al., 2009). Negative trends in population size, observed over the last few decades for several species of widespread Arctic seabirds, may be related to over-harvesting and pollution as well as climate change effects (Gaston, 2011). For those species whose distribution is limited by sea ice and cold water, polar warming could be beneficial (Mehlum, 2012).

A major ecosystem shift in the northern Bering Sea starting in the mid-1990s caused by increased temperatures and reduced sea ice cover had a negative impact on benthic prey for diving birds, and these populations have declined in the area (Grebmeier et al., 2006). More recently, the Bering Sea has turned colder again.

28.2.2.2. Antarctica

Productivity and food web dynamics in the Southern Ocean are dominated by the extreme seasonal fluctuations of irradiance and the dynamics of sea ice, along with temperature, carbonate chemistry, and vertical mixing (Massom and Stammerjohn, 2010; Boyd et al., 2012; Murphy et al., 2012a). Moreover, there is large-scale regional variability in habitats (Grant et al., 2006) and their responses to climate change. Antarctic krill, *Euphausia superba* (hereafter, krill), is the dominant consumer, eating diatoms, and, in turn, is the main prey of fish, squid, marine mammals, and seabirds. Krill is dominant from the Bellingshausen Sea east through to the Weddell Sea and the Atlantic sector of the Southern Ocean (Rogers et al., 2012). In the East Indian and southwest Pacific sectors of the Southern Ocean, the krill-dominated system lies to the south of the Southern Boundary of the Antarctic Circumpolar Current (Nicol et al., 2000a,b) while to the north copepods and myctophid fish are most important (Rogers et al., 2012). Further west, where the Weddell Sea exerts an influence, krill are found as far north as the Sub-Antarctic Circumpolar Current Front (Jarvis et al., 2010). Where sea ice dominates for most of the year, ice-obligate species (e.g., *Euphausia crystallorophias* and *Peluragramma antarcticum*) are most important (Smith et al., 2007).

Few studies were available in AR4 to document and validate the changes in these systems resulting from climate change. Those studies reported increasing abundance of benthic sponges and their predators, declining populations of krill, Adélie and emperor penguins, and Weddell seals, and a possible increase in salps, noting some regional differences in these trends. The importance of climate processes in generating these changes could not be distinguished from the indirect consequences of the recovery of whale and seal populations from past over-exploitation (Trathan and Reid, 2009; Murphy et al., 2012a,b).

28.2.2.2.1. Marine plankton, krill, fish, and other invertebrates

Distributions of phytoplankton and zooplankton have moved south with the frontal systems (Hinz et al., 2012; Mackey et al., 2012), including range expansion into the Southern Ocean from the north by the coccolithophorid *Emiliana huxleyi* (Cubillos et al., 2007) and the red-tide dinoflagellate *Noctiluca scintillans* (McLeod et al., 2012) (*medium confidence*). There is insufficient evidence to determine whether other range shifts are occurring.

Collapsing ice shelves are altering the dynamics of benthic assemblages by exposing areas previously covered by ice shelves, allowing increased primary production and establishment of new assemblages (e.g., collapse of the Larson A/B ice shelves) (*medium confidence*; Peck et al., 2009; Gutt et al., 2011). More icebergs are grounding, causing changes in local oceanography and declining productivity that consequently affects productivity of benthic assemblages (*low confidence*; Thrush and Cummings, 2011). Iceberg scour on shallow banks is also increasing, disrupting resident benthic assemblages (*medium confidence*; Barnes and Souster, 2011; Gutt et al., 2011).

Primary production is changing regionally in response to changes in sea ice, glacial melt, and oceanographic features (*medium confidence*; Arrigo et al., 2008; Boyd et al., 2012). Off the west Antarctic Peninsula, phytoplankton stocks and productivity have decreased north of 63°S, but increased south of 63°S (*high confidence*; Montes-Hugo et al., 2009; Chapter 6). This study (based on time series of satellite-derived and measured chlorophyll concentrations) also indicated a change from diatom-dominated assemblages to ones dominated by smaller phytoplankton (Montes-Hugo et al., 2009). The reduced productivity in the north may be tempered by increased inputs of iron through changes to ocean processes in the region (*low confidence*; Dinniman et al., 2012).

Since the 1980s, Antarctic krill densities have declined in the Scotia Sea (Atkinson et al., 2004), in parallel with regional declines in the extent and duration of winter sea ice (Flores et al., 2012). Uncertainty remains over changes in the krill population because this decline was observed using net samples and is not reflected in acoustic abundance time series (Nicol and Brierley, 2010); the observed changes in krill density may have been partly a result of changes in distribution (Murphy et al., 2007). Nevertheless, given its dependence on sea ice (Nicol et al., 2008), the krill population may already have changed and will be subject to further alterations (*high confidence*).

The response of krill populations is probably a complex response to multiple stressors. Decreases in recruitment of post-larval krill across the Scotia Sea have been linked to declines in sea ice extent in the Antarctic Peninsula region (*medium confidence*; Wiedenmann et al., 2009) but these declines may have been offset by increased growth arising from increased water temperature in that area (Wiedenmann et al., 2008). However, near South Georgia krill productivity may have declined as a result of the increased metabolic costs of increasing temperatures (*low confidence*; Hill et al., 2013). The combined effects of changing sea ice, temperature, and food have not been investigated.

28.2.2.2.2. Marine mammals and seabirds

In general, many Southern Ocean seals and seabirds exhibit strong relationships to a variety of climate indices, and many of these relationships are negative to warmer conditions (*low confidence*; Trathan et al., 2007; Barbraud et al., 2012; Forcada et al., 2012). Regional variations in climate change impacts on habitats and food will result in a mix of direct and indirect effects on these species. For example, Adélie penguin colonies are declining in recent decades throughout the Antarctic Peninsula while the reduction in chinstrap penguins is more regional (Lynch et al., 2012) and related to reductions in krill availability (Lima and Estay, 2013). In

contrast, gentoo penguins are increasing in that region and expanding south (*high confidence*; Lynch et al., 2012). This may be explained by the reduced sea ice habitats and krill availability in the north, resulting in a southward shift of krill predators, particularly those dependent on sea ice (Forcada et al., 2012) and the replacement of these predators in the north by species that do not depend on sea ice, such as gentoo penguins and elephant seals (*low confidence*; Costa et al., 2010; Trivelpiece et al., 2011; Ducklow et al., 2012; Murphy et al., 2013). A contrasting situation is in the Ross Sea, where Adélie penguin populations have increased (Smith, Jr. et al., 2012). The mechanisms driving these changes are currently under review and may be more than simply sea ice (Lynch et al., 2012; Melbourne-Thomas et al., 2013). For example, too much or too little sea ice may have negative effects on the demography of Adélie and emperor penguins (see Barbraud et al., 2012, for review). Also, increased snow precipitation that accumulates in breeding colonies can decrease survival of chicks of Adélie penguins when accompanied by reduced food supply (Chapman et al., 2011).

Changes elsewhere are less well known. Some emperor penguin colonies have decreased in recent decades (*low confidence*; Barbraud et al., 2008; Jenouvrier et al., 2009), and one breeding site has been recorded as having been vacated (Trathan et al., 2011). However, there is insufficient evidence to make a global assessment of their current trend. In the sub-Antarctic of the Indian sector, reductions in seal and seabird populations may indicate a region-wide shift to a system with lower productivity (*low confidence*; Weimerskirch et al., 2003; Jenouvrier et al., 2005a,b) but commercial fishing activities may also play a role.

Where frontal systems are shifting south, productive foraging areas also move to higher latitudes. In the Indian sector, this is thought to be causing declines in king penguin colonies on sub-Antarctic islands (*low confidence*; Péron et al., 2010), while the shift in wind patterns may be causing changes to the demography of albatross (*low confidence*; Weimerskirch et al., 2012).

As identified in the WGII AR4, some species' populations may suffer as a result of fisheries while others are recovering from past over-exploitation, either of which may confound interpretation of the response of these species and their food webs to climate change. The recovery of Antarctic fur seals on some sub-Antarctic islands has been well documented, and their populations may now be competing with krill-eating macaroni penguins (Trathan et al., 2012). More recently, there has been confirmation that populations of some Antarctic whales are recovering, such as humpbacks (Nicol et al., 2008; Zerbini et al., 2010), suggesting that food is currently not limiting. In contrast, a number of albatross and petrel populations are declining as a result of incidental mortality in longline fisheries in southern and temperate waters where these birds forage (Croxall et al., 2012).

28.2.3. Terrestrial Ecosystems

28.2.3.1. Arctic

Arctic terrestrial ecosystems have undergone dramatic changes throughout the late Pleistocene and Holocene (last 130,000 years), mainly driven by natural climate change. Significant altitudinal and

latitudinal advances and retreats in tree line have been common, animal species have gone extinct, and animal populations have fluctuated significantly throughout this period (e.g., Lorenzen et al., 2011; Salonen et al., 2011; Mamet and Kershaw, 2012).

28.2.3.1.1. Phenology

Phenological responses attributable to warming are apparent in most Arctic terrestrial ecosystems (*medium confidence*). They vary from earlier onset and later end of season in western Arctic Russia (Zeng et al., 2013), to little overall trend in plant phenology in the Swedish sub-Arctic (Callaghan et al., 2010), to dramatic earlier onset of phenophases in Greenland (Høye et al., 2007; Post et al., 2009a; Callaghan et al., 2011a; see Figure 28-2).

28.2.3.1.2. Vegetation

The latest assessment of changes in Normalized Difference Vegetation Index (NDVI), a proxy for plant productivity, from satellite observations between 1982 and 2012 shows that about a third of the Pan-Arctic has

substantially greened, less than 4% browned, and more than 57% did not change significantly (Xu et al., 2013; Figure 28-3). The greatest increases reported in recent years were in the North American high Arctic, along the Beaufort Sea and the east European Arctic (Zhang et al., 2008; Pouliot et al., 2009; Bhatt et al., 2010; Forbes et al., 2010; Walker et al., 2011; Epstein et al., 2012; Macias-Fauria et al., 2012; Xu et al., 2013).

The positive trends in NDVI are associated with increases in the summer warmth index (sum of the monthly mean temperatures above freezing expressed as degrees Celsius per month) that have increased on average by 5°C per month for the Arctic as a whole (Xu et al., 2013). However, the even greater 10°C to 12°C per month increase for the land adjacent to the Chukchi and Bering Seas (Figure 28-3) was associated with decreases in NDVI. On the Yamal Peninsula in Russia the pattern of NDVI is partly due to surface disturbance, such as landslide activity (Walker et al., 2009). Small rodent cycles reduce NDVI in sub-Arctic Sweden, by decreasing biomass and changing plant species composition (Olofsson et al., 2012). The changing NDVI signal should therefore generally be interpreted with care.

In common with tree line trees and herbs, the abundance and biomass of deciduous shrubs and graminoids (grasses and grass-like plants) have

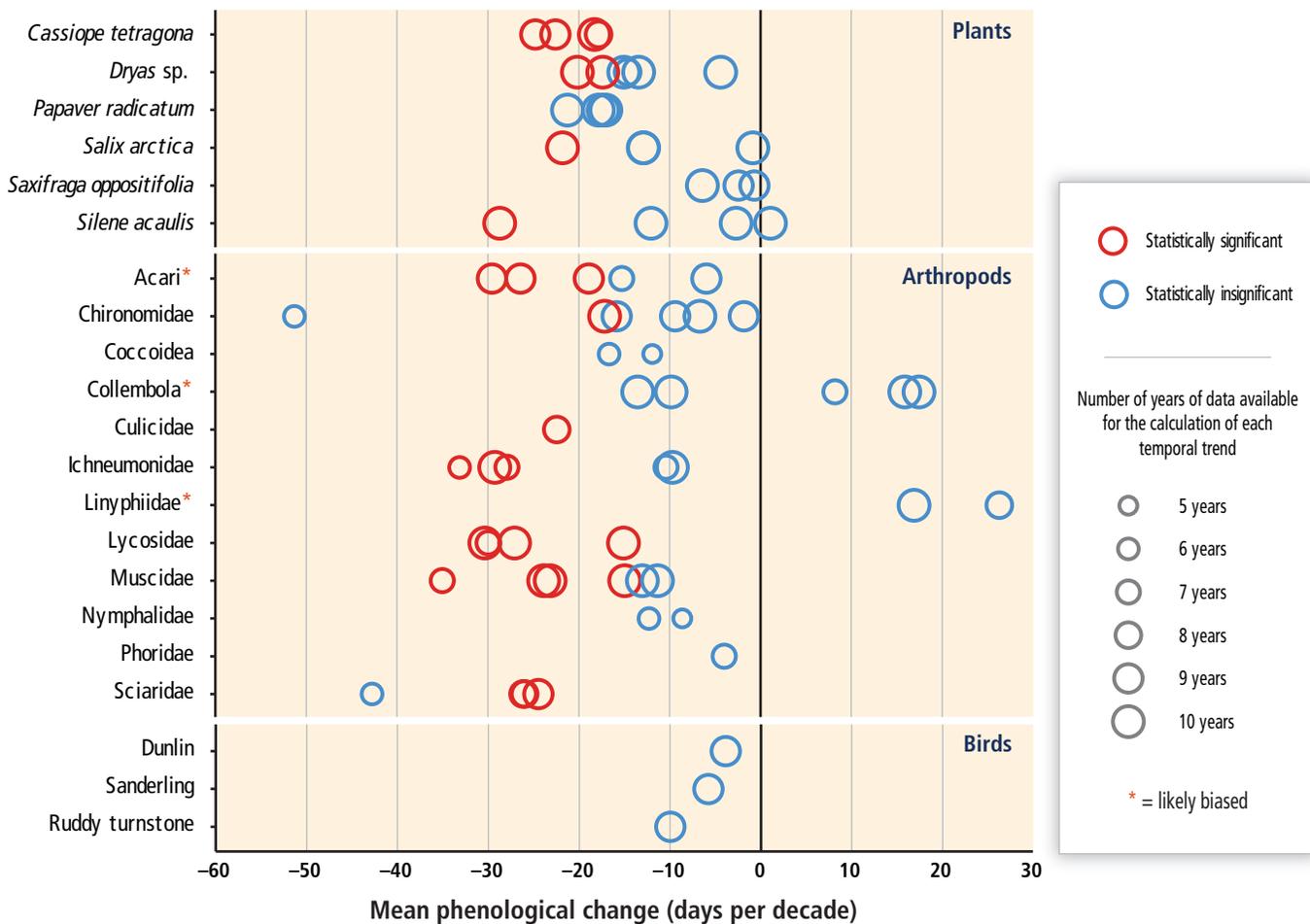


Figure 28-2 | Temporal change in onset of flowering (plants), median date of emergence (arthropods), and clutch initiation dates (birds) estimated from weekly sampling in permanent plots (plants and arthropods) and near-daily surveys through the breeding period in a 19 km² census area (birds) during 1996–2005 in high-Arctic Greenland. Trends based on 5 to 10 years of observations are red circles when statistically significant and otherwise blue. Trends in arthropod taxa marked by asterisks (*) are likely to be biased (Høye et al., 2007).

