Climate change and Canada's north coast: Research trends, progress, and future directions

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Abstract: This paper identifies and characterizes current knowledge on climate change impacts, adaptation, and vulnerability (IAV) for Canada's northern coastline, outlining key research gaps. Warming temperatures and increased precipitation have been documented across the northern coast, with the rate of sea ice decline ranging from 2.9% to 10.4% per decade. Storm intensity and frequency is increasing, and permafrost is warming across the region. Many of these changes are projected to accelerate in the future, with in excess of 8°C warming in winter possible under a high-emission scenario by 2081–2100. Vulnerability to these changes differs by region and community, a function of geographic location, nature of climate change impacts, and human factors. Capacity to manage climate change is high in some sectors, such as subsistence harvesting, but is being undermined by long-term societal changes. In other sectors, such as infrastructure and transportation, limitations in climate risk-management capacity result in continuing high vulnerabilities. There is evidence that adaptation is taking place in response to experienced and projected impacts, although readiness for adaptation is challenged by limited resources, institutional capacity, and a need for support for adaptation across levels of government. Priority areas for future research include: expanding the sectoral and geographic focus of understanding on IAV, integrating climatic and socio-economic projections into vulnerability and adaptation assessments, developing an evidence base on adaptation options, and monitoring and evaluating the effectiveness of adaptation support. Cross-cutting themes for advancing IAV research on the north coast more broadly include the need for greater emphasis on interdisciplinary approaches and cross-cultural collaborations, support for decision-orientated research, and focus on effective knowledge mobilization.

Key words: climate change, Canada, north coast, adaptation, impacts, vulnerability, Arctic

1. Introduction

Inhabited primarily by Indigenous populations living in small remote communities, Canada's northern coastline is vast, representing more than 70% of all Canadian coasts. The north coast is a hotspot for climate change, with the region experiencing some of the most rapid climate change anywhere globally, and projected future climate changes for the region will continue to be significant (Larsen and Anisimov, 2014). Many communities have a high sensitivity to climate change as they are situated on low-lying coasts, they have infrastructure built on permafrost, economies strongly linked to natural resources, high dependence on land-based harvesting activities, and they experience socio-economic disadvantage (AMAP, 2011; Arctic Council, 2013; Lemmen et al., 2008; Mason and Agan, 2015). In light of the risks posed by climate change, adaptation is emerging as an important component of climate policy in northern Canada, and encompasses a variety of strategies, actions, and behaviors that make households, communities and economic sectors more resilient to climate change (Labbe et al., 2017; Ford, Tesar, and Falk, in press).

In response to the risks posed by climate change to Canada's coastline, Natural Resources Canada (NRCan) led an assessment to examine the state of knowledge on the impacts of climate change on communities, ecosystems, and economic sectors, associated vulnerabilities, and opportunities for adaptation (Lemmen et al, 2016). Modelled on the review process of the Intergovernmental Panel on Climate Change (IPCC), and focusing primarily on the peer-reviewed scholarship but also grey literature in some instances, the assessment divided Canada's marine coasts into three large regions (East, North and West). This paper draws upon the North Coast Chapter to summarize current knowledge on climate change impacts, adaptation and vulnerability (IAV), updating it with recently published work, and using this understanding to identify and characterize key research needs. We begin the paper by providing background on the nature of Canada's north coast. This is followed by three sections that summarize key findings on IAV, profiling research needs for each. Research needs are derived from an examination of current understanding in light of recognized knowledge required for identifying and characterizing IAV; from documented needs identified by decision-makers, communities, and researchers; and from insights and experience of the authors who have been involved in interdisciplinary climate change research and policy debates in the Arctic since the 1990s. We finish by identifying cross-cutting themes for advancing the research agenda on IAV on Canada's north coast.

2. Canada's north coast

Canada's northern coastline extends more than 176 000 km from Yukon in the west to Labrador in the east. Three territories (Yukon, Northwest Territories, Nunavut) and four provinces (Manitoba, Ontario, Quebec, Newfoundland and Labrador) have northern coastlines, as do regions with land claims agreements that have been settled with Indigenous populations (Inuvialuit Settlement Region, Nunavik, Nunavut, Nunatsiavut, and the James Bay and Northern Quebec Agreement). Canada's North Coast region is home to 58 communities and more than 70 000 people, the majority of whom are Inuit, First Nations or Métis. Communities in this region have distinctive social-cultural characteristics, demographics and economies, including use of the coastal region for culturally valued and economically important harvesting activities. The wage economy is based largely on public administration, resource extraction, and arts and crafts, with tourism also being important in some regions.

The presence of sea ice is a defining feature of the northern coast, which is characterized by long, extremely cold winters interrupted by short, cool summers. Sea ice affects transportation access, shapes coastal geomorphology, and provides a platform for culturally valued and economically important harvesting activities. Precipitation is light and occurs predominantly in the summer. The region is characterized by a wide diversity of environments, with approximately 62% of the coastline consisting of unlithified materials that may be sensitive to erosion while the remainder is made up of more resistant bedrock. Permafrost underlies virtually all of Canada's north coast, and has an influence on both slope processes and coastal erosion, which is a function of both mechanical and thermal processes in the north.

