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Arctic Societies, Cultures, and Peoples in a Changing Cryosphere

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Abstract Changes in sea ice, snow cover, lake and river ice, and permafrost will affect economy, infrastructure, health, and indigenous and non-indigenous livelihoods, culture, and identity. Local residents are resilient and highly adaptive, but the rate and magnitude of change challenges the current adaptive capacity. Cryospheric changes create both challenges and opportunities, and occur along local, regional, and international dimensions. Such changes will provide better access to the Arctic and its resources thereby increasing human activities such as shipping and tourism. Cryospheric changes pose a number of challenges for international governance, human rights, safety, and search and rescue efforts. In addition to the direct effects of a changing cryosphere, human society is affected by indirect factors, including industrial developments, globalization, and societal changes, which contribute to shaping vulnerability and adaptation options. Combined with non-cryospheric drivers of change, this will result in multifaceted and cascading effects within and beyond the Arctic.

Keywords Cryospheric change · Societal effects · Adaptation · Arctic society · Governance · Indigenous and local residents

INTRODUCTION

In this article, we identify and link the key effects of cryospheric changes with key aspects of human society and activities in the Arctic. This article is part of the SWIPA assessment (AMAP 2011 and other contributions in this issue) and draws on conclusions from society relevant articles detailing changes in cryospheric components. More details can be found in chapter 10 in the SWIPA assessment (AMAP 2011). Cryospheric changes are first and foremost felt at the local level and by peoples and communities whose livelihoods and well-being are closely linked to the natural environment. Local observations confirm cryospheric changes and consequences including a significant thinning of sea- and freshwater-ice, a shortening of the winter ice season, a reduction in snow cover, changes in the distributions of wildlife and plant species, thawing permafrost, and increased coastal erosion (see Hovelsrud and Smit 2010 and references therein). Arctic communities have throughout history adapted well to high-natural variability in both climate and the resource base (e.g., Forbes et al. 2009), but the complex inter-linkages between societal, economic, and cryospheric change (Fig. 1), and the rate and magnitude of such changes represent unprecedented challenges to the current adaptive capacity and resilience of Arctic residents (Keskitalo et al. 2010).

While adaptation clearly is a local concern, institutions across societal scales (municipal, regional, international), sectors, and nations operating in the Arctic also need to adapt (Hovelsrud and Smit 2010). In addition, a cross-scale approach is essential for analyzing how cryospheric and societal conditions combine to shape adaptation (Table 1).

ADAPTATION TO CRYOPSHERIC CHALLENGES AND OPPORTUNITIES

Reactive adaptation as a direct response to current climate and risk management practices and extreme weather events (Næss et al. 2005; Amundsen et al. 2010), is insufficient as

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Fig. 1 Small skiffs used for local hunting and fishing side by side commercial fishing vessels and industrial infrastructure in Greenland. The photo illustrates the span of activities in an Arctic town and the proximity to both sea ice and ice bergs. Warming ocean has reduced the sea-ice conditions and season considerably in this part of Greenland. Local communities deal with changes in both climate and socio-economic conditions. *Photo*: Grete K. Hovelsrud

a long-term strategy to meet many of the effects of cryospheric change. Proactive adaptation and strategies are urgently needed in order to provide the basis for adequate preparedness. Without proper guidelines and regulations that anticipate the impact of future climate change on industrial development and resource-use (such as commercial fisheries, cruise traffic, and shipping), local communities may become more vulnerable to changing conditions. The development of the International Maritime Organization International 'Polar Code' (2009) for Arctic shipping is an example of a proactive form of adaptation to changing ocean conditions. The Polar Code, by setting standards for safety and reporting, is the first set of internationally recognized guidelines for the construction and operation of ships in ice-covered Arctic waters.