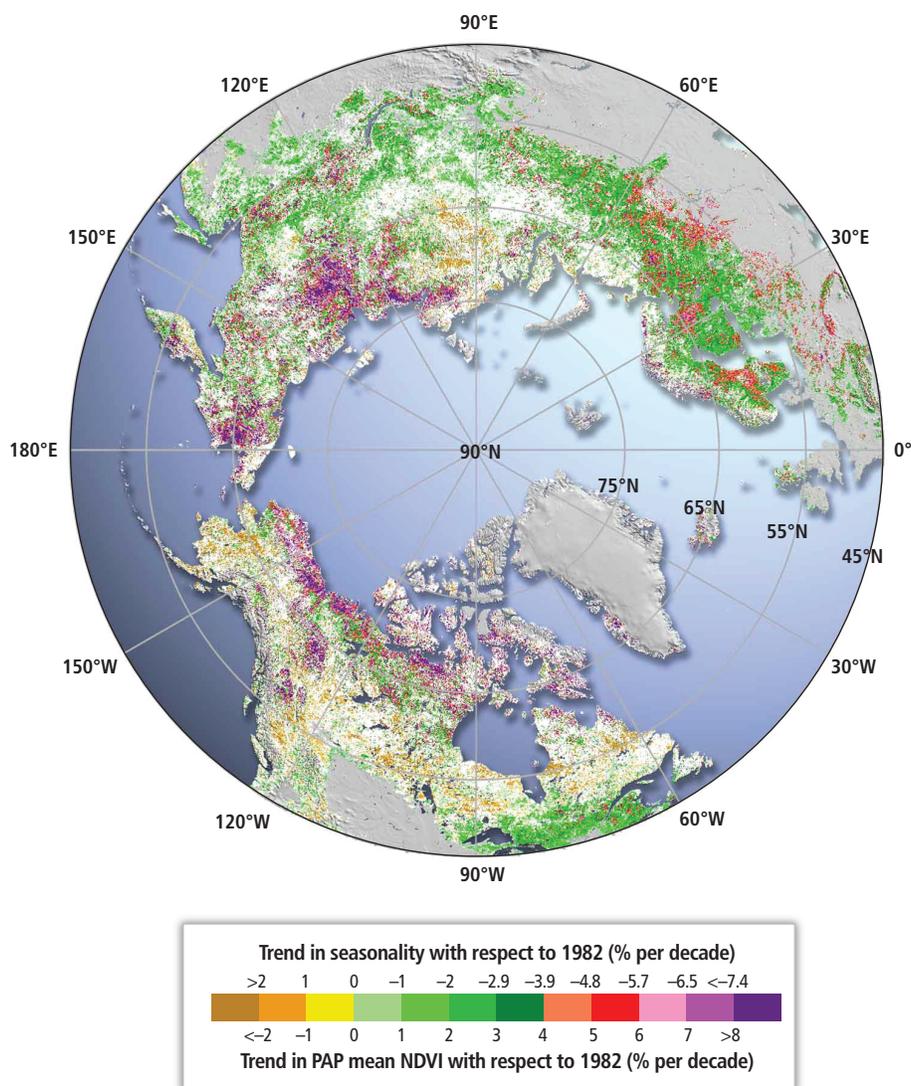


Figure 28-3 | Significant changes ($p < 0.01$) in photosynthetically active period (PAP) Normalized Difference Vegetation Index (NDVI) between 1982 and 2012 (Xu et al., 2013).

increased substantially in certain parts of the Arctic tundra in recent years, but remained stable or decreased in others (*very high confidence*). Attribution for the increases and decreases in deciduous shrubs and graminoids is heterogeneous, with drivers varying among different regions (*very likely*), including Arctic warming, differences in herbivory, industrial development, legacies from past land use, and changes in moisture (Post and Pedersen, 2008; Forbes et al., 2009, 2010; Kitti et al., 2009; Olofsson et al., 2009; Callaghan et al., 2011b, 2013; Kumpula et al., 2011, 2012; Myers-Smith et al., 2011; Elmendorf et al., 2012b; Gamon et al., 2013).

Shrubs have generally expanded their ranges and/or growth over the last 20 years (Danby and Hik, 2007; Hudson and Henry, 2009; Forbes et al., 2010; Hallinger et al., 2010; Callaghan et al., 2011b; Hedenäs et al., 2011; Hill and Henry, 2011; Myers-Smith et al., 2011a,b; Rundqvist et al., 2011; Elmendorf et al., 2012a,b; Macias-Fauria et al., 2012), and have varied from dramatic, that is, 200% area increase in study plots (Rundqvist et al., 2011) in sub-Arctic Sweden, to early invasion of a fell field community on west Greenland by low shrubs (Callaghan et al., 2011a).

A synthesis (61 sites; Elmendorf et al., 2012a) of experimental warming studies of up to 20 years duration in tundra sites worldwide showed, overall, increased growth of deciduous shrubs and graminoids, decreased cover of mosses and lichens, and decreased species diversity and evenness. Elmendorf et al. (2012a) point out that the groups that increased most in abundance under simulated warming were graminoids in cold regions and primarily shrubs in warm regions of the tundra. However, strong heterogeneity in responses to the experimental warming suggested that other factors could moderate the effects of climate warming significantly, such as herbivory, differences in soil nutrients and pH, precipitation, winter temperatures and snow cover, and species composition and density.

Snow bed habitats have decreased in sub-Arctic Sweden (Björk and Molau, 2007; Hedenäs et al., 2011). In other plant communities, changes have been less dramatic, ranging from small increases in species richness in the south west Yukon of the Canadian sub-Arctic (Danby et al., 2011), through subtle changes in plant community composition in west and southeast Greenland (Callaghan et al., 2011a; Daniëls and De Molenaar, 2011) to 70-year stability of a plant community on Svalbard (Prach et al., 2010).

The responses to Arctic warming of lichen and bryophyte (mosses) diversity have been heterogeneous, varying from consistent negative effects to significant increases in recent years (Hudson and Henry, 2009; Tømmervik et al., 2009, 2012). Forbes and Kumpula (2009) recorded long-term and widespread lichen degradation in northern Finland attributed more to trampling of dry lichens by reindeer in summer than to winter consumption as forage.

Palaeorecords of vegetation change indicate that the northern tree line should extend upward and northward during current climate warming (Callaghan et al., 2005) because tree line is related to summer warmth (e.g., Harsch et al., 2009). Although the tree line has moved northward and upward in many Arctic areas, it has not shown a general circumpolar expansion in recent decades (*high confidence*).

Model projections that suggest a displacement of between 11 and 50% of tundra by forest by 2100 (see references in Callaghan et al., 2005) and shifts upslope by 2 to 6 m yr⁻¹ (Moen et al., 2004) and northwards by 7.4 to 20 km yr⁻¹ (Kaplan and New, 2006) might be overestimating rate of tree line advance by a factor of up to 2000 (Van Bogaert et al., 2011). The fastest upslope shifts of tree lines recorded during 20th century warming are 1 to 2 m yr⁻¹ (Shiyatov et al., 2007; Kullman and Öberg, 2009) whereas the fastest so-far recorded northward-migrating tree line replaces tundra by taiga at a rate of 3 to 10 m yr⁻¹ (Kharuk et al., 2006). In some areas, the location of the tree line has not changed or has changed very slowly (Payette, 2007; MacDonald et al., 2008). A global study by Harsch et al. (2009) showed that only 52% of 166 global tree line sites studied had advanced over the past 100 years. In many cases the tree line has even retreated (Cherosov et al., 2010). At the small scale, the tree line has shown increase, decrease, and stability in neighboring locations (Lloyd et al., 2011; Van Bogaert et al., 2011).

Evidence for densification of the forest at the sub-Arctic tree line is robust and consistent within Fennoscandia (Tømmervik et al., 2009; Hedenås et al., 2011; Rundqvist et al., 2011) and Canada (Danby and Hik, 2007). Dendroecological studies indicate enhanced conifer recruitment during the 20th century in the northern Siberian taiga (Briffa et al., 2008). Some of the changes are dramatic, such as an increase in area of mountain birch in study plots in northern Sweden by 600% between 1977/1998 and 2009/2010 (Rundqvist et al., 2011) and a doubling of tree biomass in Finnmarksvidda in northern Norway since 1957 (Tømmervik et al., 2009). However, model projections of displacement of deciduous forest by evergreen forest (Wolf et al., 2008; Wramneby et al., 2010) have not so far been validated.

Where the mountain birch tree line has increased in elevation and shrub (e.g., willow, dwarf birch) abundance has increased, the response can be an interaction between climate warming, herbivory pressure, and earlier land use (Olofsson et al., 2009; Hofgaard et al., 2010; Van Bogaert et al., 2011). In Fennoscandia and Greenland, heavy grazing by large herbivores may significantly check deciduous low erect shrub (e.g., dwarf shrub and willow) growth (Post et al., 2008; Kitti et al., 2009; Olofsson et al., 2009).

Less moisture from snow and more rain now favors broadleaf trees over conifers and mosses in some areas (Juday, 2009) while moisture deficits are reducing the growth of some northern forests (Goetz et al., 2005;

Verbyla, 2008; Yarie, 2008) and making them more susceptible to insect pest outbreaks (see references in Callaghan et al., 2011c). Death of trees through drought stress or insect pest activity will increase the probability of fire, which will have positive feedbacks (increase warming) on the climate (Mack et al., 2011).

28.2.3.1.3. Changes in animal populations

The documented collapse or dampening of population cycles of voles and lemmings over the last 20 to 30 years in parts of Fennoscandia and Greenland (Schmidt et al., 2012) can be attributed with *high confidence* to climate change (Ims et al., 2007, 2011; Gilg et al., 2009; Kausrud et al., 2009). A shortening of the snow season and more thaw and/or rain events during the winter will have an effect on the subnivean space, which provides thermal insulation, access to food, and protection from predators (Berg et al., 2008; Kausrud et al., 2009; Johansson et al., 2011). However, the causes of the changes in the lemming and vole cycles are still being debated as factors other than climate change may also be of importance (Brommer et al., 2010; Krebs, 2011).

Climate-mediated range expansion both in altitude and latitude of insect pests, and increased survival due to higher winter temperatures, has been documented for bark beetles in North America (Robertson et al., 2009) and for geometrid moths in Fennoscandia (Jepsen et al., 2008, 2011; Callaghan et al., 2010), causing more extensive forest damage than before. Outbreaks of insect pests such as geometrid moths can even reduce the strengths of CO₂ sinks in some areas (Heliasz et al., 2011).

The decline in wild reindeer and caribou (both *Rangifer tarandus*) populations in some regions of about 30% over the last 10 to 15 years has been linked both to climate warming and anthropogenic landscape changes (Post et al., 2009a; Vors and Boyce, 2009; Russell and Gunn, 2010). Even though most of the Arctic has warmed, the decline in the populations has not been uniform. Some of the North American large, wild herds have, for example, declined by 75 to 90%, while other wild herds and semi-domestic herds in Fennoscandia and Russia have been stable or even increased (Forbes et al., 2009; Gunn et al., 2009; Vors and Boyce, 2009; Forbes, 2010; Joly et al., 2011; Kumpula et al., 2012).

The expected and partially observed increased primary productivity of Arctic tundra may potentially increase the supply of food for Arctic ungulates. However, the overall quality of forage may decline during warming, for example, if the nitrogen content of key fodder species for ungulates were to drop during warming (Turunen et al., 2009; Heggberget et al., 2010), while lichen biomass, an important winter fodder for reindeer, is decreasing over parts of the Arctic region. Herbivory also changes the vegetation itself in concert with the warming, further complicating the prediction of vegetation changes and their impacts on ungulate populations (van Der Wal et al., 2007; Turunen et al., 2009).

More frequent rain-on-snow icing events and thicker snowpacks caused by warmer winters and increased precipitation may restrict access to vegetation and may have profound negative influences on the population dynamics of Arctic ungulates (Berg et al., 2008; Forchhammer et al., 2008; Miller and Barry, 2009; Stien et al., 2010, 2012; Hansen et al., 2011). Such events have caused heavy mortality in some semi-domestic

reindeer herds and musk oxen in recent years (Grenfell and Putkonen, 2008; Forbes, 2009; Bartsch et al., 2010), and have also been shown to synchronize the dynamics of a resident vertebrate community (small mammals, reindeer, and Arctic fox) in Svalbard (Hansen et al., 2013). In contrast, Tyler et al. (2008) and Tyler (2010) suggested that generally warmer winters enhance the abundance of reindeer populations.

It has been suggested that warming-induced trophic mismatches between forage availability and quality and timing of calving have a role in the decline of circumpolar reindeer and caribou populations (Post and Forchhammer, 2008; Post et al., 2009a,b), although such trophic mismatch has been disputed (Griffith et al., 2010).

Adjustment via phenotypic plasticity instead of adaptation by natural selection is expected to dominate vertebrate responses to rapid Arctic climate change, and many such adjustments have already been documented (Gilg et al., 2012).

28.2.3.1.4. Long-term trends and event-driven changes

Long-term climate change impacts on vegetation and animal populations are accelerated when tipping points are triggered by events such as extreme weather, fire, insect pest, and disease outbreaks. The impacts of winter thaw events on ecosystems are now well documented (e.g., Bokhorst et al., 2011) but studies of the severe impacts of tundra fires on vegetation and biospheric feedbacks are recent (Mack et al., 2011). Results from experimental winter thaws were validated by a natural event in northern Norway and Sweden in 2007 that reduced NDVI by almost 30% over at least 1400 km² (Bokhorst et al., 2009). Studies on relationships between climate change and plant disease are rare, but Olofsson et al. (2011) showed that increased snow accumulation led to a higher incidence of fungal growth on sub-Arctic vegetation.