3. Climate change impacts on the north coast

The north coast has experienced some of the most rapid climate change globally. Both science and the observations of communities based on local/traditional knowledge (LK/TK) have helped to identify and characterize changes in climate already being experienced and their associated impacts. Studies have also projected potential future change, but there are significant gaps in understanding future impacts over the short, medium, and long term.

3.1. Current knowledge

- ***Changing temperature and precipitation regimes:*** All of Canada's north coast lies in climate regions that have warmed more than the Canadian average (Environment Canada, 2015). The Mackenzie District in the western Canadian Arctic, for example, has warmed by 2.6°C during the period 1948–2014, and Nunavut by 1.6°C during the same period (Environment Canada, 2015). An increase in annual precipitation has been documented for 1950–2010 at virtually all northern coastal sites, along with an increase in the ratio of snow to rain (Mekis and Vincent, 2011a, b). Warming is projected to continue under all climate change scenarios, and is expected to be greatest in winter and least in summer. Under the IPCC high-emission scenario (RCP8.5), a temperature increase in excess of 8°C is projected during winter for 2081–2100, while the low-emission scenario (RCP2.6) projects a winter temperature increase of 2.4°C (Environment and Climate Change Canada, 2016). Precipitation is projected to increase under all scenarios, with increases in excess of 25% projected for parts of the eastern and central Arctic in winter by 2050 (Bush et al., 2014). Across the northern coastline, communities have documented increasing weather variability and higher frequencies of thunderstorms and extreme weather events, coinciding with decreased ability to predict the weather (Gearheard et al., 2011; Reynolds et al., 2012; Royer and Herrmann, 2013; Royer et al., 2013; Savo et al., 2016; Weatherhead et al., 2010).
- ***Sea ice:*** Throughout the Canadian Arctic, the extent of sea ice has been decreasing. Over the period 1968-2008, summer sea ice loss ranged from 2.9% per decade in the Canadian Arctic Archipelago to 10.4% per decade in Hudson Bay (Tivy et al., 2011). These trends are expected to continue or accelerate (Dumas et al., 2006; Holland et al., 2006; IPCC, 2013; Screen and Williamson, 2017), with some models projecting almost complete loss of summer ice cover before mid-century (e.g., Wang and Overland, 2012; Screen and Williamson, 2017). The occurrence of multiyear ice is also declining (Maslanik et al., 2007; 2011). Overall, Arctic sea ice is thinning; average spring ice thickness was 2.4 m in 2008 but is projected to be only 1.4 m by 2050 (Kwok et al., 2009; Stroeve et al., 2012). The ice free open-water period is increasing by 3.2–12.0 days per decade in the Canadian north (Howell et al., 2009; Stroeve et al., 2014), with freeze up delays and in some cases melt seasons that are more than a month longer than they were previously (St-Hilaire-Gravel et al., 2012). Across northern communities, changing ice dynamics, thinner ice, later freeze up and earlier break up have been observed (Gearheard et al., 2011; Gearheard et al., 2006; Laidler et al., 2009; Pearce et al., 2010).
- ***Storm intensity:*** There is strong evidence that the frequency and intensity of storms in the Arctic is increasing (IPCC, 2013; Akperov et al., 2015). The positive correlation between the amount of open water and cyclone intensity in the Arctic suggests that storms will likely be larger and stronger as sea-ice extent continues to decrease (Simmonds and Keay, 2009; Perrie et al., 2012). The consequence of more intense storms on coasts will be greatest in areas of significant fetch, such as the Beaufort Sea, and during seasons with less sea ice cover (Atkinson, 2005; Manson et al. 2005; Lintern et al., 2013). The frequency and intensity of storm surges are also likely to continue to increase along susceptible, shallow coastal areas.
- ***Sea level:*** Observed changes in relative sea level vary greatly across the north coast, rising in communities in the west and east such as Tuktoyaktuk and Nain, respectively, and declining in central

Arctic communities such as Churchill and Resolute, driven primarily by glacial isostatic adjustments. The spatial pattern of projected relative sea-level changes is similarly influenced by glacial isostatic adjustments, although other factors related to ongoing ice mass changes are also important (James et al., 2014). Where there are high rates of land uplift, sea level is projected to continue to fall, even under a high-emission scenario; where the land is subsiding, sea level is projected to rise by more than 40 cm by 2100 and is projected to increase both the frequency of extreme water-level events and the potential for erosion and flooding (Lamoureux et al., 2015). In Tuktoyaktuk, NWT, for example, the height of a 10-year event is projected to increase from 1.1 m to 2.1 m, without accounting for increased fetch with sea ice melt (ibid.).