Infrastructure

Increasing permafrost thaw, subsidence, and coastal erosion (Martin et al. 2009) pose new hazards for infrastructure, and for commercial traffic on ice roads and lake- and river-ice networks for travel and transport of heavy loads (Woo et al. 2007; Furgal and Prowse 2008) and for access to traditional food sources by Arctic residents (e.g., Ford et al. 2008). Later formation of sea ice and increased frequency of extreme weather events (Kolstad and Bracegirdle 2008) increase coastal exposure, and in combination with rising sea level, shifting river discharges, runoff, and altered sedimentation rates in coastal areas will increasingly affect Arctic coasts, coastal marine ecosystems and infrastructure (Forbes et al. 2008; Perovich and Richter-Menge 2009). Open water also leads to the formation of low clouds and fog, creating freezing drizzle and significant icing on aircrafts and vessels. Wind action may cause significant ice ride-up and pile-ups, which can extend more than 100 m inland and damage transport infrastructure (Kovacs and Sodhi 1980). Adaptation measures to such events include development of protective infrastructure and relocation of settlements and infrastructure (Furgal and Prowse 2008).

In areas where open rivers currently are critical for reaching remote regions, such as in Russia, a longer ice-free season will provide better access and is economically beneficial. River barges and land-based all-weather roads

Table 1 Cross-cutting challenges and adaptation

Cryospheric change (exposure sensitivity)	Implications and challenges	Adaptation strategies and governance implications
Sea ice Shorter duration of land-fast sea ice; poorer ice quality; reduced sea ice; longer and larger open-water season at the coast	Land-fast ice travel and hunting hampered; safety of sea ice-based hunting compromised; changes in fish stocks and fisheries, increased access for fisheries, increased traffic at sea, increased industrial activity, oil and gas exploration; Increased fetch (and storminess) erodes coastline	Changes in transport mode, shift to open-sea hunting and fishing, new equipment such as GPS and satellite phone required, Fishery regulations must change, International Maritime Organization (IMO) standards for shipping in the Arctic, higher costs of security provision, stricter environmental regulations; Shoreline stabilization and engineering options, eventually relocation; authority to relocate communities
Thawing permafrost Increased coastal erosion, increased runoff, drainage of forested areas	Threatens coastal settlements; damage to poorly engineered and constructed infrastructure; release of legacy pollutants that affect the food chain and have negative health effects; tree death caused by drought; increased forest fire occurrence	Shoreline stabilization and engineering options, eventually relocation, authority to relocate communities, design and engineering to counteract permafrost changes; increased surveillance of contaminants in traditional/local foods; investigation of health and ecosystem effects on biota; increased surveillance and response capabilities to fires; altered management regimes to enhance harvesting of 'at risk' forests
Glacier and ice caps Retreating, increased calving	Threat to planned infrastructure development, marine transport, fisheries, and oil and gas exploration; increased hydropower production, reduced attractiveness to tourists	Improved mapping, surveillance, and monitoring; increased water storage capacity
Snow Increased frost and thaw and ice cover on tundra; increased amount of snow, snowfall and winter temperatures; increased growing season; increased winter thaw, earlier snowmelt, shorter and milder winters	Reindeer access to fodder altered, increased mortality; increased hydropower production, damage to forests, increase in avalanches; increased productivity in forestry and agriculture; increased tree death for certain conifers and damage to forests from insects and pests, drought in dryer areas in spring and summer, less frost damage on pastures; reduced opportunities for winter tourism	TEK—traditional ecological knowledge use of castrated male reindeer to break the ice crust; flexibility in choice of pastures; Increased water storage capacity; implications for fire regimes (see above); increased forecasting and surveillance of hazards
Rivers and lakes Reduction in ice duration and ice thickness	Reduced operation of ice roads, increased barge transport on rivers and lakes	Concentrate on the coldest period of winter, eventually construction of land-based road or rail networks, development and enhancement of infrastructure to support such (e.g., dredging)

and railways and increased infrastructure for servicing such transport (e.g., enhanced dredging of rivers) will be needed to ensure continued access to industrial developments and communities as an alternative to ice roads (Prowse et al. 2009). Infrastructure located in river channels (e.g., gas fields in the Mackenzie River Delta) may be exposed to flood damage from ice jams and backwater flooding (Prowse et al. 2009). Future adaptations to reduced transport possibilities on ice roads include enhanced surface flooding or spray-ice layering and modification of transport schedules to concentrate on the coldest part of winter (Prowse et al. 2009).