28.2.3.2. Antarctica

Antarctic terrestrial ecosystems occur in 15 biologically distinct areas (Terauds et al., 2012), with those in the maritime and sub-Antarctic islands experiencing the warmest temperatures, reduced extreme seasonality and greatest biodiversity (Convey, 2006). In the cooler conditions on the continent, species must be capable of exploiting the short periods where temperature and moisture availability are above physiological and biochemical thresholds. In many areas, there is no visible vegetation, with life being limited, at the extreme, to endolithic (within rock) communities of algae, cyanobacteria, fungi, bacteria, and lichens (Convey, 2006).

Few robust studies are available of biological responses to observed climatic changes in natural Antarctic terrestrial ecosystems. The rapid population expansion and local-scale colonization by two native flowering plants (*Deschampsia antarctica* and *Colobanthus quitensis*) in maritime Antarctica (Parnikoza et al., 2009) remains the only published repeat long-term monitoring study of any terrestrial vegetation or location in Antarctica. Radiocarbon dating of moss peat deposits has shown that growth rates and microbial productivity have risen rapidly on the Antarctic Peninsula since the 1960s, consistent with temperature

changes, and are unprecedented in the last 150 years (Royles et al., 2013). In east Antarctica, moss growth rates over the last 50 years have been linked to changes in wind speed and temperature and their influence on water availability (Clarke et al., 2012). A contributing factor is that air temperatures have increased past the critical temperature at which successful sexual reproduction (seed set) can now take place, changing the dominant mode of reproduction and increasing the potential distance for dispersal (*low confidence*; Convey, 2011). Similar changes in the local distribution and development of typical cryptogamic vegetation of this region have been reported (Convey, 2011), including the rapid colonization of ice-free ground made available through glacial retreat and reduction in extent of previously permanent snow cover (Olech and Chwedorzewska, 2011). As these vegetation changes create new habitat, there are concurrent changes in the local distribution and abundance of the invertebrate fauna that then colonize them (*low confidence*).

28.2.4. Health and Well-being of Arctic Residents

The warming Arctic and major changes in the cryosphere are significantly impacting the health and well-being of Arctic residents and projected to increase, especially for many Indigenous peoples. Although impacts are expected to vary among the diverse settlements that range from small, remote, predominantly Indigenous to large cities and industrial settlements, this section focuses more on health impacts of climate change on Indigenous, isolated, and rural populations because they are especially vulnerable to climate change owing to a strong dependence on the environment for food, culture, and way of life; their political and economic marginalization; existing social, health, and poverty disparities; as well as their frequent close proximity to exposed locations along ocean, lake, or river shorelines (Ford and Furgal, 2009; Galloway-McLean, 2010; Larsen et al., 2010; Cochran et al., 2013).

28.2.4.1. Direct Impacts of a Changing Climate on the Health of Arctic Residents

Direct impacts of climate changes on the health of Arctic residents include extreme weather events, rapidly changing weather conditions, and increasingly unsafe hunting conditions (physical/mental injuries, death, disease), temperature-related stress (limits of human survival in thermal environment, cold injuries, cold-related diseases), and UV-B radiation (immunosuppression, skin cancer, non-Hodgkin's lymphoma, cataracts) (*high confidence*; Revich, 2008; AMAP, 2009; IPCC, 2012). Intense precipitation events and rapid snowmelt are expected to impact the magnitude and frequency of slumping and active layer detachment, resulting in rock falls, debris flow, and avalanches (Kokelj et al., 2009; Ford et al., 2010). Other impacts from weather, extreme events, and natural disasters are the possibility of increasingly unpredictable, long duration, and/or rapid onset of extreme weather events, storms, and inundation by large storm surges, which, in turn, may create risks to safe travel or subsistence activities, loss of access to critical supplies and services to rural or isolated communities (e.g., food, telecommunications, fuel), and risk of being trapped outside one's own community (*high confidence*; Laidre et al., 2008; Parkinson, 2009; Brubaker et al., 2011b,c). Changing river and sea ice conditions affect the safety of travel for

Indigenous populations especially, and inhibit access to critical hunting, herding, and fishing areas (Andrachuk and Pearce, 2010; Derksen et al., 2012; Huntington and Watson, 2012).

Cold exposure has been shown to increase the frequency of certain injuries (e.g., hypothermia, frostbite), accidents, and diseases (respiratory, circulatory, cardiovascular, musculoskeletal) (Revich and Shaposhnikov, 2010). Studies in northern Russia have indicated an association between low temperatures and social stress and cases of cardiomyopathy (Revich and Shaposhnikov, 2010). It is expected that winter warming in the Arctic will reduce winter mortality rates, primarily through a reduction in respiratory and cardiovascular deaths (Shaposhnikov et al., 2010). Researchers project that a reduction in cold-related injuries may occur, assuming that the standard for protection against the cold is not reduced (including individual behavior-related factors) (Nayha, 2005). Conversely, studies are showing respiratory and cardiac stress associated with extreme warm summer days and that rising temperatures are accompanied by increased air pollution and mortality, especially in Russian cities with large pollution sources (Revich, 2008; Revich and Shaposhnikov, 2012).

28.2.4.2. Indirect Impacts of Climate Change on the Health of Arctic Residents

Indirect effects of climate change on the health of Arctic residents include a complex set of impacts such as changes in animal and plant populations (species responses, infectious diseases), changes in the physical environment (ice and snow, permafrost), diet (food yields, availability of country food), built environment (sanitation infrastructure, water supply system, waste systems, building structures), drinking water access, contaminants (local, long-range transported), and coastal issues (harmful algal blooms, erosion) (*high confidence*; Maynard and Conway, 2007; Parkinson and Evengård, 2009; Brubaker et al., 2011a; see also Chapter 11).

In addition to the climate change impacts and processes are the complicated impacts from contaminants such as persistent organic pollutants (POPs), radioactivity, and heavy metals (e.g., mercury), which create additional and/or synergistic impacts on the overall health and well-being of all Arctic communities (Armitage et al., 2011; UNEP and AMAP, 2011; Teran et al., 2012). Ambient temperature variability and temperature gradients directly affect the volatilization, remobilization, and transport pathways of mercury and POPs in the atmosphere, ocean currents, sea ice, and rivers. Transport pathways, inter-compartmental distribution, and bioaccumulation and transformation of environmental contaminants such as POPs, mercury, and radionuclides in the Arctic may consequently be affected by climate change (*high confidence*; AMAP 2011b; Ma et al., 2011; UNEP and AMAP 2011; Teng et al., 2012). Ma et al. (2011) and Hung et al. (2010) demonstrated that POPs are already being remobilized into the air from sinks in the Arctic region as a result of decreasing sea ice and increasing temperatures.

Contaminants and human health in the Arctic are tightly linked to the climate and Arctic ecosystems by factors such as contaminant cycling and climate (increased transport to and from the Arctic), and the related increased risks of transmission to residents through subsistence life

ways (Maynard, 2006; AMAP, 2010; Armitage et al., 2011; UNEP and AMAP, 2011; Teran et al., 2012). The consumption of traditional foods by Indigenous peoples places these populations at the top of the Arctic food chain and through biomagnification, therefore, they may receive some of the highest exposures in the world to certain contaminants (Armitage et al., 2011; UNEP and AMAP, 2011). Contaminants such as POPs are known for their adverse neurological and medical effects on humans, particularly the developing fetus, children, women of reproductive age, and the elderly; thus it is important to include contaminants as a significant part of any climate impact assessment (UNEP and AMAP, 2011).

Radioactivity in the Arctic is also a concern because there are many potential and existing radionuclide sources in some parts of the Arctic, and contamination can remain for long periods of time in soils and some vegetation, creating potentially high exposures for people (AMAP, 2010). Climate changes can mobilize radionuclides throughout the Arctic environment, and also potentially impact infrastructure associated with nuclear activities by changes in permafrost, precipitation, erosion, and extreme weather events (AMAP, 2010).

Warming temperatures are enabling increased overwintering survival and distribution of new insects that sting and bite as well as many bird, animal, and insect species that can serve as disease vectors and, in turn, causing an increase in human exposure to new and emerging infectious diseases (Parkinson et al., 2008; Epstein and Ferber, 2011). Examples of new and emerging diseases are tick-borne encephalitis (brain infection) in Russia and Canada (Ogden et al., 2010; Tokarevich et al., 2011) and Sweden (Lindgren and Gustafson, 2001) and *Giardia* spp. and *Cryptosporidium* spp. infection of ringed seals (*Phoca hispida*) and bowhead whales (*Balaena mysticetus*) in the Arctic Ocean (Hughes-Hanks et al., 2005). It is also expected that temperature increases will increase the incidence of zoonotic diseases as relocations of animal populations occur (Revich et al., 2012; Hueffler et al., 2013).

Harmful algal blooms (HABs), whose biotoxins can be a serious health hazard to humans or animals (paralysis, death), are increasing globally and expected to increase in the Arctic, and HABs are influenced directly by climate change-related factors such as temperature, winds, currents, nutrients, and runoff (Portier et al., 2010; Epstein and Ferber, 2011; Walsh et al., 2011; see also Chapters 6, 11). Increasing ocean temperatures have caused an outbreak of a cholera-like disease, caused by *Vibrio parahaemolyticus*, in Alaskan oysters (McLaughlin et al., 2005). In addition, warmer temperatures raise the possibility of anthrax exposure in Siberia from permafrost thawing of historic cattle burial grounds (Revich and Podolnaya, 2011).

The impacts of climate change on food security and basic nutrition are critical to human health because subsistence foods from the local environment provide Arctic residents, especially Indigenous peoples, with unique cultural and economic benefits necessary to well-being and contribute a significant proportion of daily requirements of nutrition, vitamins, and essential elements to the diet (Ford, 2009; Ford and Berrang-Ford, 2009). However, climate change is already an important threat because of the decrease in predictability of weather patterns, low water levels and streams, timing of snow, and ice extent and stability, impacting the opportunities for successful hunting, gathering, fishing,

and access to food sources and increasing the probability of accidents (*high confidence*; Ford and Furgal, 2009; Ford et al., 2010). In recent years, populations of marine and land mammals, fish, and water fowl are also being reduced or displaced, thus reducing the traditional food supply (Gearheard et al., 2006; West and Hovelsrud, 2010; Lynn et al., 2013).

Traditional food preservation methods such as drying of fish and meat, fermentation, and ice cellar storage are being compromised by warming temperatures, thus further reducing food available to the community (Brubaker et al., 2011b,c). For example, food contamination caused by thawing of permafrost “ice cellars” is occurring and increasingly wet conditions make it harder to dry food for storage (Hovelsrud et al., 2011). Indigenous people increasingly have to abandon their semi-nomadic lifestyles, limiting their overall flexibility to access traditional foods from more distant locations (www.arctichealth.yukon.ca). These reductions in the availability of traditional foods plus general globalization pressures are forcing Indigenous communities to increasingly depend on expensive, non-traditional, and often less healthy Western foods, increasing the rates of modern diseases associated with processed food and its packaging, such as cardiovascular diseases, diabetes, dental caries, and obesity (Armitage et al., 2011; Berrang-Ford et al., 2011; Brubaker et al., 2011b,c).

Climate change is beginning to threaten community and public health infrastructure, often in communities with no central water supply and treatment sources. This is especially serious in low-lying coastal Arctic communities (e.g., Shishmaref, Alaska, USA; Tuktoyaktuk, Northwest Territories, Canada) through increased river and coastal flooding and erosion, increased drought, and thawing of permafrost, resulting in loss of reservoirs, damage to landfill sites, or sewage contamination (GAO, 2009; Bronen, 2011). Saltwater intrusion and bacterial contamination may also be threatening community water supplies (Parkinson et al., 2008; Virginia and Yalowitz, 2012). Quantities of water available for drinking, basic hygiene, and cooking are becoming limited owing to damaged infrastructure, drought, and changes in hydrology (Virginia and Yalowitz, 2012). Disease incidence caused by contact with human waste may increase when flooding and damaged infrastructure spreads sewage in villages with no municipal water supply. This can result in higher rates of hospitalization for pneumonia, influenza, skin infections, and respiratory viral infections (Parkinson and Evengård, 2009; Virginia and Yalowitz, 2012). Compounding these impacts in rural areas as well as cities are respiratory and other illnesses caused by air-borne pollutants (e.g., contaminants, microbes, dust, mold, pollen, smoke) (Revich, 2008; Rylander and Schilling, 2011; Revich and Shaposhnikov, 2012).

It is now well documented that the many climate-related impacts on Arctic communities are causing significant psychological and mental distress and anxiety among residents (Levintova, 2010; Portier et al., 2010; Coyle and Susteren, 2012; see also Chapter 11). For example, changes in the physical environment (e.g., through thawing permafrost and erosion) that may lead to forced or voluntary relocation of residents out of their villages or loss of traditional subsistence species are causing mental health impacts among Indigenous and other vulnerable, isolated populations (Curtis et al., 2005; Albrecht et al., 2007; Coyle and Susteren, 2012; Maldonado et al., 2013). Special concern has been expressed by many communities about the unusually high and increasing numbers of suicides in the Arctic, especially among Indigenous youth, and efforts

are underway to try to develop a thorough assessment as well as establish effective intervention efforts (Albrecht et al., 2007; Portier et al., 2010; USARC, 2010).