- ***Permafrost:*** With few exceptions, permafrost temperatures are increasing across the Canadian north (Smith et al., 2013; Ednie and Smith, 2015; Romanovsky et al., 2016), and this trend is projected to continue as the climate continues to warm (e.g., Woo et al., 2007; IPCC, 2013; Guo and Wang, 2016). It is expected that permafrost changes will not be directly proportional to local temperature change, but will also be affected by local permafrost characteristics and soil composition (Smith and Burgess, 2004). Higher permafrost temperatures can intensify coastal processes and destabilize coastal infrastructure (Aré et al., 2008, Hoque and Pollard, 2009; Fritz et al. 2017).

3.2. Research gaps

- **Uncertainty in Physical Models:** Regional climate models, and ice cover and thickness models, are increasingly offering greater precision at regional scales and accommodating more parameters. Significant uncertainties and knowledge gaps remain, however. Model disagreements arise from uncertainty about greenhouse gas emissions, parameterization of physical processes (e.g. snow sublimation or Antarctic ice melt rates), and model structure variance (e.g. resolution, constants) (Mekis and Vincent, 2015; Hodson, 2013). While models continue to improve, it is important to note why uncertainties arise and what the resulting ranges of climate projections mean for communities and policy makers. Precipitation models continue to offer wide confidence intervals at regional levels, particularly when examining multi-variable conditions, such as blizzard conditions (snow-water equivalent, wind, and surface temperatures are all factors) (Mekis and Vincent, 2015). Sea level rise projections are complicated by uncertainty about the stability of the Antarctic ice sheet, with additional tens of centimeters of sea level rise possible (James, 2015; Mekis and Vincent, 2015; Deconto and Pollard, 2016). Further, there are knowledge gaps surrounding the impacts of Atlantic Ocean heat exchange on sea ice melt, regional permafrost thaw projections are limited at community scales, and there continue to be challenges in modeling future surface wind dynamics (useful for aviation among other industries) (Stroeve et al, 2012). While these knowledge gaps do not challenge broad regional projections (no model shows increases in Arctic sea ice by 2100), they do demonstrate the continued need for research and highlight the windows of uncertainty that communities and policy makers are working in.
- **Future impacts:** Northern coastal communities have experienced some of the most rapid climate change globally, and projected changes for the region will continue to be significant (Larsen and Anisimov, 2014). The high temporal and spatial variability of coastal processes, however, can make determination of the rates of change difficult. This is compounded by the lack of an integrated physical process model of Arctic coastal dynamics. Impacts to communities are due to the cumulative effect of many factors and not necessarily due to the effect of one predominant factor (e.g. the decrease in sea ice cover in September creates increased fetch, increase in cyclonic activity especially in the summer and fall, sea level rise in numerous communities, and shoreline permafrost instability from temperature rise, could create high vulnerability for storm surges and coastal loss). Community-based observatories and monitoring systems incorporating Indigenous knowledge can help address some of these gaps. As model precision continues to improve at more local scales, community-level analysis will need to be a central focus for future vulnerability and risk assessments. As observed with

local variations in vertical land motion and sea level change across the Arctic, communities will experience unique challenges based on their geography.

- **Implications for decision-makers:** Collaboration among communities, policy makers, and researchers is essential to ensure that observations and models are informed by Indigenous and local knowledge, studies are oriented around planning and adaptation knowledge gaps, and research is effectively disseminated (Brunet et al., 2014; Ford et al., 2014; Savo et al., 2016). Climate projections show that across northern Canada there will be shifting hazards for communities, with some communities facing substantial challenges in the coming century. As models increasingly offer downscaled projections, results and outputs will be easier to translate into infrastructure, social programs, and economic planning. In this context, it is anticipated that collaboration among policy makers, community leaders, and climate scientists will become increasingly commonplace and beneficial. Continued support of scientific investigation from regional and national decision-makers will also be essential for continued advancements. There is a continued need for support to foster information sharing between scientists and government agencies, creation of usable science, and funding for Arctic research stations and vessels, remote sensing equipment maintenance and deployment (monitoring buoys and satellites), as well as fostering information sharing among scientists and government agencies (Perrie et al, 2012; Ford et al., 2013; Brunet et al., 2014). Yet, as important as advancing our understanding of future change is, some degree of uncertainty will always characterize future projections, and better downscaling does not necessarily mean more accurate or robust information on likely changes.

4. Climate change vulnerability on the north coast

Vulnerability can be thought of as the susceptibility of households, communities, and economic sectors to harm arising from climate change impacts and other external stressors, and is determined not only by how the climate is changing and affecting biophysical systems (exposure and sensitivity) but also the adaptive capacity of human systems (IPCC, 2014). The inherent biophysical sensitivity of coasts, as well as the magnitude of projected future climate changes, suggest that northern coastal communities and industries are highly susceptible to future climate impacts, although capacity to manage such impacts is high in some sectors. Studies have begun to identify and characterize vulnerabilities associated with climate change and understand the processes that create or attenuate vulnerability. Knowledge on vulnerability is summarized below by sector.