Hunting patterns and strategies for traveling on sea ice will increasingly be affected, compromising safety, food security, and cultures (Hovelsrud and Smit 2010). A reduction in land-fast ice combined with more open water make the sea-ice conditions less predictable and result in unpredictable fog events, making coastal travel treacherous (e.g., Barber et al. 2008). These changes force people to travel longer distances and along unknown routes (Pearce et al. 2010; Hovelsrud et al. 2008). In adapting to this situation new technology is utilized (e.g., GPS global positioning system, satellite phone) in addition to local/traditional knowledge (e.g., Tremblay et al. 2008). Other adaptations include changing modes of transportation from snowmobiles to boats (Hovelsrud and Smit 2010).

Smaller communities are especially vulnerable to increased contaminant levels from salt-water intrusion as permafrost thaws, the coasts erode, and infrastructure is damaged (ACIA 2005). Permafrost engineers must address

the problem of preserving infrastructure under projected future climate conditions. Especially in coastal mountainous areas, rockslides, debris flows, ice avalanches, glacial mudflows, and outburst floods caused by permafrost thaw, decreasing glaciers, and increased storminess might cause additional hazards to infrastructure and safety. In addition, the frequency of severe snowfalls and extreme precipitation events is expected to increase over large areas of the Arctic (Christensen et al. 2007), with consequences for buildings and infrastructure (Strasser 2008).

Techniques to reduce warming and thawing are already common practice in North America, Scandinavia, and Russia (ACIA 2005). Monitoring programs are important in pipeline projects both to facilitate the mitigation of environmental impacts associated with the project and to mitigate the effects of climate change (Prowse et al. 2009).

Hydroelectric Power

Expansion of industries and populations in some Arctic areas has already increased electricity demands (Furgal and Prowse 2008), and this trend is expected to continue. Hydroelectric power production has a vast potential with large unregulated northern rivers, and with the expected increased precipitation, snow melt, and runoff. The hydropower potential in northern Europe is expected to grow by up to 30% by the 2070s (Anisimov et al. 2007). Increased hydroelectric capacity might result in cascading development effects as energy surpluses may attract industries (e.g., aluminum smelters) that need abundant, cheap, and 'green' energy. A key factor is the stability of the water supply to the new power plants (Beltaos and Prowse 2009). In addition, increased amounts of silt and sand in glacial melt water may fill dammed lakes and affect the viability of the dams. Alternatively, the bedrock topography exposed to the retreating ice may cause new melt water drainage patterns, leading to a partial or complete drying out of the hydropower water supply. New reservoir capacity and mechanisms to counter problems relating to future ice conditions will be needed, taking into account potential environmental effects from altered flow regimes and contaminants.

Oil, Gas, and Mining Activity

Increased access to Arctic oil and gas resources afforded by cryospheric changes will create both opportunities and challenges for extraction. In 2007, one tenth of the world's total oil production and one-quarter of the world's total gas production was derived from Arctic regions of which 80% of the oil and 99% of the gas was extracted in the Russian Arctic (AMAP 2007) and it is estimated that roughly 84% of the undiscovered oil and gas in the Arctic occurs offshore (USGS 2008). In addition, the Arctic holds large stores of minerals (Glomsrød and Aslaksen 2009) and potentially large reserves of undiscovered sources of raw materials, which will become increasingly accessible with diminishing glaciers, ice sheets, and sea ice.