28.2.5. Indigenous Peoples and Traditional Knowledge

Indigenous populations in the Arctic—the original Native inhabitants of the region—are considered especially vulnerable to climate change because of their close relationship with the environment and its natural resources for physical, social, and cultural well-being (Nuttall et al., 2005; Parkinson, 2009; Cochran et al., 2013). Although there are wide differences in the estimates, including variations in definitions of the Arctic region, Arctic Indigenous peoples are estimated to number between 400,000 and 1.3 million (Bogoyavlensky and Siggner, 2004; Galloway-McLean, 2010). According to 2010 census data, there are approximately 68,000 Indigenous people living in the Russian Arctic. These Arctic residents depend heavily on the region’s terrestrial, marine, and freshwater renewable resources, including fish, mammals, birds, and plants; however, the ability of Indigenous peoples to maintain traditional livelihoods such as hunting, harvesting, and herding is increasingly being threatened by the unprecedented rate of climate change (*high confidence*; Nakashima et al., 2012; Cochran et al., 2013). In habitats across the Arctic, climate changes are affecting these livelihoods through decreased sea ice thickness and extent, less predictable weather, severe storms, sea level rise, changing seasonal melt/freeze-up of rivers and lakes, changes in snow type and timing, increasing shrub growth, permafrost thaw, and storm-related erosion, which, in turn, are causing such severe loss of land in some regions that a number of Alaskan coastal villages are having to relocate entire communities (Oskal, 2008; Forbes and Stammler, 2009; Mahoney et al., 2009; Bartsch et al., 2010; Weatherhead et al., 2010; Bronen, 2011; Brubaker et al., 2011b,c; Eira et al., 2012; Huntington and Watson, 2012; McNeeley, 2012; Maldonado et al., 2013). In addressing these climate impacts, Indigenous communities must at the same time consider multiple other stressors such as resource development (oil and gas, mining); pollution; changes in land use policies; changing forms of governance; and the prevalence in many Indigenous communities of poverty, marginalization, and resulting health disparities (Abryutina, 2009; Forbes et al., 2009; Reinert et al., 2009; Magga et al., 2011; Vuojala-Magga et al., 2011; Nakashima et al., 2012; Mathiesen et al., 2013).

Traditional knowledge is the historical knowledge of Indigenous peoples accumulated over many generations and it is increasingly emerging as an important knowledge base for more comprehensively addressing the impacts of environmental and other changes as well as development of appropriate adaptation strategies for Indigenous communities (WGII AR4 Chapter 15; Oskal, 2008; Reinert et al., 2008; Wildcat, 2009; Magga et al., 2011; Vuojala-Magga et al., 2011; Nakashima et al., 2012; Vogesser et al., 2013). For example, Saami reindeer herders have specialized knowledge of dynamic snow conditions, which mediate access to forage on autumn, winter, and spring reindeer rangelands (Roturier and Roue, 2009; Eira et al., 2012; Vikhamar-Schuler et al., 2013) and traditional governance systems for relating to natural environments (Sara, 2013). Increasingly, traditional knowledge is being combined with Western scientific knowledge to develop more sustainable adaptation strategies for all communities in the changing climate.

For example, at Clyde River, Nunavut, Canada, Inuit experts and scientists both note that wind speed has increased in recent years and that wind direction changes more often over shorter periods (within a day) than it did during the past few decades (Gearheard et al., 2010; Overland et al., 2012). In Norway, Sámi reindeer herders and scientists are both observing direct and indirect impacts to reindeer husbandry such as changes in snow and ice cover, forage availability, and timing of river freeze-thaw patterns from increasing temperatures (Eira et al., 2012). On the Yamal Peninsula in western Siberia, detailed Nenets observations and recollections of iced-over autumn and winter pastures due to rain-on-snow events have proven suitable for calibrating the satellite-based microwave sensor SeaWinds (Bartsch et al., 2010) and NASA's AMSR-E sensor.

28.2.6. Economic Sectors

28.2.6.1. Arctic

28.2.6.1.1. Agriculture and forestry

Climate change presents benefits and costs for forestry and agriculture (Aaheim et al., 2009; Hovelsrud et al., 2011). In Iceland, for example, tree limits are found at higher altitudes than before, and productivity of many plants has increased (Björnsson et al., 2011). Grain production in Iceland has increased in the last 2 decades, and work on soil conservation and forestry has benefited from warming (Sigurdsson et al., 2007; Björnsson et al., 2011), but also the number of new insect pests on trees and shrubs has increased in the past 20 years. A strong relationship between rate of new insect pest colonization and outbreak intensity in forests exists with changes in annual temperature during the past century (Halldórsson et al., 2013). Climate change impacts on species change and fire frequency have potential impact on commercial forest harvesting activity. Vulnerability of forestry to changes that affect road conditions and thus accessibility during thawing periods has been found in Sweden (Keskitalo, 2008). A case study on Greenland found challenges for plant diseases in potatoes and grass fields, with pathogens and pests present in agricultural cropping systems, for example, black scurf (*Rhizoctonia*) and common scab (*Streptomyces scabies*) (Neergaard et al., 2009).

28.2.6.1.2. Open and freshwater fisheries

Current commercial fisheries are sharply divided between regions of high-yield and value (e.g., commercial fisheries in the southern Bering Sea, Baffin Bay, the east and west Greenland Seas, the Iceland Shelf Sea, the deep Norwegian/Greenland Sea, and the Barents Sea) and subsistence fisheries in the coastal regions of the Arctic Ocean. The relative absence of commercial fishing activity in the Arctic Ocean results from a combination of fisheries policy, the abundance of the resource, the lack of infrastructure for capturing and processing fish, and the difficulties in accessing fishing grounds, especially during winter. In most regions, fisheries management strategies have been developed to build sustainable fisheries and rebuild overfished stocks (Froese and Proelß, 2010; Livingston et al., 2011). Recently observed changes in the spatial distribution and abundance of mackerel (*Scomber scombrus*) has challenged existing international agreements for shared resources in

the North Atlantic (Arnason, 2012; Astthorsson et al., 2012). Although loss of sea ice in summer is allowing greater access to fisheries resources in the Arctic Ocean, some nations have prohibited commercial fishing within their exclusive economic zones until there is sufficient understanding of stock status to ensure that proposed fisheries would be managed sustainably (Stram and Evans, 2009; Wilson and Ormseth, 2009).

Several Arctic coastal sea-run fishes are targeted for subsistence and commercial use in the Arctic. Commercial transactions from fishing are typically for local markets; however, the socioeconomic and cultural importance of these fishes to Indigenous peoples far outweighs their monetary value. Reist et al. (2006) and Fechhelm et al. (2007) found that climate-related factors that influenced the water level and freshening of rivers were related to run size of Arctic cisco (*Coregonus autumnalis*). Similarly, a recent study based on Chinook salmon (*Oncorhynchus tshawytscha*) run timing for the period 1961–2009 showed that success in the fishery was dependent on the timing of the marine exit, which was tightly coupled to environmental conditions that were linked to climate (Mundy and Evenson, 2011).

28.2.6.1.3. Marine transportation

Observations and climate models indicate that in the period between 1979–1988 and 1998–2007 the number of days with ice-free conditions (less than 15% ice concentration) increased by 22 days along the Northern Sea Route (NSR) in the Russian Arctic, and by 19 days in the Northwest Passage (NWP) in the Canadian Arctic, while the average duration of the navigation season in the period 1980–1999 was 45 and 35 days, respectively (Mokhov and Khon, 2008). Increased shipping associated with the opening of the NSR will lead to increased resource extraction on land and in the sea, and with two-way commodity flows between the Atlantic and Pacific. The future status of marine, terrestrial, and freshwater biota may be negatively affected as a result of substantial coastal infrastructure to facilitate offshore developments (Meschytyb et al., 2005). Also, the frequency of marine transportation along the NSR is at its highest during the most productive and vulnerable season for fish and marine mammals, which is the late spring/summer, when these resources can be found throughout the NSR area (Østreg, 2006).

28.2.6.1.4. Infrastructure

Much of the physical infrastructure in the Arctic relies on and is adapted to local sea ice conditions, permafrost, and snow (Huntington et al., 2007; Sundby and Nakken, 2008; Sherman et al., 2009; West and Hovelsrud, 2010; Forbes, 2011). Damage from ice action and flooding to installations such as bridges, pipelines, drilling platforms, and hydropower poses major economic costs and risks, which are more closely linked to the design of the structure than with thawing permafrost. Current engineering practices are designed to help minimize the impacts (Prowse et al., 2009). Much of the infrastructure has been built with weather conditions in mind, but remains vulnerable and inadequate to respond to environmental emergencies, natural disasters, and non-environmental accidents (NRTEE, 2009). Northern safety, security, and environmental integrity are much dependent on transportation infrastructure. Ice as a provisioning system

provides a transportation corridor and a platform for a range of activities and access to food sources in the Arctic (Eicken et al., 2009).

In northern Canada climate warming presents an additional challenge for northern development and infrastructure design. While the impacts of climate change become increasingly significant over the longer time scales, in the short term of greater significance will be the impacts associated with ground disturbance and construction (Smith and Risebrough, 2010).

Climate change impacts have increased the demand for improved communication infrastructure and related services and community infrastructure for the safety and confidence in drinking water (NRTEE, 2009). The access, treatment, and distribution of drinking water is generally dependent on a stable platform of permafrost for pond or lake retention. Several communities have reported the need for more frequent water-quality testing of both municipal systems and untreated water sources to ensure its suitability for drinking (Furgal, 2008).

28.2.6.1.5. Resource exploration

The Arctic has large reserves of minerals (Lindholt, 2006; Harsem et al., 2011; Peters et al., 2011) and potentially large reserves of undiscovered sources of raw minerals and oil and gas. Predicted new access to offshore energy resources is hypothesized to be a significant share of the global supply of oil and gas (Gautier et al., 2009; Berkman, 2010). The socioeconomic impacts of oil and gas exploration activity may be positive or negative (Duhaime et al., 2004; Huntington et al., 2007; Forbes, 2008; Forbes et al., 2009; Kumpula et al., 2011; Harsem et al., 2011).

Climatic warming is accelerating access to northern lands for development (Forbes et al., 2009). Yamal in Western Siberia has approximately 90% of Russia's gas reserves, but at the same time represents the largest area of reindeer herding in the world (Jernsletten and Klovov, 2002; Stammler, 2005; Forbes and Kumpula, 2009). Development activities to obtain these resources would shrink the grazing lands, and have been characterized as one of the major human activities in the Arctic contributing to loss of "available room for adaptation" for reindeer husbandry (Nuttall et al., 2005; Oskal, 2008; Forbes et al., 2009). Sharp increases in future oil and gas and other resource development in the Russian north and other Arctic regions are anticipated—along with associated infrastructure, pollution, and other development byproducts—which will reduce the availability of pasturelands for reindeer and use by Indigenous communities (Derome and Lukina, 2011; Degteva and Nellermann, 2013).

28.2.6.1.6. Informal, subsistence-based economy

Hunting, gathering, herding, and fishing for subsistence, as well as commercial fishing, all play an important role in the mixed cash-subsistence economies (Nuttall et al., 2005; Poppel and Kruse, 2009; Crate et al., 2010; Larsen and Huskey, 2010). In the early 1990s—initially in western Canada, and later elsewhere—Indigenous communities started reporting climate change impacts (Berkes and Armitage, 2010). According to some herders, whalers, and walrus hunters, non-predictable conditions

resulting from more frequent occurrence of unusual weather events are the main effect of recent warming (Forbes and Stammler, 2009; Forbes et al., 2009; Ignatowski and Rosales, 2013).

The Inuit and Saami have expressed strong concern about the effects of climate warming on their livelihoods (Forbes and Stammler, 2009; Magga et al., 2011). For the Inuit, the issues revolve around sea ice conditions, such as later freeze-up in autumn; earlier melt-out and faster sea ice retreat in spring; and thinner, less predictable ice in general (Krupnik and Jolly, 2002; Cochran et al., 2013). Diminished sea ice translates into more difficult access for hunting marine mammals, and greater risk for the long-term viability of subsistence species such as polar bear populations (*high confidence*; Laidre et al., 2008). Most Inuit communities depend to some extent on marine mammals for nutritional and cultural reasons, and many benefit economically from polar bear and narwhal hunting. A reduction in these resources represents a potentially significant economic loss (Hovelsrud et al., 2008). Among Fennoscandian Saami, the economic viability of reindeer herding is threatened by competition with other land users coupled with strict agricultural norms (Forbes, 2006; Magga et al., 2011). Reindeer herders are concerned that more extreme weather may exacerbate this situation (Oskal, 2008).

Climate change is affecting reindeer herding communities through greater variability in snow melt/freezing, ice, weather, winds, temperatures, and precipitation, which, in turn are affecting snow quality and quantity—the most critical environmental variables for reindeer sustainability (Bartsch et al., 2010; Magga et al., 2011; Eira et al., 2012). Increasing temperature variations in wintertime, with temperatures rising above freezing with rain, followed by refreezing ("rain-on-snow" conditions), are becoming more frequent, forming ice layers in the snow that then block the animals' access to their forage and subsequent starvation (Bartsch, 2010; Maynard et al., 2011; Eira et al., 2012).

28.2.6.2. Antarctica and the Southern Ocean

Economic activities in the Antarctic have been limited to fishing and tourism (IPCC, 2007). Ship-based tourism is a significant industry in Antarctica but does not involve permanent shore-based infrastructure. Over recent decades, the number of tourists landing in Antarctica has risen from 7322 in 1996/1997 to 32,637 in 2007/2008 (IAATO, 2012). Visits generally coincide with the times when wildlife are breeding and are often restricted because of the presence of fast ice, sea ice, or icebergs. They are expected to continue to increase, with an increasing chance of terrestrial alien species being introduced from tourism and other vectors as ice-free areas increase from climate change (Chown et al., 2012). Scientific activity by a number of nations is also taking place and has the potential to impact upon local ecologies. Mineral resource activity is prohibited south of 60°S under the Protocol on Environmental Protection to the Antarctic Treaty.

Fisheries in Antarctica, primarily through fisheries for Antarctic krill, could amount to approximately 6% of existing global marine capture fisheries (Nicol et al., 2012). The pattern of the krill fishery has been affected by changes in the sea ice extent around the Antarctic Peninsula, where the fishery has been taking advantage of the ice-free conditions and taking

more of its catch during winter in that region (*high confidence*; Kawaguchi et al., 2009). Ecosystem-based management of krill fisheries by the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) has yet to include procedures to account for climate change impacts, although the need to do so has been identified (Trathan and Agnew, 2010; Constable, 2011).