4.1. Current knowledge

- ***Infrastructure and transportation:*** Transportation networks and infrastructure (e.g. roads, buildings, municipal facilities, industrial facilities, etc.) along the northern coast are uniquely sensitive to climate change impacts due to permafrost and sea ice dynamics. While opportunities are associated with the increasing open-water season for marine transportation, impacts are generally believed to be negative. For instance, while the Port of Churchill, MB, is expected to benefit from longer access with reduced sea ice coverage, greater risks relate to the single-track rail bed that supplies the port, which is being undermined by thawing of the discontinuous permafrost, and heavy precipitation events that lead to landslides, flooding and washouts on the tracks (Bristow and Gill, 2011; Addison et al., 2015). In Nunavik meanwhile, marine infrastructure, including breakwaters and water access ramps, in some communities have already experienced localized failure due to movements of ice cover, while extreme water levels documented in Salluit have affected the wharf (Ropars et al., 2012; Palko and Lemmen, 2017). Permafrost degradation is increasing infrastructural instability by increasing erosion and surface subsidence, affecting built infrastructure (e.g. airports, roads, houses) (Allard and Lemay, 2012; Hawkins 2013; Boucher and Guimond, 2012; Lamoureux et al., 2015; Doré et al., 2016;). Changing snow and ice regimes, less predictable weather and changing wind patterns are also making travel by semi-permanent trails more dangerous and less dependable, compromising the ability of residents to engage in harvesting activities and travel between communities (Bell et al., 2014; Clark et al., 2016; Durkalec et al., 2015; Laidler et al., 2009).

- ***Health and well-being***: Communities along the north coast face both direct and indirect health effects of climate change. In particular, key risks around food security, water security, mental well-being, and danger while engaging in land-based activities have been identified, with the potential for new and emerging diseases (e.g. food and waterborne illnesses) (Furgal and Seguin, 2006; Messier et al. 2012; Bourque and Willox, 2014; Ford et al., 2014; Harper et al., 2015). Harper et al (2011), for instance, found that increased rainfall and snowmelt were significantly associated with increased Escherichia coli (E. coli) and total coliform concentrations in untreated brook water in Rigolet, Nunatsiavut, and 2–4 weeks after heavy rainfalls or rapid snowmelts, there was a significant increase in clinic visits for diarrhea and vomiting. Underlying socio-economic conditions (e.g. high rates of housing and food insecurity, poverty etc.), associated health seeking behaviors, and challenge to health care systems are expected to magnify the impacts of climate change on northern health (Ford et al., 2010a; Harper et al., 2015).
- ***Business and economy***: Economic opportunities with climate change are associated mainly with the increased viability of marine transportation driven by reduced sea-ice cover. Some models project that non-ice-strengthened ships should be able to cross the middle of the Arctic Ocean by 2040 (Smith and Stephenson, 2013), increasing the opportunities for cruise-boat tourism and cargo shipping, and improving the viability of northern ports. Private yacht and commercial cruise-ship traffic increased by 110% and 400%, respectively, between 2005 and 2015, with transits in the Northwest Passage increasing by 70% since 2006 (Stewart et al., 2010; Dawson et al., 2014; Pizzolato et al., 2014). Quebec’s Plan Nord identifies warmer winters, extended periods of ice-free waters, and sea-ice retreat as improving accessibility to ports enhancing potential for development (Plan Nord, 2015). Despite these opportunities, there are significant risks related to the lack of supporting infrastructure, including comprehensive bathymetric charts and search and rescue capabilities, while potential increased shipping and associated resource development could have negative impacts on ecosystems (Clarke and Harris, 2003; Carmack and Macdonald, 2008; Burek et al., 2008; Cameron, 2012; Philie, 2013; Clark and Ford, 2017). Declining sea ice may also negatively impact local economies through, for example, lost incomes from reduced fishing catch. Despite the success of the winter turbot fishery in Pangnirtung—about 300 tonnes of turbot is caught annually by hand through the ice, representing a point of sale value at 2016 prices of approximately $2.25 million—the fishery is vulnerable to a shortening of the ice season (Arctic Council, 2013). However, while some species are being threatened by climatic changes, the northerly range shift of other species, including cod, due to rising ocean temperatures, could present new opportunities (Power et al., 2012; Bélanger et al. 2013).
- ***Culture and education***: For northern coastal communities, culture is closely linked to the coastal environment and the activities it sustains (Cunsolo Willox et al., 2012; MacDonald et al., 2015). Even subtle alterations to the land and environment can impact individuals, communities, and cultures by affecting the ability to engage in land-based activities and access traditional sites, and through impacts on culturally valued wildlife species (Cuerrier et al., 2015; Harper et al., 2015; Royer and Herrmann, 2013; Sayles and Mulrennan, 2010; Tam et al., 2013a). Cultural impacts may also arise when permafrost thaw, sea-level rise and coastal erosion occur at sites of historical value (e.g., graveyards, outpost camps) (Radosavljevic et al., 2015; Andrews et al., 2016). Education will be affected by climate change as traditional learning and the preservation and promotion of traditional values are both closely connected to land-based activities, which are becoming more challenging with climate change (Pearce et al., 2015).
- ***Subsistence harvesting:*** Subsistence harvesting activities, including fishing, trapping, and berry picking, have strong economic, dietary, and cultural importance for communities on the north coast (Kuhnlein and Receveur, 2007; Wenzel, 2013). This close association with the natural environment

creates unique sensitivities to the rapidly changing climate, with constrained ability to harvest, reduced opportunities for younger generations to engage in land activities, and conflict over wildlife management in light of changing species health, abundance, and migration timing (Durkalec et al., 2015; Ford et al., 2010b; Hori et al., 2012; Royer and Herrmann, 2013; Tam et al., 2013b).