The extraction industries will benefit from improved maritime transport possibilities, but will need to consider expected risks from drifting ice, storm, and wave conditions. New technological advances have already been made in current focal areas of Arctic sub-sea processing, compression and power transmission, drilling and pumping technologies, and communication technology. Other focal areas are ice-load and ice-scour prediction; offshore Arctic drilling systems; Arctic tanker technology; Emergency, evacuation, and spill response systems and technology; and cost-effective logistics. Challenges for oil and gas facilities include employing appropriate technology, developing risk assessments, and meeting regulatory requirements and increasing societal expectations related to environmental performance, regulatory oversight, and social benefits (VanderZwaag et al. 2008).

Maritime Shipping

An increasingly ice-free Arctic Ocean offers a number of opportunities for shipping. A shorter route for ships could save energy, reduce emissions, promote trade, diminish pressure on the main trans-continental navigation channels, and have great economic benefits for both the maritime industry and the Arctic regions (Commission of the European Communities 2008). Reduced sea ice will open up seaways, but will also create new hazards for shipping and offshore oilrigs. Although summer sea-ice cover is projected to disappear toward 2020, operators will have to adapt to seasonal and regional variations in drift ice and icebergs, annual variations in ice cover, and continued local sea-ice formation leading to significant navigation hazards. In addition, icing related to increased storm surges and wind, and icings on ships and installations due to increased storm surges and wind are a challenge (Molenaar and Corell 2009). Adaptation solutions include using dedicated ice-strengthened vessels or ice-breakers for the ice-covered areas and applying ship-to-ship transfer in open water, satellite navigation systems for improved maritime surveillance, and ships with the bow optimized for open-water conditions and the stern designed for icebreaking (Ho 2010; IMO 2009).

An overarching issue for all activities in the Arctic is a general lack of preparedness across local, national, and international levels, to support high levels of marine traffic and respond to increased pollution, accidents, and search and rescue needs as access to ice-free areas increases. The new waterways are not sufficiently charted. There is a need

for iceberg and environmental monitoring, for infrastructure (ports, navigation aids, and supplies), better weather forecasting, and for enhanced capacity to respond to emergencies and accidents.

Tourism

Access to the Arctic, and with it tourism, has increased through improved transport technologies (UNEP 2007; Stewart and Draper 2006). Arctic tourism relies on traditional perceptions of the Arctic environment and expectations about the experience of ice and snow, mountains and tundra, and wildlife. The sector is diverse, including sports fishing and hunting, ecotourism, adventure tourism, dog-sledding, mountaineering, and cultural and heritage tourism. With the exception of major cruise lines, and some Alpine ski operations, tourism in the region consists of small-scale operations. It has become an alternative source of income for many local communities and gateway cities, enabling a positive interaction between new economic opportunities and traditional activities (Rasmussen 2005; UNEP 2007).

Changing climatic conditions will have implications for outdoor tourism activities (Dawson et al. 2007) as well as affecting landscape amenity values such as the opportunity to view glaciers, and snow- and ice-dependent wildlife (Orlove et al. 2008). Increasing access for cruise ships (Glomsrød and Aslaksen 2009) also requires better infrastructure for maintenance, and search and rescue (Stewart and Draper 2006).

Hunting and Fishing

Hunting and fishing activities are important for nutrition, health, and household and community economies, and also have great cultural value in many indigenous and local communities (e.g., Poppel and Kruse 2009). Because of extensive food-sharing networks, changing sea-ice conditions that have an impact on hunting will also affect those not directly involved in hunting (e.g., Hovelsrud and Smit 2010). It is estimated that in four of ten Inuit households more than 50% of the meat consumed is harvested (Poppel and Kruse 2009). Despite limitations, seal hunting remains essential for feeding sled dogs which are critical for hunting, fishing and tourism (Pearce et al. 2010).