28.3. Key Projected Impacts and Vulnerabilities

28.3.1. Hydrology and Freshwater Ecosystems

28.3.1.1. Arctic

Accompanying projected increases in high-latitude river flow (Section 3.4.5; WGI AR5 Section 12.4.5.4) are earlier spring runoff (Pohl et al., 2007; Dankers and Middelkoop, 2008; Hay and McCabe, 2010), greater spring snowmelt (Adam et al., 2009), and increases in spring sediment fluxes (Lewis and Lamoureux, 2010). Enhanced permafrost thaw (WGI AR5 Section 12.4.6.2) will continue to affect the dynamics of thermokarst lakes and related ecological effects (Section 28.2.1.1). Thawing permafrost and changes in the hydrological regime of the Arctic rivers, particularly those traversing regions affected by industrial developments, will increase the contaminant flow (Nikanorov et al., 2007). Loss of glacier ice masses will alter runoff hydrographs; sediment loads; water chemistry; thermal regimes; and related channel stability, habitat, and biodiversity (Milner et al., 2009; Moore et al., 2009). Although snow, freshwater ice, and permafrost affect the morphology of arctic alluvial channels, their future combined effects remain unclear (McNamara and Kane, 2009). For small permafrost streams, however, longer projected periods of flowing water will modify nutrient and organic matter processing (Greenwald et al., 2008; Zarnetske et al., 2008) but long-term negative impacts of increased sediment load on biological productivity could outweigh any positive effects from increased nutrient loading (Bowden et al., 2008).

Changes to river-ice flooding are also projected to occur as a result of changes in (1) hydraulic gradients for near-coastal locations because of sea level rise, (2) streamwise air-temperature gradients, and (3) the timing and magnitude of spring snowmelt (Prowse et al., 2011). Synergistic/antagonistic effects among these factors, however, require detailed site-specific analyses for accurate projections of future conditions (Beltaos and Prowse, 2009). Reduced (increased) ice-jam flooding will have positive (negative) benefits for river-side northern communities/infrastructure but could also alter delta-riparian (Lesack and Marsh, 2010) and coastal marine (Emmerton et al., 2008) ecosystems. The quality of river water entering the marine environment will also be affected by the reduction or loss of stamukhi lakes that process river inputs (Dumas et al., 2006; Galand et al., 2008).

Future changes to lake ice regimes will include delayed freeze-up, advanced break-up, thinner ice and changes in cover composition (especially white ice in areas of enhanced winter precipitation), increased water temperature, and earlier and longer-lasting summer stratification (Dibike et al., 2011), all of which will affect a range of aquatic processes, including secondary productivity (Borgström and Museth, 2005; Prowse et al., 2007; Prowse and Brown, 2010b). Patterns of species richness and diversity are also projected to change with alterations to ice duration—

increased open-water periods favoring the development of new trophic levels, colonization of new aquatic species assemblages (Vincent et al., 2009), greater atmosphere-water gas exchange, and a decrease in winter kill of resident fish with cascading effects on lower trophic levels (Balayla et al., 2010). The loss of ice, however, can also decrease key habitat availability and quality (Vincent et al., 2008). Geochemical responses of Arctic lakes will also be altered. As observed for thermokarst lakes, the loss of ice cover and associated warming can greatly increase methane production (Metje and Frenzel, 2007; Laurion et al., 2010). Because temperature sensitivity has a stronger control over methane production than oxidation (Duc et al., 2010), elevated water temperatures will enhance methanogenesis, causing increased methane release from sediments. The net balance of these two processes operating under a broad range of future changing environmental factors, however, remains to be quantified (Walter et al., 2007a,b, 2008; Laurion et al., 2010).

As well as methane, increased water temperatures are projected to lead to reduced organic carbon (OC) burial. Projections, based on a range of six climate warming scenarios (IPCC, 2007), indicate that there will be a 4 to 27% decrease (0.9 to 6.4 TgC yr⁻¹) in OC burial across lakes of the northern boreal zone by the end of the 21st century as compared to rates for the approximately last half-century (Gudasz et al., 2010). Although these estimates assume that future OC delivery will be similar to present-day conditions, even with enhanced supply from thawing permafrost, higher water temperatures will increase OC mineralization and thereby lower burial efficiency. The amount of burial also depends on lake depth and mixing regimes. For non-thermally stratified shallow lakes, there will be a greater opportunity for water-sediment mixing, and hence greater carbon recycling back into the water column. By contrast, for lakes that become increasingly thermally stratified, carbon sinking below the thermocline will tend not to return to the surface until an increasing later fall turnover, thereby decreasing the probability of sediment-stored carbon being returned to the water column (Flanagan et al., 2006).

Changes in ice cover, thermal regimes, and stratification patterns will also affect the fate of contaminants in northern lakes. Higher water temperatures can enhance the methylation of mercury and modify food web and energy pathways, such as through enhanced algal scavenging (a major food web entry pathway for mercury), resulting in increased mercury bioavailability to higher trophic levels (Outridge et al., 2007; Carrie et al., 2010).

28.3.1.2. Antarctica

This assessment reinforces conclusions of AR4. Increased temperatures will impact aquatic ecosystems in Antarctica (*high confidence*), but the exact nature of these impacts will vary regionally. The most vulnerable freshwater systems are in the northern Antarctic Peninsula and maritime Antarctic islands, where a small increase in temperature can have widespread ecosystem impacts because the average temperature is within a few degrees of the melting point (*high confidence*; Quesada and Velázquez, 2012). Potential impacts are expected to range from immediate catastrophic impacts such as loss of bounding ice masses causing drainage of freshwater and epishelf lakes (Smith et al., 2006; Hodgson, 2011), to more gradual impacts on changes in the amount and duration

of catchment ice and snow cover; accelerated glacier melting; declining volumes of precipitation falling as snow; permafrost; and active layer and hydrological changes, such as water retention times (*medium confidence*; e.g., Vieira et al., 2010; Quesada and Velázquez, 2012; Bockheim et al., 2013).

Changes in the thickness and duration of seasonal ice cover, longer melt seasons, and larger volumes of water flowing into the lakes are expected in the future (*medium confidence*; Lyons et al., 2006) but the ecological effects will vary between lakes, depending on their depth to surface area ratio, with insufficient evidence to fully assess future changes in these systems. Longer ice-free seasons may cause physical conditions to be more favorable for primary production (Hodgson and Smol, 2008) but very high irradiances experienced during summer in some systems can substantially inhibit algal blooms under ice-free conditions (Tanabe et al., 2007), which would favor the growth of benthic cyanobacteria species (Hodgson et al., 2005). In other lakes, increases in meltwater supply may increase suspended solids and reduce light penetration and may offset the increases in the underwater light regime predicted as a result of extended ice-free periods (Quesada et al., 2006).

Under a warming climate an increase in microbial biomass is expected because of the increased water supply from glacial melt and warmer temperatures, and could result in further development of soils and elevated nutrient and dissolved OC delivery to lakes (Velázquez et al., 2013). This organic supply will promote growth and reproduction in the benthos and plankton and imbalances in population dynamics (Quesada and Velázquez, 2013). Nutrient enrichment of some freshwater habitats in the vicinity of fur seal colonies will increase because of expanding fur seal populations (*high confidence*; Quayle et al., 2013).

Away from glacial forelands, increasing aridity will occur in the long term in some areas of the continent (Hodgson et al., 2006b) and on sub-Antarctic islands (*medium confidence*; Smith, Jr. et al., 2012). Closed basin lakes can dry up completely causing local extinctions or retreat into cryptic or resistant life-cycle stages, as experienced in Arctic lakes (Smol and Douglas, 2007b). Other effects include desiccation of moss banks due to increased evaporation and sublimation rates (*medium confidence*; Wasley et al., 2006). Studies have also shown that warming of once cold freshwater habitats in Antarctica will allow the sub- and maritime Antarctic species to re-invade and establish self-maintaining populations on the Antarctic continent, particularly where human vectors are involved (*medium confidence*; Barnes et al., 2006; Hodgson et al., 2006b). For other organisms with lower dispersal capabilities there is increasing evidence of endemism, particularly in microbial groups (Vyverman et al., 2010), with a possibility that surface Antarctic lakes contain endemic species that are relics of Gondwana (cf. Convey and Stevens, 2007) and that would become extinct should they be lost from these lakes as a result of climate change.

28.3.2. Oceanography and Marine Ecosystems

28.3.2.1. Ocean Acidification in the Arctic and Antarctic

The effects of ocean acidification on polar marine food webs can have considerable implications (*medium confidence*). For example, if some

regions in the Arctic become understaturated with respect to aragonite (the primary structural component of the shells of some marine calcifiers such as molluscs and urchins), the growth and survival of these organisms will be impacted (WGI AR5 Figure 6.28; Chierici and Fransson, 2009; Fabry et al., 2009; Yamamoto-Kawai et al., 2009). In laboratory experiments, Arctic pteropods (*Limacina helicina*, a small planktonic mollusc) held under conditions consistent with projected ocean warming and acidification in the Arctic Ocean in early spring were able to extend their shells in corrosive waters but dissolution marks were observed (Comeau et al., 2010, 2012). Additional studies are needed to scale up regional impacts to assess the population level impact of ocean acidification on *Limacina helicina* and other vulnerable species (Orr et al., 2009). At the current time there are insufficient data to fully assess the ecosystem consequences of acidification on pteropods because it is unclear whether other species, with a similar nutritive value, will replace pteropods.

In the Southern Ocean, foraminifera have thinner shells than in the Holocene and there is evidence for shell thickness to be related to atmospheric CO₂, supporting the hypothesis that ocean acidification will affect this abundant protozoan in this region (Moy et al., 2009). Similarly, shells are thinner from sediment traps in aragonite undersaturated water (below the aragonite saturation horizon (ASH)) compared to those captured above the ASH in sub-Antarctic waters, but there is no time series of data related to change in the ASH (Roberts et al., 2011). Shell dissolution has been observed in surface waters in the Atlantic sector as a result of both upwelling and atmospheric changes in CO₂ (*medium confidence*; Bednarsek et al., 2012). Other impacts of acidification on Southern Ocean organisms are currently uncertain, but short-term negative impacts need to be considered together with an organism's capacity to adapt in the longer term (Watson et al., 2012).

Only a few studies have been conducted on commercially exploited polar species on ocean acidification. Antarctic krill embryonic development (Kawaguchi et al., 2011) and post-larval krill metabolic physiology (Saba et al., 2012) may be impeded by elevated CO₂ concentrations, which may negatively impact the reproductive success of krill more generally under emission scenarios used in Coupled Model Intercomparison Project Phase 5 (CMIP5) (*medium confidence*; Kawaguchi et al., 2013). Long et al. (2013) examined the effects of acidification on red king crab (*Paralithodes camtschaticus*) and found animals exposed to reduced pH exhibited increased hatch duration, decreased egg yolk, increased larval size, and decreased larval survival. In contrast, Hurst et al. (2012) conducted laboratory experiments at levels of elevated CO₂ predicted to be present in the Gulf of Alaska and Bering Sea in the next century and found that juvenile walleye pollock (*Gadus chalcogrammus*) exhibited a general resiliency of growth energetics to the direct effects of CO₂ changes.

28.3.2.2. Arctic

28.3.2.2.1. Marine plankton, fish, and other invertebrates

Phenological response

Projected changes in the timing, spatial distribution, and intensity of spring blooms may result in mismatches with the timing of the emergence of Arctic grazers (Søreide et al., 2010). Based on past experience,

some species will adapt to local conditions by shifting key life cycle events (hatch date, maturity schedule, and reproductive timing) or diet to accommodate differences in the regional timing and availability of prey and environmental conditions (Ormseth and Norcross, 2007; Sundby and Nakken, 2008; Vikebø et al., 2010; Darnis et al., 2012). For example, loss of sea ice cover in spring is expected to change fish behavior in ice-bound areas (Mundy and Evenson, 2011). It is uncertain whether endemic animals will be able to alter key phenologies fast enough to keep pace with the projected rates of change in the Arctic Ocean.

Projected spatial shifts

Simulation studies revealed that a 2-week longer growing season and a 2°C increase in temperature would not be sufficient to allow expatriate species (*Calanus finmarchicus* or *C. marshallae*) to invade the Arctic Ocean (Ji et al., 2012). Ellingsen et al. (2008) projected future zooplankton distribution and abundance in the Barents Sea for the period 1995–2059 using a regional climate model that was forced with climate model output based on the *Special Report on Emission Scenarios* (SRES) B2 scenario. They projected that by 2059, Atlantic origin zooplankton will increase and Arctic origin zooplankton will decrease in the Barents Sea.

The literature is mixed with respect to the potential for future movement of fish and shellfish into the Arctic Ocean. Modeling studies project that marine fish stocks potentially will shift their distributions into the Arctic Ocean, resulting in an increase in biodiversity in the region (Cheung et al., 2009, 2011; see also Box CC-MB). However, other studies show the persistence of cold seawater temperatures on the shelf regions of the Arctic Ocean and northern Bering Sea will restrict or retard movement of several sub-Arctic fish and shellfish species into the Arctic Ocean (Sigler et al., 2011; Stabeno et al., 2012b; Hunt, Jr. et al., 2013). In waters off the coasts of Europe there is a potential for increased fish production because of the combined effects of intrusion of Atlantic water over the relatively broader shelf regions and advective corridors for larval drift and range expansion of spawners. Huse and Ellingsen (2008) forced a spatially explicit coupled biophysical model for the Barents Sea with future climate scenarios to project the implications of climate change on the spawning distribution of capelin (*Mallotus villosus*). Projections show that the spawning distribution of capelin will shift to the east and new spawning grounds will be colonized. A key factor governing this expansion will be the availability of pelagic prey. In the southeast Bering Sea, there is evidence that planktivorous species such as walleye pollock will shift their distribution in response to shifts in ocean temperature (Kotwicki and Lauth, 2013). In summary, the spatial distribution of some fish and shellfish in the Barents and southeast Bering Seas will shift in response to climate change (*high confidence*).

Projected impacts on production

In the deep basins of the Arctic Ocean the number of ice-free days in summer are expected to result in longer productive seasons (*high confidence*; Slagstad et al., 2011). Ellingsen et al. (2008) projected that annual primary production would increase by 2059 in the Barents Sea. Tremblay et al. (2012) hypothesized that longer ice-free periods in summer in the Arctic Ocean could provide for more opportunities for episodic

nutrient pulses that would enhance secondary production through the growing season. However, in the Arctic Ocean, these changes in primary production may be offset later in the year by increased zooplankton grazing (Olli et al., 2007) or nutrient depletion due to stronger stratification and shifts in the mixed layer depth (Wassmann, 2011; Tremblay et al., 2012). Therefore, there is *medium confidence* that annual phytoplankton production will increase in the central Arctic Ocean.