4.2. Research gaps & needs

- ***Sectoral and regional knowledge gaps:*** For some sectors in the north coast region, it has been argued that sufficient information on vulnerability exists to begin adapting (e.g., harvesting and culture), albeit with the need for targeted work focusing on regions and populations where research has not been conducted (Dawson et al., 2016; Ford et al., 2012; Ford et al., 2014). In other sectors, it is recognized that our understanding of the risks posed by climate change is insufficient, including business and economy, infrastructure and transportation, and health (Cameron, 2012; Ford et al., 2012a; Wolf et al., 2013; Bourque and Cunsolo Willox, 2014; Ford et al., 2014. Moreover, current understanding of vulnerability is derived mainly from local studies in small communities and focuses on 'traditional' activities, with a need to develop a broader and more diverse geographic and sectoral knowledge base. Larger settlements on the north coast (e.g., Iqaluit, NU; Rankin Inlet, NU; Churchill, MB) are hubs of economic development, and have quite different vulnerabilities than smaller communities. For example, transportation infrastructure in the larger communities often acts as a gateway for access to smaller communities (e.g. Iqaluit airport and proposed deep sea port); larger communities have a more extensive infrastructural footprint; and have a larger private sector where climate disruptions to trade networks in other regions in Canada or globally can have significant local impacts. Further, across sectors, knowledge is most advanced for regions and sectors north of 60, with the sub-Arctic and First Nations (e.g. James Bay region) underrepresented in the literature (Downing and Cuerrier, 2011; Sheremata et al., 2016).
- ***Accounting for future vulnerability:*** An important component of vulnerability assessments (VAs) is identifying and characterizing vulnerabilities in light of projected climatic and socio-economic changes. Research has examined the potential impacts of climate change on ecosystems, sea ice environments, landscape processes, and extreme weather, yet few VAs have explicitly incorporated this work, or community knowledge, to assess how socio-economic demographic trends (e.g. population change and structure, employment projections) and projected climate impacts might combine to affect regional and community vulnerability, resilience, and adaptation options. Rather the majority of studies focus on documenting current and experienced risks, underlining a need for futures-orientated work across sectors. For instance, few, if any, integrated VAs have examined what different climate projections mean for vulnerability of sectors and/or communities on the north coast. Participatory scenario planning is one approach that holds promise for engaging communities and decision-makers in creating future scenarios to identify future risks and adaptation options (Wesche and Armitage, 2014). A failure to sufficiently account for future vulnerabilities risks maladaptation, where policies, programs, and behaviour increase vulnerability in the long term.
- ***Enhanced understanding of vulnerability processes***: Existing vulnerability research has made notable contributions to our understanding of how climate change interacts with society along the north coast, yet our knowledge remains incomplete (Ford and Pearce, 2012; Archer et al., 2017). In particular, there is limited medium- or long-term monitoring of how communities are experiencing and responding to climate change over time, constraining understanding of the dynamic nature of vulnerability, understanding of thresholds, and of the potential for adaptive learning (Ford et al., 2013b). Herein, the majority of empirical research has relied on retrospective study design where qualitative and quantitative methods have been used to identify and describe how communities and regions are currently experiencing and responding to climate change (Fawcett et al., 2017). This work has developed important information on human-environment interactions, but typically only spans a few multi-month field seasons, is focused primarily on the present day, and is thus not well positioned to capture the nuanced temporal dynamics of vulnerability drivers and interactions (e.g. adaptive learning,

risk accumulation, restructuring, changing risk perceptions). During fieldwork, sources of vulnerability may be hidden by temporary variations in climatic and/or human factors, and coping mechanisms that appear indicative of adaptability in-light of observed conditions may be maladaptive in the long term depending on how they play out in the context of fast and slow variables (Fawcett et al., 2017). Further, there is a dearth of studies focusing on cumulative effects (e.g. resource development) and how these will affect vulnerability to climate change both today and in the future, and an absence of research accounting for regional and global factors affecting vulnerability in specific places (e.g. wildlife harvesting regulations, market prices, trade networks) (Cameron, 2012; Ford et al., 2015b; Wenzel, 2009).