Coastal livelihood activities are adapted to local sea-ice conditions and to the behavior of species harvested, but a changing cryosphere will have consequences for access to coastal and offshore fisheries. Reduced sea ice has impacts on the abundance, migration, seasonal distribution, and composition of key commercial fish, marine mammals, and seabirds, resulting in shortages of traditional/local foods (Wiig et al. 2008; Brander 2010) (Fig. 2).

Although projections of how biophysical changes and sea-ice loss will influence commercial fisheries resources, in terms of specific stocks and species, are limited and uncertain (ACIA 2005; Loeng 2008) it is expected that key stocks will increase and likely shift their summer distribution northward (Stenevik and Sundby 2007). Coastal marine ecosystems may be adversely affected by increased glacial runoff and river discharges, and rising ocean temperature is currently causing changes in nutrient transfer (Martin et al. 2009).

Whether the effects of changing sea-ice conditions on fish and wildlife will present challenges or opportunities at the local level depends on the local socio-economic situation, individual entrepreneurship, and politics. Existing technology and knowledge may not be sufficient to exploit new species, and new investments and techniques may be needed. Social safety nets of sharing and cooperation also play an important role. Flexibility in response to changing conditions, such as the ability to harvest different species of fish or game, or supplement with cash-earning activities is critical to reducing vulnerabilities to change and for ensuring well-being, societal integrity, and human security (Hovelsrud and Smit 2010 and references therein).

Reindeer Husbandry

Reindeer husbandry is an important livelihood activity for the Sámi across Fennoscandia and in Arctic Russia. Reindeer pastures will be directly affected by changing snow, permafrost, and lake- and river-ice conditions (Anisimov et al. 2007). Herding strategies are shaped by experiences of factors such as season, snow type, temperature, landscape, unusual weather conditions, and the physical condition of the animals (Magga 2006; Roturier and Roué 2009). Increased frequency of rain-on-snow events may contribute to an earlier start of the growing season in some regions of the Arctic (Meltofte et al. 2008) with a generally positive impact on the herbivores' pastures (Forchhammer et al. 2005). Changes in the lake and river freeze up affect reindeer migrations which in turn affect calving success and income from slaughter (Hovelsrud and Smit 2010). Rain-on-snow and winter warming events increase ice layer formation, affecting reindeer access to pastures (Forbes et al. 2008, 2009). To counter these effects herders may retain a few strong castrated males to break through the hard ice and snow layers (Reinert et al. 2008; Forbes et al. 2009).

Because of industrial developments and other encroachments the avoidance of certain reindeer pastures can lead to less optimal range use, complications with herding, increased costs, and reduced production. The combination of restricted pasture access due to industrialization, and changes to pasture quality and migration

Fig. 2 New hunting opportunities, emerging risks. Inuit hunter, Adam Kolouhok Kudlak, retrieves a ringed seal (*natiq*) from the open water lead (*aolagot*) near Holman Island (Qikiktakyoak) using an open water boat (*oinikhiot*). Owing to thin, unstable, temporary sea-ice cover that is vulnerable to winds and currents, *aolagot*s are becoming more common in winter months presenting new hunting opportunities and dangers to hunters. *Photo*: Tristan D. Pearce

possibilities due to cryospheric changes will require the development of new adaptive strategies to support continued activity.

Forestry

Large tracts of boreal forest cover the sub-Arctic and low Arctic areas (Furgal and Prowse 2008). Similar to other ecosystems, a healthy terrestrial ecosystem is essential to the cultural, spiritual, and social well-being of Arctic residents. Large economic benefits are currently derived from timber production. Increased productivity in boreal forests is expected, but a higher frequency of freeze–thaw events may cause damage to forests and timber. Increased fungal or insect attacks may destroy drying timber especially when access to felled timber is delayed due to earlier snowmelt.

Snow is an important factor in forest damage (Kilpelainen et al. 2010). Heavier snowfalls and icing crush tree canopies and hinder new growth. In regions with projected reductions in snow fall, the risk of snow damage to forests is projected to decrease. Drought in forests because of reduced melt water in spring may represent another challenge for the forest industry.