In the few cases where future abundance of fish has been projected using climate change scenarios, species exhibited different trends related to their vulnerability. Forward extrapolation of observed responses suggests that increased summer sea surface temperatures in the Bering and Barents Seas will cause a decrease in the abundance of energy-rich copepods and euphausiids (Coyle et al., 2011; Slagstad et al., 2011). This change in prey quality is expected to lower survival of walleye pollock in the eastern Bering Sea by 2050 (Mueter et al., 2011). Climate-enhanced stock projection models showed time trends in cross-shelf transport of juvenile northern rock sole (*Lepidopsetta polyxystra*) to nursery areas will not be substantially altered by climate change (Wilderbuer et al., 2012).

28.3.2.2.2. Marine mammals, polar bears, and seabirds

The effects of the projected reduction in sea ice extent in this century (Wang and Overland, 2009) on Arctic marine mammals and seabirds will vary spatially and temporally (Laidre et al., 2008). Many ice-associated marine mammals and seabirds will be affected by ice loss, with altered species distributions, migration patterns, behavior, interspecific interactions, demography, population changes, and vulnerability to extinction but there is *limited evidence* of changes for most species (*high confidence*).

The polar bear population of the southern Beaufort Sea is projected to decline by 99% by 2100, with a probability estimated at 0.80 to 0.94 under A1B (Hunter et al., 2010). The northern Beaufort Sea population is stable although decline is predicted with warming (Stirling et al., 2011). Projected extirpation of approximately two-thirds of the world's polar bears was predicted for mid-century under A1B (Amstrup et al., 2008). Aspects of this study were criticized (Armstrong et al., 2008) but refuted (Amstrup et al., 2009). The two-thirds decline is consistent with other studies and has *robust evidence* with *medium agreement*. Projected extinction of polar bears is *unlikely*. There is *very high confidence* of subpopulation extirpation.

It is *likely* that the high Arctic seabird species partly or completely dependent on the sympagic ecosystem or the cold Arctic waters close to the ice edge will be negatively impacted if the projected changes in these physical parameters occur (*medium confidence*). A general increase in sea surface temperatures, retreat of the ice cover, and earlier break up of fast ice may improve the environmental conditions and food abundance for seabird species that have their range in the southern part of the Arctic or south of the Arctic (*medium confidence*). A poleward expansion of the range of these species is expected during a continued warming (*medium confidence*).

Several factors other than climate influence seabird population dynamics (Regular et al., 2010), and projections of changes with a continued Arctic

warming are therefore highly uncertain. Pattern of change will be non-uniform and highly complex (ACIA, 2005). At present, the resolution of Atmosphere-Ocean General Circulation Models are not detailed enough to project spatial changes in mesoscale oceanographic features such as frontal zones and eddies of importance to Arctic seabirds.

28.3.2.3. Antarctica and the Southern Ocean

Continued rising temperatures in the Southern Ocean will result in increased metabolic costs in many ectothermic pelagic species, southward movement of temperate species, and contraction of the range of polar species (*medium confidence*). Southward movement of ocean fronts and associated biota that are prey of sub-Antarctic island-based predators will result in energetic inefficiencies for some of those predators (*low confidence*; Péron et al., 2012; Weimerskirch et al., 2012).

For Antarctic krill, insufficient evidence is available to predict what will happen to circumpolar productivity because of regional variability of the effects of climate change on the different factors (positive and negative) that affect krill, directly and indirectly. For example, increased metabolic and growth rates from warming may be countered by a reduced food supply and the effects of ocean acidification (Sections 28.2.2.2, 28.3.2.1). Also, areas that are already warm may result in slower growth with further warming, such as could happen in the northern Scotia Arc (Wiedenmann et al., 2008; Hill et al., 2013). Models of recruitment and population dynamics indicate that the biomass of krill will decline if surface warming continues, but preliminary projections incorporating a range of factors are uncertain (*low confidence*; Murphy et al., 2007, 2012b). Physiological and behavioral responses might also ameliorate impacts. For example, krill are now known to exploit the full depth of the ocean, which could provide escapes from further warming (Schmidt et al., 2011) as well as refuge from air-breathing predators.

The strong dependence of species in more southern regions (e.g., southern west Antarctic Peninsula and Ross Sea region) on sea ice means that changes in sea ice distribution will cause spatial shifts in the structure of ice-obligate food webs (*low confidence*; Murphy et al., 2012b). Projections show that loss of summer sea ice from the west Antarctic Peninsula is expected to result in ice-dependent seals declining and being replaced by other seal species that are not dependent on sea ice (*low confidence*; Siniff et al., 2008; Costa et al., 2010). There is insufficient evidence to determine whether there will be a mismatch in phenologies of different species as a result of changes in the winter sea ice season (timing and winter extent), such as might occur if the timing of sea ice melt was not at a time of optimal growing conditions for phytoplankton (Trathan and Agnew, 2010).

Reductions in krill abundance in the marine food webs around the South Atlantic islands may result in a shift in their structure toward a more fish-centered ecosystem as observed in the Indian Sector (*low confidence*; Trathan, et al., 2007, 2012; Shreeve et al., 2009; Waluda et al., 2010; Murphy et al., 2012a,b). Also, salps have been postulated to be competitors with krill for phytoplankton around the Antarctic Peninsula when oceanic conditions displace shelf and near-shelf waters during times of low sea ice (Ducklow et al., 2012). In the absence of krill, longer food chains have lower trophic efficiency (Murphy et al.,

2013), and the long-term implications of this for higher trophic levels are unknown.

Coastal environments will be impacted by the dynamics of fast ice, ice shelves, and glacier tongues. These factors will positively affect local primary production and food web dynamics (Peck et al., 2009) but negatively affect benthic communities (*low confidence*; Barnes and Souster, 2011). Projections of the response of emperor penguins and Southern Ocean seabirds based on AR4 model outputs for sea ice and temperature in east Antarctica indicate that general declines in these populations are to be expected if sea ice habitats decline in the future (*low confidence*; Barbraud et al., 2011; Jenouvrier et al., 2012). However, these responses are also expected to be regionally specific because of the regional differences in expectations of change in the ice habitats (*high confidence*). Additional studies at other sites are needed to improve confidence levels of predictions.

28.3.3. Terrestrial Environment and Related Ecosystems

28.3.3.1. Arctic

The boreal forest is generally projected by models to move northward under a warming climate, which will displace between 11 and 50% of the tundra within 100 years (Callaghan et al., 2005; Wolf et al., 2008; Tchebakova et al., 2009; Wramneby et al., 2010) in a pattern similar to that which occurred during the early Holocene climatic warming (*high confidence*). Pearson et al. (2013) projected that at least half of vegetated Arctic areas will shift to a different physiognomic class, and woody cover will increase by as much as 52%, in line with what has been occurring in northwest Eurasia (Macias-Fauria et al., 2012).

Dynamic vegetation models applied to Europe and the Barents Region project a general increase in net annual primary production by climate warming and CO₂ fertilization (Wolf et al., 2008; Wramneby et al., 2010; Anisimov et al., 2011). Boreal needle-leaved evergreen coniferous forest replaces tundra and expands into the mountain areas of Fennoscandia, but this advance may be delayed or prevented in regions already occupied by clonal deciduous shrubs whose *in situ* growth has increased significantly in recent decades (Macias-Fauria et al., 2012).

In contrast to these expected results, shrubs, currently expanding in area in many Arctic locations, were modeled to decrease in extent over the next 100 years after an initial increase (Wolf et al., 2008). Also, counterintuitively, tundra areas increased in the projections. This was a result of changes at the highest latitudes that opened land for colonization at a rate exceeding displacement of tundra by shrubs in the south.

Several studies have calculated the magnitude of the effects of vegetation change in the Arctic on negative feedbacks of CO₂ sequestration and increased evapotranspiration and the positive feedback of decreased albedo (Swann et al., 2010; Wramneby et al., 2010; Wolf et al., 2010; Pearson et al., 2013). It is *likely* that vegetation changes will result in an overall positive feedback on the climate.

Recent changes and results of climate change simulation experiments in the field have shown that there are considerable uncertainties in the

projected rates of change (e.g., Van Bogaert et al., 2010). Furthermore, the models do not yet include vertebrate and invertebrate herbivory, extreme events such as tundra fire, and extreme winter warming damage or changes in land use that either reduce the rate of vegetation change or open up niches for rapid change. Projections suggest increases in the ranges of the autumn and winter months that have outbreaks in populations resulting in the defoliation of birch forest (Jepsen et al., 2008, 2011) and a general increase in the “background” (non-outbreak) invertebrate herbivores (Wolf et al., 2008).

Animal terrestrial biodiversity is generally projected to increase in the Arctic during warming by immigration of new species from the south, vegetation changes, and indirectly by introduction of invasive species caused by increased human activities and increased survival of such species (*high confidence*; Post et al., 2009; Gilg et al., 2012; CAFF, 2013). Many native Arctic species will *likely* be increasingly threatened during this century.

28.3.3.2. Antarctica

Projected effects of climate change on Antarctic terrestrial species are limited to knowledge of their ecophysiological tolerances to changes in air temperature, wind speed, precipitation (rain and snowfall), permafrost thaw, and exposure of new habitat through glacial/ice retreat. The climate is expected to become more tolerable to a number of species, leading to increases in biomass and extent of existing ecological communities.

The frequency with which new potential colonizing plant and animal species arrive in Antarctica (particularly the Antarctic Peninsula region) from lower latitudes, and the subsequent probability of their successful establishment, will increase with regional climate warming and associated environmental changes (*high confidence*; Chown et al., 2012). Human-assisted transfers of biota may be more important by two orders of magnitude than natural introductions (Frenot et al., 2005) as the transfer is faster and avoids extreme environments such as altitude or oceans (Barnes et al., 2006). The potential for anthropogenic introduction of non-indigenous species to Antarctic terrestrial areas, which could have devastating consequences to the local biodiversity, will increase (*high confidence*; Convey et al., 2009; Hughes and Convey, 2010; Convey, 2011; Braun et al., 2012). At present, established non-indigenous species in the sub- and maritime Antarctic are very restricted in their distributions (Frenot et al., 2005). Climate change could result in a greater rate of spread of invasive species through colonization of areas exposed by glacial retreat, as has occurred at South Georgia (Cook et al., 2010) and in the maritime Antarctic (Olech and Chwedorzewska, 2011). Biosecurity measures may be needed to help control dispersal of established non-indigenous species to new locations, particularly given the expected increase in human activities in terrestrial areas (Hughes and Convey, 2010; Convey et al., 2011). An important gap in understanding is the degree to which climate change may facilitate some established but localized alien species to become invasive and widespread (Frenot et al., 2005; Convey 2010; Hughes and Convey, 2010; Cowan et al., 2011), which has been shown for the sub-Antarctic (Chown et al., 2012).

Overall, the likely impacts of existing and new non-indigenous species on the native terrestrial ecosystems of Antarctica and the sub-Antarctic

islands, along with the continued increased presence of Antarctic fur seals, are likely to have far greater importance over the time scale under consideration than are those attributable to climate change itself (Convey and Lebouvier, 2009; Turner et al., 2009; Convey, 2010).

28.3.4. Economic Sectors

Projections of economic costs of climate change impacts for different economic sectors in the Arctic are limited, but current assessments suggest that there will be both benefits and costs (AMAP, 2011a; Forbes, 2011). Non-Arctic actors are likely to receive most of the benefits from increased shipping and commercial development of renewable and non-renewable resources, while Indigenous peoples and local Arctic communities will have a harder time maintaining their way of life (Hovelsrud et al., 2011).

Contributing to the complexity of measuring the future economic effects of climate change is the uncertainty in future predictions and the rapid speed of change, which are linked with the uncertainty of the technological and ecological effects of such change (NorAcia, 2010). Communities within the same eco-zone may experience different effects from identical climate-related events because of marked local variations in site, situation, culture, and economy (Clark et al., 2008).

Economic cost estimates have been made for the case of the Alaskan economy, for example, which suggest that a heavy reliance on climate-sensitive businesses such as tourism, forestry, and fisheries renders the economy vulnerable to climate change, and that Alaska Native peoples, reliant on the biodiversity of the Alaskan ecosystem, are being affected disproportionately (Epstein and Ferber, 2011). Some Alaskan villages such as Shishmaref, Kivalina, and Newtok have already lost critical infrastructure and services and are becoming unlivable because of permafrost thaw, storm damage, and coastal erosion but the high costs and limitations of government mechanisms are significant barriers to the actual relocation of these communities (Bronen, 2011; Brubaker et al., 2011c; Cochran et al., 2013; Maldonado et al., 2013).

28.3.4.1. Fisheries

Climate change will impact the spatial distribution and catch of some open ocean fisheries in the Barents and Bering Seas (*high confidence*); however, the future of commercial fisheries in the Arctic Ocean is uncertain. There is strong evidence and considerable data showing links between climate-driven shifts in ocean conditions and shifts in the spatial distribution and abundance of commercial species in the Bering and Barents Seas (Section 28.3.2.2.1). In limited cases, coupled biophysical models or climate-enhanced stock projection models have been used to predict future commercial yield or shifts in fishing locations. However, these predictions are uncertain (Huse and Ellingsen, 2008; Ianelli et al., 2011; Wilderbuer et al., 2012). Cheung et al. (2011) used projections from an Earth System Model to estimate shifts in bio-climatic windows that included climate change effects on biogeochemistry (oxygen and acidity) and primary production to project future catch potential of 120 demersal fish and invertebrates. Results from their model suggested that the catch potential will increase in the Barents and Greenland Seas and regions

at greater than 70° north latitude (Cheung et al., 2011). In contrast, vulnerability analysis suggests that only a few species are expected to be abundant enough to support viable fisheries in the Arctic Ocean (Hollowed et al., 2013). Potential fisheries for snow crab (*Chionoecetes opilio*) on shelf areas of the Arctic Ocean may be limited by the associated impacts of ocean acidification. If fisheries develop in the Arctic Ocean, adoption of sustainable strategies for management will be a high priority (Molenaar, 2009). The moratorium on fishing in the US portion of the Chukchi and Beaufort Seas would prevent fishing until sufficient data become available to manage the stock sustainably (Wilson and Ormseth, 2009).