5. Climate change adaptation and Canada's northern coast

Climate change adaptation can be defined as "*the process of adjustment to actual or expected climate and its effects, in order to either lessen or avoid harm or exploit beneficial opportunities*" (IPCC, 2014). Adaptation encompasses a variety of strategies, actions, and behaviors that make households, communities, and societies more resilient to climate change, and may target reducing sensitivity to climate change impacts, and/or focus on strengthening adaptive capacity to manage and take advantage of change. Adaptation options cross scales, from personal and household decisions, to community/local, national, and international policies. Adaptation actions are already taking place in northern Canada through action by governments at different levels, with examples of adaptation and leadership documented across scales, regions, and sectors (Ford and Pearce, 2010; Pearce et al., 2010; Labbe et al., 2017). Leadership and innovation at the local level are also underpinning autonomous adaptations undertaken by individuals and households, particularly in the context of subsistence-based activities, while strong social networks and traditional knowledge systems have been documented to confer significant adaptive capacity (Berkes and Jolly, 2002; Pearce et al., 2015; Ford et al., 2014, 2016),

5.1. Current knowledge

- ***Adaptation programming:*** The emergence of adaptation during the past decade as an important focus of research and policy has involved the creation of a number of northern-focused federal programs and initiatives for adaptation, all of which have an important coastal dimension. These include programs designed to explicitly engage northerners in assessing the risks posed by climate change and identify adaptation options delivered by Indigenous and Northern Affairs Canada, Health Canada, Public Health Agency of Canada, Natural Resources Canada, Standards Council of Canada, and Transport Canada. In 2011, Nunavut, NWT and Yukon formed the Pan-Territorial Adaptation Partnership and released the Pan-Territorial Adaptation Strategy, which outlines strategies for action and steps to achieve them. The strategy has a strong focus on mainstreaming adaptation into policies, programs, revisions to best practices and standards, monitoring programs, as well as increasing collaborations with traditional and community-based knowledge holders. At the regional and territorial levels, there has also been action on adaptation. The Government of Nunavut, for instance, released its adaptation strategy in 2011 (Government of Nunavut, 2011), and the Inuvialuit Regional Corporation (IRC) is creating/updating adaptation plans for each community in the ISR, which will be compiled to create a Regional Climate Change Adaptation Strategy. Indigenous organizations have stressed the importance of adaptation, which has been an important component of work through Inuit Tapiriit Kanatami's Inuit Qaujisarvingat (Inuit Knowledge Centre) (ITK, 2016). At a local level, several communities have led climate change projects and are planning for climate impacts (Labbe et al., 2017).
- ***Adaptation opportunities:*** Studies have documented a variety of potential adaptation options across regions and sectors. Some of these options have an intentional and substantial focus on responding to climate change impacts, both experienced and projected. Such 'climate centred adaptations' that have been identified for the north coast include investing in coastal protection measures such as installing

Longard tubes (woven polyethylene fabric tubes filled with sand), installing wave breakers, relocating critical infrastructure, investing in new port and fish processing facilities, hazard mapping, and retrofitting older infrastructure through the utilization of adaptive foundation types (e.g. piles and spaceframes) (Couture et al., 2002; Johnson et al, 2003; Champalle et al., 2013; Forbes et al., 2014 ; Lamoureux et al, 2015). Alternatively, 'vulnerability centered adaptations' have been identified to focus on underlying social-economic-political factors that lead to climate vulnerability by undermining or constraining adaptive capacity and/or increasing sensitivity to impacts. Such work emphasizes the importance of mainstreaming adaptation into existing policy process, with examples including: cultural revitalization, programming to promote and preserve land skills and knowledge, enhanced local decision-making power, and efforts to address marginalization and poverty (Armitage et al., 2011; Armitage, 2005; Berkes and Armitage, 2010; Cash and Moser, 2000; Ford et al., 2007; Ford et al., 2014; Pearce et al., 2015). In many cases, such actions may not substantively or intentionally target climate change but nevertheless contribute to vulnerability reduction.

- ***Adaptation progress***: There are significant geographic and sectoral disparities in adaptation program development and planning across the northern coast. In Labbe et al's (2017) work in Nunavut for example, local leaders and 'adaptation champions' were found to have an influential role in advancing adaptation initiatives in some locations, but for over a third of communities there was little indication of any formal government-led adaptations taking place that specifically target climate change (i.e. climate centred adaptation). This reflects constraints to local capacity and institutional challenges to plan for climate change given low levels of funding and the wide array of challenges facing municipal planning in many northern communities (Boyle and Dowlatabadi, 2011; Pearce et al., 2012; Champalle et al., 2013). Lack of consideration of adaptation across different levels of government, institutional fragmentation, limited inclusion of traditional knowledge and cultural values in adaptation planning, and an absence of cross-departmental mandates for integrating climate considerations into planning have also been identified as constraining adaptation progress (Brunet et al., 2014; Pearce et al., 2012; Labbe et al., 2017; Shah et al., 2017), although there is limited information available on if/how the private sector is adapting.