Agriculture

Agriculture is a relatively small Arctic industry in terms of value added (e.g., Glomsrød and Aslaksen 2009), and is a mixture of large-scale commercial and subsistence production. Given that snow cover duration, freeze–thaw events, icing, and permafrost constitute the primary cryospheric limitations to Arctic agricultural production, cryospheric change is expected to have predominantly positive impacts although current agricultural developments are constrained by remoteness, lack of infrastructure, and sparse population (ACIA 2005; Hovelsrud and Smit 2010). Earlier snowmelt will lengthen the growing season and reduce the likelihood of fungal damage to crops (e.g., Falloon and Betts 2009).

Weather instability may result in thaw and refreeze events damaging crops, and less snow may expose plants to wind and frost damage through reduced insulation (Bjerke and Tømmervik 2008). Agricultural soil erosion could

increase considerably due to increased precipitation and runoff combined with freeze–thaw episodes (Grønlund 2009). Increased runoff may also enhance contaminant transfer to rivers, lakes, and the sea (Falloon and Betts 2009). Other negative impacts of excess water include soil water-logging, anaerobicity, and reduced plant growth (Bradley et al. 2005). Farming operations on wet soils may cause compaction damage because agricultural machinery may not be suitable for wet soil conditions (Eitzinger et al. 2007).

Human Health and Well-Being

The changing cryosphere affects the health of Arctic inhabitants both directly, through risk of injury from more hazardous travel conditions, and indirectly through altered ultraviolet levels affecting health and higher temperatures increasing the northward migration of zoonotic and other disease agents (ACIA 2005; AMAP 2009). Concern is also raised regarding the possibility of increased rates of food- and water-borne diseases and respiratory infections due to longer open freshwater seasons and to damage to community sanitation and drinking water infrastructure from thawing permafrost or extreme weather events (Parkinson and Evengård 2009).

Increased transport and industrial activity in the Arctic will increase contaminants levels, while melting ice, thawing permafrost, and degrading glacial snow may release legacy pollutants (POPs and metals) from past human activities. Erosion may expose waste dumps at abandoned military and oilfield sites, with potentially severe effects on the health of wildlife and local communities (AMAP 2009). These may negatively affect the immune system in animals and humans (e.g., AMAP 2009) as well as degrade the quality of traditional/local foods. Food contamination problems may become particularly acute where permafrost 'ice houses,' used for local food storage become less effective due to thawing permafrost (Parkinson and Evengård 2009).

The psychological health of Arctic peoples may suffer as the environment changes beyond their experience. The current rate and magnitude of change challenges the relevance of traditional knowledge affecting the well-being of older generations and with implications for cultural and social relations (Weatherhead et al. 2010 and references therein).

GOVERNANCE

Governance is key to solving societal challenges emerging from a changing cryosphere across local, national, and international scales. Cryospheric changes increase access to the Arctic with consequences for local communities, national management, and international regulations. Human rights, including indigenous rights may be challenged, and resolution mechanisms required. Governance challenges resulting from a changing Arctic cryosphere must be addressed in connection with other issues affecting the region (Armitage et al. 2007; Young 2009). Oil, natural gas, and mineral developments; airborne pollutants; sovereignty claims and security concerns; the socio-economic dimensions of renewable resource (e.g., fisheries and wildlife) extraction; and demands of northerners to have a greater role in decision-making as they adapt to changes all involve interrelated, multi-scale, and complex issues of governance.

Good governance across societal levels is also critical for facilitating adaptation and for strengthening adaptive capacity. Institutional guidelines or policies, economic and market pressures, technology, and the potential for diversification determine the adaptive capacity of a community or sector (e.g., Hovelsrud and Smit 2010). Social learning, responsive local institutions, livelihood flexibility and diversification, and adaptive management have also emerged as critical elements (Hovelsrud and Smit 2010 and references therein).