Predicting how harvesters will respond to changing economic, institutional, and environmental conditions under climate change is difficult. Current techniques track fishers' choices based on revenues and costs associated with targeting a species in a given time and area with a particular gear given projected changes in the abundance and spatial distribution of target species (Haynie and Pfeiffer, 2012). However, estimates of future revenues and costs will depend, in part, on future demand for fish, global fish markets, and trends in aquaculture practices (Rice and Garcia, 2011; Merino et al., 2012).

28.3.4.2. Forestry and Farming

Climate change is *likely* to have positive impacts for agriculture, including extended growing season (*medium* to *high confidence*; Falloon and Betts, 2009; Grønlund, 2009; Tholstrup and Rasmussen, 2009), although variations across regions are expected (Hovelsrud et al., 2011), and the importance of impacts to the Arctic economy will likely remain minor (Eskeland and Flottorp, 2006). Potential positive effects of climatic warming for forestry include decreased risk of snow damage. Kilpeläinen et al. (2010) estimate a 50% decrease in snow damage in Finland toward the end of the century. A warmer climate is likely to impact access conditions and plant diseases for forestry and farming. Grønlund (2009) found in the case of northern Norway—where about half of the arable land area is covered by forest and 40% by marshland—that the potential harnessing of arable land for farming will be at the cost of forestry production, or dried-up marshlands, which may contribute to more greenhouse emissions. Larger field areas may contribute to land erosion through rainfall and predicted unstable winters, and may increase conditions for plant diseases and fungal infections (Grønlund, 2009). If the winter season continues to shorten due to climate change (Xu et al., 2013), accessibility to logging sites will be negatively affected. Accessibility is higher when frozen ground makes transportation possible in sensitive locations or areas that lack road. If weather changes occur when logging has taken place, sanding of roads may be necessary which carries significant economic costs. Impact on carrying capacity of ground or road accessibility will thus affect forestry economically. Challenges may include limited storage space for wood (Keskitalo, 2008).

28.3.4.3. Infrastructure, Transportation, and Terrestrial Resources

Rising temperatures and changing precipitation patterns have the potential to affect all infrastructure types and related services, as much

of the infrastructure in the North is dependent on the cryosphere to, for example, provide stable surfaces for buildings and pipelines, contain waste, stabilize shorelines, and provide access to remote communities in the winter (*high confidence*; Huntington et al., 2007; Furgal and Prowse, 2008; Sundby and Nakken, 2008; Sherman et al., 2009; West and Hovelsrud, 2010; Forbes, 2011). In the long-term, marine and freshwater transportation will need to shift reliance from ice routes to open-water or land-based transportation systems. Relocation remains one community-based adaptation to deal with projections of persistent flooding and bank erosion (Furgal, 2008; NRTEE, 2009). Changing sea ice (multi-year) conditions are expected to have a regulating impact on marine shipping and coastal infrastructure (i.e., via introduced hazards; Eicken et al., 2009).

By adapting transportation models to integrate monthly climate model (Community Climate System Model 3 (CCSM3)) predictions of air temperature—combined with data sets on land cover, topography, hydrography, built infrastructure, and locations of human settlements—estimates have been made of changes to inland accessibility for landscapes northward of 40°N by the mid-21st century (Stephenson et al., 2011). Milder air temperatures and/or increased snowfall reduce the possibilities for constructing inland winter-road networks, including ice roads, with the major seasonal reductions in road potential (based on a 2000-kg vehicle) being in the winter shoulder-season months of November and April. The average decline (compared to a baseline of 2000–2014) for eight circumpolar countries was projected to be –14%, varying from –11 to –82%. In absolute terms, Canada and Russia (both at –13%) account for the majority of declining winter-road potential with approximately 1×10^6 km² being lost (see Table 28-1). The winter road season has decreased since the 1970s on the Alaskan North Slope, from as much as 200 to 100 days in some areas (Hinzman et al., 2005).

Climate change is expected to lead to a nearly ice-free Arctic Ocean in late summer and increased navigability of Arctic marine waters within this century. New possibilities for shipping routes and extended use of existing routes may result from increased melting of sea ice (*high confidence*; Corbett et al., 2010; Khon et al., 2010; Paxian et al., 2010; Peters et al., 2011; Stephenson et al., 2011).

Table 28-1 | Annually averaged changes in inland and maritime transportation accessibility by mid-century (2045–2059) versus baseline (2000–2014).

	Change (%) in winter road-accessible land area (km ²) (2000-kg GVWR vehicle)	Change (%) in maritime-accessible ocean area (km ²) (type A vessel)—current EEZ
Canada	–13	19
Finland	–41	0
Greenland	–11	28
Iceland	–82	<1
Norway	–51	2
Russia	–13	16
Sweden	–46	0
USA (Alaska)	–29	5
High seas	n/a	406
Total	–14	23

(a) Northern Sea Route

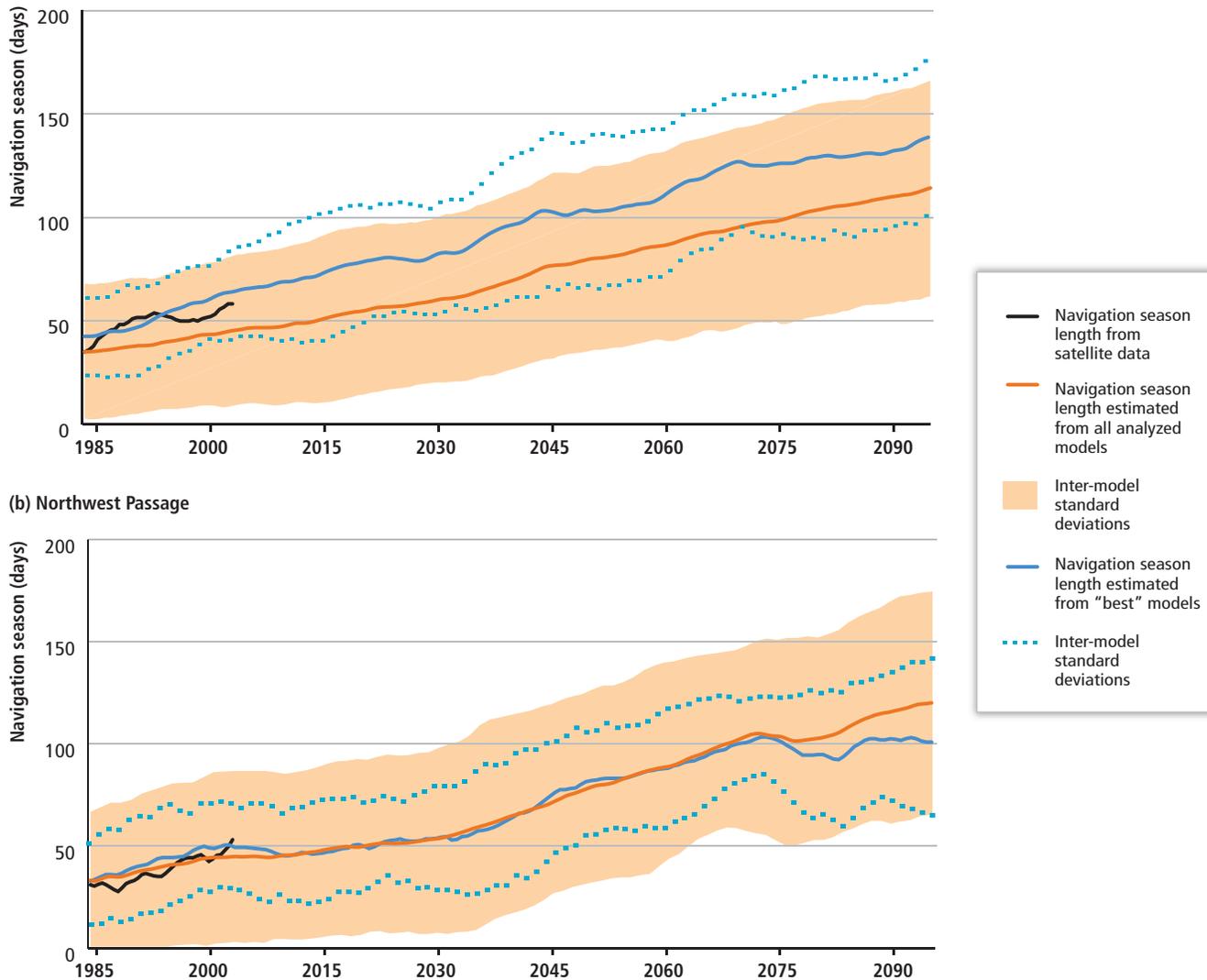


Figure 28-4 | Projected duration of the navigation period (days) over the Northwest Passage and Northern Sea Route (Khon et al., 2010).

Projections made by Stephenson et al. (2011) suggest that all five Arctic littoral states will gain increased maritime access to their current exclusive economic zones, especially Greenland (+28%, relative to baseline), Canada (+19%), Russia (+16%), and the USA (+15%). In contrast, Iceland, Norway, Sweden, and Finland display little or no increase in maritime accessibility (Table 28-1; Stephenson et al., 2011).

General Circulation Models (GCMs) developed for the AR4 generally have underestimated the duration of the ice-free period in the Arctic Ocean and simulate slower changes than those observed in the past decades (Stroeve et al., 2007). Mokhov and Khon (2008) used a subset of climate models that better reproduce observed sea ice dynamics than other GCMs to project the duration of the navigation season along the NSR and through the NWP under the moderate SRES A1B emission scenario. According to their results, by the end of the 21st century, the NSR may be open for navigation 4.5 ± 1.3 months per year, while the NWP may be open 2 to 4 months per year (see Figure 28-4). The models did not predict any significant changes of the ice conditions in the NWP until the early 2030s.

An increase in the length of the summer shipping season, with sea ice duration expected to be 10 days shorter by 2020 and 20 to 30 days shorter by 2080, is likely to be the most obvious impact of changing climate on Arctic marine transportation (Prowse et al., 2009). Reduction in sea ice and increased marine traffic could offer opportunities for economic diversification in new service sectors supporting marine shipping. Loss of sea ice may open up waterways and opportunities for increased cruise traffic (e.g., Glomsrød and Aslaksen, 2009), and add to an already rapid increase in cruise tourism (Howell et al., 2007; Stewart et al., 2007, 2010). Climate change has increased the prevalence of cruise tourism throughout Greenland, Norway, Alaska, and Canada because of decreasing sea ice extent.

Projected declines in sea ice cover leading to development of integrated land and marine transportation networks in northern Canada may stimulate further mine exploration and development (Prowse et al., 2009). These possibilities, however, also come with challenges including their predicted contribution to the largest change in contaminant movement into or within the Arctic, as well as their significant negative impacts

on the traditional ways of life of northern residents (Furgal and Prowse, 2008). Added shipping and economic activity will increase the amount of black carbon and reinforce warming trends in the region (Lack and Corbett, 2012), leading to additional economic activity.

A longer shipping season and improved access to ports may lead to increased petroleum activities, although possible increased wave activity and coastal erosion may increase costs related to infrastructure and technology. Peters et al. (2011) find by using a bottom-up shipping model and a detailed global energy market model to construct emission inventories of Arctic shipping and petroleum activities in 2030 and 2050—and based on estimated sea ice extent—that there will be rapid growth in transit shipping; oil and gas production will be moving into locations requiring more ship transport; and this will lead to rapid growth in emissions from oil and gas transport by ship.

The Arctic contains vast resources of oil, which is hard to replace as transportation fuel, and vast resources of gas, a more climate-benign fuel than coal. Petroleum resources are unevenly distributed among Arctic regions and states. Arctic resources will play a growing role in the world economy, but increased accessibility is expected to create challenges for extraction, transport, engineering, search-and-rescue needs, and responses to accidents (Hovelsrud et al., 2011), and climatic change presents the oil and gas industry with challenges in terms of planning and predictions (Harsem et al., 2011). Increased emissions due to rapid growth in Arctic Ocean transportation of oil and gas are projected (Peters et al., 2011). Owing to high costs and difficult access conditions, the impact on future oil and gas production in the Arctic remains unclear (Peters et al., 2011; Lindholdt and Glomsrød, 2012).

28.4. Human Adaptation

There is general agreement that both Indigenous and non-Indigenous people in the Arctic have a history of adapting to natural variability in the climate and natural resource base, as well as recent socioeconomic, cultural, and technological changes (*high confidence*; Forbes and Stammer, 2009; Wenzel, 2009; Ford and Pearce, 2010; West and Hovelsrud, 2010; Bolton et al., 2011; Cochran et al., 2013). Climate change exacerbates the existing stresses faced by Arctic communities (*high confidence*; Crate and Nuttall, 2009; Rybråten and Hovelsrud, 2010), and is only one of many important factors influencing adaptation (Berrang-Ford et al., 2011). Climate adaptation needs to be seen in the context of these interconnected and mutually reinforcing factors (Tyler et al., 2007; Hovelsrud and Smit, 2010). The challenges faced today by communities in the Arctic are complex and interlinked and are testing their traditional adaptive capacity (*low to medium confidence*).

Climatic and other large-scale changes have potentially large effects on Arctic communities, in particular where simple economies leave a narrower range of adaptive choices (Berkes et al., 2003; Anisimov et al., 2007; Ford and Furgal, 2009; Andrachuk and Pearce, 2010; Ford et al., 2010; Forbes, 2011). There is considerable evidence that changing weather patterns, declining sea ice and river as well as lake ice, thawing permafrost, and plant and animal species' abundance and composition have consequences for communities in the Arctic (see Sections 28.2.4, 28.2.5.2, and 28.3.4). Sea ice is particularly important for coastal

communities that rely upon it for transportation to and from hunting areas (Krupnik et al., 2010). Changes in the duration and condition of sea ice and the consequent changes to country food availability significantly impact the well-being of communities (Furgal and Seguin, 2006; Ford and Berrang-Ford, 2009; Ford et al., 2010), outdoor tourism (Dawson et al., 2010), and hunting and fishing (*high confidence*; Wiig et al., 2008; Brander, 2010).

Adaptation to climate change is taking place at the local and regional levels where impacts are often felt most acutely and the resources most readily available (Oskal, 2008; Hovelsrud and Smit, 2010). Current experiences and projections of future conditions often lead to technological adaptation responses such as flood and water management and snow avalanche protection (Hovelsrud and Smit, 2010; West and Hovelsrud, 2010) rather than policy responses (Hedensted Lund et al., 2012; Rudberg et al., 2012). Climate variability and extreme events are found to be salient drivers of adaptation (Amundsen et al., 2010; Berrang-Ford et al., 2011; Dannevig et al., 2012).