5.2. Research gaps

- ***Improved understanding of vulnerability, adaptive capacity, and adaptation options:*** Understanding what makes human systems vulnerable or resilient to climate change is necessary for informing policies, programs, and actions for adapting (Moss et al., 2013). As noted above, significant gaps in understanding vulnerability currently constrain our ability to plan for climate impacts on the north coast, with targeted studies needed to assess geographic and sectoral disparities, and identify and characterize future vulnerabilities. Uncertainty has also been identified as a major challenge for planning for future change. To some extent, uncertainty will always characterize our understanding of future risks, including the potential for surprise, necessitating that adaptation options in many instances build upon general climate projections for the region (Ford et al., in press; Klein and Juhola, 2014). A variety of approaches from the general adaptation scholarship offer potential insights about designing adaptation in light of uncertainty, including: i). thinking around 'low-' or 'no-regrets' adaptation, where adaptation has immediate as well as longer term benefits and is integrated into ongoing decision-making processes (Dovers, 2009; Heltberg et al., 2009). Herein, there is need to better document the multiple benefits of actions that go beyond adapting to climate conditions; ii). 'adaptation pathways' where adaptations are designed to alter over time as impacts materialize and evidence of their effectiveness emerges, such as designing infrastructure that can easily be retrofitted for new uses or modified (Fazey et al., 2016; Wise et al., 2014); iii). or adaptive management or ecosystem stewardship that seeks to ensure flexibility, agility, and diversification to stand ready for more variable conditions and a variety of potential futures (Chapin et al., 2015; Dowsley et al., 2010; Young, 2012). Aside from work on co-management of wildlife resources, these approaches have not been widely used in research on the north coast, and offer significant opportunities for identifying and designing adaptation options.

- ***Adaptation evaluation studies:*** The majority of adaptation-related research on the north coast typically identifies a portfolio or "wish list" of potential response options, with most research focused on impacts and vulnerability assessment (Ford et al., 2014, 2016). Only a limited number of studies have systematically evaluated adaptation options, documented barriers to adaptation, or provided guidance on which adaptations to prioritize (Champalle et al., 2015; Ford et al., 2014). Such gaps are also noted in the general adaptation scholarship (Noble and Huq, 2014), and are exacerbated on the north coast by an absence of work focusing on future vulnerability, or drawing upon broader approaches noted previously (e.g. adaptation pathways). A number of potential criteria for evaluation of adaptations have been outlined, including: effectiveness in reducing vulnerability in the short and long-term, sustainability in terms of the viability of given resources and policy priorities, acceptability and legitimacy, timescale of adaptation in terms of how long options take to implement, equity implications, cost, and synergies and/or contradictions that might occur between and among adaptation options and other policies (Champalle et al., 2015; de Bruin et al., 2009; Debels et al., 2009; Ebi and Burton, 2008). Such criteria need to be further developed in the context of the unique geographies and cultural context of the north coast, with the active engagement of communities and decision-makers across scales.
- ***Adaptation monitoring and evaluation:*** Developing and implementing adaptation is not an endpoint in itself but an ongoing process that needs to be underpinned by monitoring and evaluation (M&E) (Ebi and Semenza, 2008; Bours et al., 2015). Monitoring refers to a continuous process of examining progress made in planning and implementing climate adaptation; evaluation refers to assessment of the effectiveness of climate adaptation plans, policies and actions. M&E is a key part of strategic planning on adaptation to identify mal-adaptations or unforeseen effects that may develop, assess outcomes of adaptation measures, provide learning opportunities, share good practices and inform planning and decision-making (Bours et al., 2015; Lamhauge et al., 2013; OECD, 2015). Work monitoring and evaluating adaptation initiatives focusing on the north coast is nascent, primarily involving benchmarking studies focusing on Inuit regions which documents the broad contours of how adaptation has been approached)(Ford and Pearce, 2010; Labbe et al 2017). While many federal adaptation programs supporting northern adaptation have also been internally evaluated in the last 5-8 years, these have largely focused on program structure, and have not examined effectiveness in reducing vulnerability or documented community and/or decision-maker perspectives on their success. The dearth of such studies precludes assessment of the effectiveness of programs and measures in reducing vulnerability and building resilience, and compromises accountability and transparency.

There are serious challenges however, that have hampered progress on how to track adaptation in general, including an absence of an agreed upon definition for adaptation; the lack of a consistent unit of analysis, with adaptation success only measurable in theory vis a vis a hypothetical future that is operationally impossible to construct, and frames of reference are complicated by the potential to redistribute impacts over space and time; and limited datasets on adaptation (Biesbroek et al., 2010; Ford and Berrang-Ford, 2016). Various approaches have been proposed to track adaptation, including outcome-based approaches that directly measure adaptation progress and effectiveness with reference to avoided climate change impacts, to approaches which focus on developing indicators or proxies by which adaptation can be monitored (e.g. systematic measures of adaptation readiness, processes undertaken to advance adaptation, policies and programs implemented to adapt, and measures of the impacts of these policies and programs on changing vulnerability) (Ford et al., 2013). These all offer promise in Arctic regions, with an emerging scholarship on adaptation tracking offering insights (Ford and Berrang-Ford, 2016), along with other work on program evaluation (e.g. Moxham, 2009; Lecy et al., 2011).