Cryospheric changes will place additional pressure on existing frameworks for cooperation developed by Arctic nations (Young 2005; Stokke and Honneland 2007) and efforts to secure sovereignty claims to Arctic territory raise militarization issues in relation to natural resource development. The Arctic Council, a non-treaty, intergovernmental, ministerial-level forum, addresses issues of common concern, and has been identified as a critical actor in environmental governance (Young 2005). The 1982 United Nations Convention on the Law of the Sea remains the primary and legally binding mechanism for resolving potential territorial disagreements and development challenges.

Future developments of industrial activities in the Arctic are likely to attract diverse stakeholders. In particular trans-Arctic marine shipping is expected to be an important driver of Arctic development (Molenaar and Corell 2009), and regulation of shipping and other resource issues regarding the Arctic requires local institutional engagement and a more inclusive approach (Ho 2010).

CUMULATIVE EFFECTS AND SYNERGIES IN AND BEYOND THE ARCTIC

The combination of cryospheric and climatic changes (e.g., temperature rise and sea level rise) and non-climatic drivers (e.g., increased industrial activity, socio-economic development, and changing demographic patterns,

governance, and health and well-being of the Arctic societies and people) will result in multifaceted and cascading effects.

The combined effects of multiple factors create opportunities and challenges locally and beyond the Arctic. Projections of such complex cryospheric–societal interactions are difficult to make. In addition, the consequences of such interactions depend on context and location. In some cases, adaptive measures may have unexpected negative consequences and may even exacerbate the problem (maladaptation). This section recognizes the limitations of current knowledge, but through available examples ventures to discuss some possible cumulative effects and synergies.

Cryospheric Drivers of Change: Some Examples

Coastal areas with saline and discontinuous permafrost are particularly exposed to the combination of increased wave action, sea level rise, and thermal erosion, and presently no simple engineering solutions exist. This combination will lead to increased coastal erosion, with consequences for infrastructure and increased contaminant load (see also Outridge et al. 2008). In addition, cumulative effects on permafrost (temperature, precipitation, storm frequency and magnitude, and slow, down-slope movements over time) will add to its thawing rate and will potentially increase impacts on settlements, roads and railways, and other infrastructure.

Melting sea ice combined with thawing permafrost will release contaminants trapped in the frozen ground and ice, and it will open waterways and increase the pathways for transport of contaminants into the Arctic Ocean. Owing to air and ocean currents carrying pollutants into the Arctic from their source regions at lower latitudes, the Arctic acts as a sink for pollution (AMAP 2009). Several studies indicate that airborne pollution leads to accelerated melting of sea ice, and a proposed industrial development in Arctic regions may enhance this effect. To ensure safe communities, decisions about land use and transportation routes need to incorporate pollutant release and coastal erosion as well as the potential increased risk of slope failure and rockfalls resulting from the combined effects of thawing and refreezing and increased snow load on slope stability.

Non-cryospheric Drivers of Change

Cryospheric changes occur in the context of other factors including resource access and policies; limited economic opportunities; demographics; perceptions of change; local-to-global linkages; infrastructure; threats to cultural identity and well-being; transfer of local and traditional knowledge; economic and livelihood flexibility; and enabling institutions, which are rarely independent of each other and frequently combine across scales and sectors (Hovelsrud and Smit 2010). In most cases, socio-economic changes are likely to have greater immediate impact than cryospheric changes. For example, the effects of industrial development and infrastructural encroachment experienced by reindeer herders throughout the Arctic are far more significant than those of cryospheric change or extreme weather events (e.g., Forbes et al. 2009).

Another example is the projected increase in tourism, with potential economic benefits for local communities. Further expansion of tourist seasons may result in extended use of infrastructure and longer duration of employment and income benefits. How Arctic communities allow their natural and cultural resources to be used by large numbers of visitors and whether or not this is viewed as a disruption depends on the attitude and resources of the community. Impacts may be mitigated through collaborative management with tour operators and in some instances, tax revenues, and special fees may offset local costs.