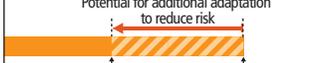
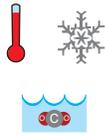
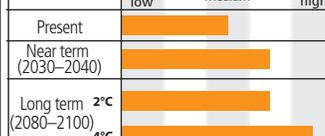
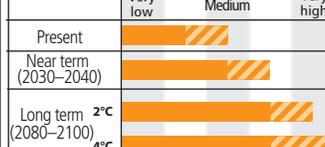
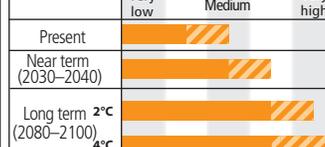
The lack of local scale climate projections, combined with uncertainties in future economic, social, and technological developments, often act as barriers to adaptation. These barriers, together with other societal determinants such as ethics, cultures, and attitudes toward risk, may cause inaction (Adger et al., 2009; West and Hovelsrud, 2010). Resolving divergent values across and within different communities poses a challenge for governance regimes. A determining factor in building adaptive capacity is the flexibility of enabling institutions to develop robust options (Forbes et al., 2009; Kesitalo et al., 2009; Hovelsrud and Smit, 2010; Ford and Goldhar, 2012; Whyte, 2013). Refer to Table 28-2 for key climate-related risks and potential adaptation practices. In the North American and Scandinavian context, adaptive co-management responses have been developed through land claims settlements and/or multi-scale institutional cooperation to foster social learning (Armitage et al., 2008; Berkes, 2009).

Indigenous Peoples

Although Arctic indigenous peoples with traditional lifestyles are facing unprecedented impacts to their ways of life from climate change and resource development (oil and gas, mining, forestry, hydropower, tourism, etc.), they are already implementing creative ways of adapting (*high confidence*; Cruikshank, 2001; Forbes et al., 2006; Krupnik and Ray, 2007; Salick and Ross, 2009; Green and Raygorodetsky, 2010; Alexander et al., 2011; Cullen-Unsworth et al., 2011).

While many of these adaptation activities tend to be short term or reactive in nature (e.g., dealing with other issues such as disaster response planning), some Indigenous communities are beginning to develop more formal adaptation plans (Galloway-McLean, 2010; Brubaker et al., 2011b,c; Nakashima et al., 2012). Comprehensive adaptation planning must take into account underlying social issues of some Indigenous populations when addressing the new challenges from climate and development. Indigenous communities are especially vulnerable to climate change because of their strong dependence on the environment for food, culture, and way of life; their political and economic marginalization; the social, health, and poverty disparities; and community locations

Table 28-2 | Key climate-related risks in the Arctic and Antarctic, and potential adaptation practices.

Climate-related drivers of impacts			Level of risk & potential for adaptation	
 Warming trend	 Snow cover	 Ocean acidification	Potential for additional adaptation to reduce risk  Risk level with high adaptation Risk level with current adaptation	
Key risk	Adaptation issues & prospects	Climatic drivers	Timeframe	Risk & potential for adaptation
Risks for freshwater and terrestrial ecosystems (<i>high confidence</i>) and marine ecosystems (<i>medium confidence</i>), due to changes in ice, snow cover, permafrost, and freshwater/ocean conditions, affecting species' habitat quality, ranges, phenology, and productivity, as well as dependent economies [28.2-4]	<ul style="list-style-type: none"> Improved understanding through scientific and indigenous knowledge, producing more effective solutions and/or technological innovations Enhanced monitoring, regulation, and warning systems that achieve safe and sustainable use of ecosystem resources Hunting or fishing for different species, if possible, and diversifying income sources 		Very low Medium Very high Present Near term (2030–2040) Long term (2080–2100) 2°C 4°C	
Risks for the health and well-being of Arctic residents, resulting from injuries and illness from the changing physical environment, food insecurity, lack of reliable and safe drinking water, and damage to infrastructure, including infrastructure in permafrost regions (<i>high confidence</i>) [28.2-4]	<ul style="list-style-type: none"> Co-production of more robust solutions that combine science and technology with indigenous knowledge Enhanced observation, monitoring, and warning systems Improved communications, education, and training Shifting resource bases, land use, and/or settlement areas 		Very low Medium Very high Present Near term (2030–2040) Long term (2080–2100) 2°C 4°C	
Unprecedented challenges for northern communities due to complex inter-linkages between climate-related hazards and societal factors, particularly if rate of change is faster than social systems can adapt (<i>high confidence</i>) [28.2-4]	<ul style="list-style-type: none"> Co-production of more robust solutions that combine science and technology with indigenous knowledge Enhanced observation, monitoring, and warning systems Improved communications, education, and training Adaptive co-management responses developed through the settlement of land claims 		Very low Medium Very high Present Near term (2030–2040) Long term (2080–2100) 2°C 4°C	

along exposed ocean, lake, or river shorelines (Ford and Furgal, 2009; Galloway-McLean, 2010; Larsen et al., 2010; Cochran et al., 2013).

capacity (Forbes 2007; Ford et al., 2007; Hovelsrud and Smit, 2010; Bolton et al., 2011).

The adaptive capacity of Arctic Indigenous peoples is largely due to an extensive traditional knowledge and cultural repertoire, and flexible social networks (*medium confidence*; Williams and Hardison, 2013; see Section 12.3). The dynamic nature of traditional knowledge is valuable for adapting to current conditions (Kitti et al., 2006; Tyler et al., 2007; Eira et al., 2012). The sharing of knowledge ensures rapid responses to crises (Ford et al., 2007). In addition, cultural values such as sharing, patience, persistence, calmness, and respect for elders and the environment are important. Some studies suggest that traditional knowledge may not always be sufficient to meet the rapid changes in climate (see Chapter 12) and it may be perceived to be less reliable because the changing conditions are beyond the current knowledge range (Ingram et al., 2002; Ford et al., 2006; Hovelsrud et al., 2010; Valdivia et al., 2010).

Examples of Indigenous adaptation strategies have included changing resource bases; shifting land use and/or settlement areas; combining technologies with traditional knowledge; changing timing and location of hunting, gathering, herding, and fishing areas; and improving communications and education (Galloway-McLean, 2010). Protection of grazing land will be the most important adaptive strategy for reindeer herders under climate change (Forbes et al., 2009; Magga et al., 2011; Kumpula et al., 2012; Degteva and Nellemann, 2013; Mathiesen et al., 2013). Renewable resource harvesting remains a significant component of Arctic livelihoods, and with climate change hunting and fishing has become a riskier undertaking and many communities are already adapting (Gearheard et al., 2011; Laidler et al., 2011). Adaptation includes taking more supplies when hunting, constructing permanent shelters on land as refuges from storms, improved communications infrastructure, greater use of global positioning systems (GPS) for navigation, synthetic aperture radar (SAR) to provide estimates of sea ice conditions (Laidler et al., 2011), and the use of larger or faster vehicles (Ford et al., 2010). Avoiding dangerous terrain can result in longer and time-consuming journeys that can be inconvenient to those with wage-earning employment (Ford et al., 2007).

Over the last half-century, the adaptive capacity in some Indigenous communities has been challenged by the transition from semi-nomadic hunting groups to permanent settlements, accompanied by impacts to health and well-being from loss of connection to the land, traditional foods, and culture (Ford et al., 2010; Galloway-McLean, 2010). Forced or voluntary migration as an adaptation response can have deep cultural impacts (Shearer, 2011, 2012; Maldonado et al., 2013). On the other hand, the establishment of permanent communities, particularly those associated with new industrial development, can also lead to increasing employment opportunities and income diversification for Indigenous peoples. The intergenerational transfers of knowledge and skills through school curricula, land camps, and involvement in community-based monitoring programs may strengthen adaptive

Reindeer herders have developed a wide range of adaptation strategies in response to changing pasture conditions. These include moving herds to better pastures (Bartsch et al., 2010), providing supplemental feeding (Helle and Jaakkola, 2008; Forbes and Kumpula, 2009), retaining a few castrated reindeer males to break through heavy ice crust (Oskal, 2008; Reinert et al., 2008), ensuring an optimal herd size (Tyler et al., 2007;

Forbes et al., 2009), and creating multicultural initiatives combining traditional with scientific knowledge (Vuojala-Magga et al., 2011). Coastal fishers have adapted to changing climate by targeting different species and diversifying income sources (Hovelsrud et al., 2010).

In some Arctic countries Indigenous peoples have successfully negotiated land claims rights and have become key players in addressing climate change (Abele et al., 2009). In some instances, this has given rise to tensions over land/water use between traditional livelihoods and new opportunities, for example, tourism and natural resource development (Forbes et al., 2006; Hovelsrud and Smit, 2010). Some territorial governments in northern Canada have promoted adaptation by providing hunter support programs (Ford et al., 2006, 2010).

Health of many Indigenous people is being affected by the interaction of changes in the climate with ongoing changes in human, economic, and biophysical systems (Donaldson et al., 2010). The distribution of traditional foods between communities and the use of community freezers in the Canadian Arctic has improved food security, an important factor for health (Ford et al., 2010). Although wage employment may

enhance the possibilities for adaptive capacity, greater involvement in full-time jobs can threaten social and cultural cohesion and mental well-being by disrupting the traditional cycle of land-based practices (Berner et al., 2005; Furgal, 2008).

28.5. Research and Data Gaps

There remains a poor knowledge of coupling among, and thresholds within, biogeophysical and socioeconomic processes to fully assess the effects of a changing climate, and to separate them from those due to other environmental stressors:

- Existing integrative models are either lacking or insufficiently validated to project and to assess the cascading effects on, and feedbacks from, the systems in the polar regions, in particular socioeconomic systems.
- There is a need to enhance or establish a coordinated network of long-term representative sites for monitoring and assessment of climate change detection and attribution studies in the polar regions. Regional differences and confounding variables will need to be

Frequently Asked Questions

FAQ 28.1 | What will be the net socioeconomic impacts of change in the polar regions?

Climate change will have costs and benefits for polar regions. Climate change, exacerbated by other large-scale changes, can have potentially large effects on Arctic communities, where relatively simple economies leave a narrower range of adaptive choices.

In the Arctic, positive impacts include new possibilities for economic diversification, marine shipping, agricultural production, forestry, and tourism. The Northern Sea Route is predicted to have up to 125 days per year suitable for navigation by 2050, while the heating energy demand in the populated Arctic areas is predicted to decline by 15%. In addition, there could be greater accessibility to offshore mineral and energy resources although challenges related to environmental impacts and traditional livelihoods are possible.

Changing sea ice condition and permafrost thawing may cause damage to bridges, pipelines, drilling platforms, hydropower, and other infrastructure. This poses major economic costs and human risks, although these impacts are closely linked to the design of the structure. Furthermore, warmer winter temperatures will shorten the accessibility of ice roads that are critical for communications between settlements and economic development and have implications for increased costs. Statistically, a long-term mean increase of 2°C to 3°C in autumn and spring air temperature produces an approximately 10- to 15-day delay in freeze-up and advance in break-up, respectively.

Particular concerns are associated with projected increase in the frequency and severity of ice-jam floods on Siberian rivers. They may have potentially catastrophic consequences for the villages and cities located in the river plain, as exemplified by the 2001 Lena River flood, which demolished most of the buildings in the city of Lensk.

Changing sea ice conditions will impact Indigenous livelihoods, and changes in resources, including marine mammals, could represent a significant economic loss for many local communities. Food security and health and well-being are expected to be impacted negatively.

In the Antarctic, tourism is expected to increase, and risks exist of accidental pollution from maritime accidents, along with an increasing likelihood of the introduction of alien species to terrestrial environments. Fishing for Antarctic krill near the Antarctic continent is expected to become more common during winter months in areas where there is less winter sea ice.

Frequently Asked Questions

FAQ 28.2 | Why are changes in sea ice so important to the polar regions?

Sea ice is a dominant feature of polar oceans. Shifts in the distribution and extent of sea ice during the growing season impacts the duration, magnitude, and species composition of primary and secondary production in the polar regions. With less sea ice many marine ecosystems will experience more light, which can accelerate the growth of phytoplankton, and shift the balance between the primary production by ice algae and water-borne phytoplankton, with implications for Arctic food webs. In contrast, sea ice is also an important habitat for juvenile Antarctic krill, providing food and protection from predators. Krill is a basic food source for many species in polar marine ecosystems.

Changes in sea ice will have other impacts, beyond these “bottom-up” consequences for marine food webs. Mammals and birds utilize sea ice as haul-outs during foraging trips (seals, walrus, and polar bears in the Arctic and seals and penguins in the Antarctic). Some seals (e.g., bearded seals in the Arctic and crab eater and leopard seals in the Antarctic) give birth and nurse pups in pack ice. Shifts in the spatial distribution and extent of sea ice will alter the spatial overlap of predators and their prey. According to model projections, within 50 to 70 years, loss of hunting habitats may lead to elimination of polar bears from seasonally ice-covered areas, where two-thirds of their world population currently live. The vulnerability of marine species to changes in sea ice will depend on the exposure to change, which will vary by location, as well as the sensitivity of the species to changing environmental conditions and the adaptive capacity of each species. More open waters and longer ice-free periods in the northern seas enhance the effect of wave action and coastal erosion, with implications for coastal communities and infrastructure.

Although the overall sea ice extent in the Southern Ocean has not changed markedly in recent decades, there have been increases in oceanic temperatures and large regional decreases in winter sea ice extent and duration in the western Antarctic Peninsula region of West Antarctica and the islands of the Scotia Arc.

considered in designing field and modeling studies. Standardized methods and approaches of biophysical and socioeconomic analysis along with coordinated sampling in more regions will be necessary.

There are more specific research gaps, including:

- Many mechanisms of how climate change and ocean acidification may be affecting polar ecosystems have been proposed but few studies of physiological tolerances of species, long-term field studies of ecosystem effects, and ecosystem modeling studies are available to be able to attribute with high confidence current and future change in these ecosystems to climate change.
- More comprehensive studies including long-term monitoring on the increasing impacts from climate changes on Arctic communities (urban and rural) and their health, well-being, traditional livelihoods, and life ways are needed. There is a need to assess more fully vulnerabilities and to develop response capacities at the local and regional levels.

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