Ongoing demographic aspects such as gender development and generation shifts are two salient factors (Hovelsrud and Smit 2010). Traditional gender roles regarding who the breadwinner is in a family are rapidly changing. In some indigenous communities for example, there is an increasing shift away from the traditional male 'hunter' toward female wage earners, and the new generation may seek other forms of employment than the traditional resource-use activities. Out-migration is another critical demographic factor with consequences for livelihood activities (Hovelsrud and Smit 2010).

Globalization and world markets are also important players in shaping change in the Arctic. The immediate and additive effects of cryospheric change will compound the effects of such changes in the Arctic.

Beyond the Arctic

The Arctic cryosphere is linked to the rest of the world through physical (e.g., climate system feedbacks), chemical (e.g., pollutant transport), biological (e.g., ecosystem connections), and societal (e.g., tourism, resource extraction, management, politics) linkages. While global warming is exacerbating Arctic cryospheric change, these changes have subsequent effects of global consequence. The Arctic region acts as a sink for heat, greenhouse gases, particulate aerosols, and contaminants and performs regulatory functions for the global climate system. Cumulative effects with consequences for society on a broader scale include the feedback from changing surface albedo, and the release of methane by thawing permafrost accelerating global warming. Such amplification needs to be included

when developing mitigation efforts and in updated models projecting future climate change.

Cryospheric changes coupled with other climate-driven changes have hemispheric and global-scale societal effects, such as enhanced ice outflow (icebergs and ice export) leading to shipping hazards; alteration of oceanic and riverine heat and freshwater transport to Arctic environments affecting ecosystems and impacting fisheries and hunting activities; increased activities in the Arctic, leading to increased risk of pollution and increased shipping bringing noise pollution and ballast water containing contaminants and invasive species; uptake of pollutants into the Arctic food web, with possible local and global health impacts; economic opportunities; and significant contributions to global sea level rise, and follow-on effects for low-lying coastal regions throughout the world.

Gaps in knowledge and future needs, including research needs, observation, monitoring, modelling and downscaling needs, and governance and technology needs are discussed in detail in the online supplementary material.

CONCLUSIONS

The changing cryosphere causes physical and biological changes with consequences for livelihoods and living conditions. Major uncertainties remain in terms of the direct and indirect impacts of cryospheric change on human society, in and beyond the Arctic, and in terms of the timescale of changes and adaptations.

While the indigenous peoples and local Arctic communities will likely continue to be challenged to maintain their way of life, opportunities, including increased shipping, and commercial development of renewable and non-renewable resources, are expected to benefit mainly non-Arctic actors. These changes may have positive spinoffs for the Arctic, creating employment opportunities and revenues and providing economic opportunities in developing the renewable and non-renewable resources in the region. The projected trend of increased tourism including cruise-ship tourism will create opportunities for entrepreneurs and operators in the region, provided the human skills and financial resources are available. A changing snow regime may provide an increased hydropower potential, and thus opportunities for industrial development in remote areas with demand for more power. The changing permafrost may offer opportunities for some agricultural activities where it thaws completely. Other local benefits may include increased agricultural and forestry opportunities, more navigable seaways and greater marine access to resources.

Altered access to the Arctic is likely to trigger development and infrastructure needs. The main challenges include maintaining traditional land use and sea use; hunting, harvesting, and herding activities; infrastructure; search and rescue; pollution; human health; and indigenous and local rights and involvement. Coastal erosion, thawing permafrost, and changing sea-ice conditions when combined with non-cryospheric drivers of change, such as increased economic activity, socio-economic development, demographics, governance, and the health and well-being of the Arctic society and people will result in multifaceted and cascading effects. Indigenous peoples and other local residents are resilient and active rather than passive actors, but the rate of cryospheric changes will continue to challenge the current adaptive capacity.

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