6. Discussion

In this paper we summarize understanding on climate change impacts, adaptation, and vulnerability for the north coast. We document significant understanding on various components of impacts, adaptation, and vulnerability, with a considerable increase in research published in the peer reviewed and grey literature over the last decade. Taking stock of this knowledge base, we also document gaps in understanding, outlining specific avenues for further study. Building on the specific research needs noted in the paper, in the discussion we identify and examine cross-cutting themes for advancing the research agenda on climate change impacts, adaptation, and vulnerability on Canada's north coast, based on our perspectives as university- and federal government-based researchers with backgrounds in the social and physical sciences. As such, we recognize that such discussion also needs to be informed by broader input.

Firstly, in the evolving research landscape, greater emphasis is needed on interdisciplinary approaches and cross-cultural collaborations. Vulnerability assessments (VAs), for example, need to account for exposure, sensitivity, and adaptive capacity, and by their very nature require input from various scientific disciplines and local/traditional knowledge (LK/TK) (Ford and Smit, 2004; Moss et al., 2013; Smith and Sharp, 2012). Despite this, as Champalle et al (2013) document for the north coast, many assessments continue to approach vulnerability from a specific disciplinary specialization, epistemologically framed by the social, engineering, or biophysical sciences, paralleling broader trends in the vulnerability field (Giupponi and Biscaro, 2015; McDowell et al., 2016). Each approach contributes unique understanding to IAV, and a strong disciplinary base is important for knowledge generation, but 'siloized' thinking risks providing incomplete understanding and constraining links to decision-making (Castree et al., 2014; Murphy, 2011), potentially creating what Hulme (2010) refers to as 'brittle' knowledge.

Greater promotion of interdisciplinarity is required from funding agencies to catalyze the creation of research teams that span disciplines. While a number of special calls through Canada's tri-councils have sought to promote collaborations among the social, health, and physical sciences, and support for interdisciplinarity is increasing, disciplinary focused funding remains dominant. Other studies meanwhile, have documented that interdisciplinary projects generally have lower funding success (Bromham et al., 2016), and have argued that few collaborations successfully bridge disciplines (Brown et al., 2015; MacMynowski, 2007; Murphy, 2011). Federal, provincial, and territorial governments also fund impacts, adaptation, and vulnerability research on the north coast, often supporting projects targeted to specific risks or sectors, or directly funding communities or other levels of government. Such projects offer strategic opportunities to promote interdisciplinarity, including through requiring projects to have northerners in decision-making roles, prioritizing studies with an interdisciplinary focus, and promoting engagement across funded projects (Ford et al., 2015a). Projects that are driven by community issues also tend to be interdisciplinary, addressing the need for integrative solutions to complex issues (e.g., food security, housing (Bell, 2016)). Equally, there are opportunities for 'bottom-up' promotion of collaboration and networking across projects to overcome 'siloized' thinking, through for instance, interdisciplinary workshops, project exchanges, web-based platforms, and the development of communities of practice (Brown et al., 2015; Ford et al., 2015a).

Secondly, while impacts, adaptation, and vulnerability studies increasingly note the importance of producing 'usable science' that incorporates LK/TK, promotes stakeholder engagement, and seeks to inform decision-making, basic/fundamental science approaches continue to dominate northern research (Brunet et al., 2014). This is evident in how northern stakeholders (i.e. communities, decision-makers, civil society organizations) have been engaged in research, which is largely *informative*, concerned with informing stakeholders on research processes, results sharing, and/or through scientific training; or *consultative*, whereby stakeholders contribute their expertise to research as sources of LK/TK, as local field guides, and/or as research assistants; but rarely *decisional*, where objectives and research approaches are co-designed, and stakeholders are actively engaged in data analysis, judgement on data quality, and write-up (Brunet et al., 2014; Ford et al., 2013a; Gearheard and Shirley, 2007; McDonald et al., 2016; Pearce et al., 2009). Further, where TK is 'incorporated' into research, it is typically treated as one source of data contributing to Western scientific understanding, through the documentation of factual observations (e.g. observations on how the climate is changing). Ontological orientated components of TK around ethics and values, culture and identity, and cosmology, however, have often been marginalized (Cameron et al., 2015; Houde, 2007; Pearce et al., 2015). This is illustrated, for instance, in the literature on future risks and adaptation options where there is limited consideration of how Western understandings of projecting and planning for the future align with beliefs held by Indigenous peoples (Haalboom and Natcher, 2012; Natcher et al., 2007). In Inuit philosophies, for instance, it is seen as arrogant to assume you can predict the future and an overreliance on planning can be seen as reducing the ability to prepare and react flexibly to situations (Bates, 2007).

Fundamental science has a critical role in generating understanding of how the climate is changing, identifying impacts, and understanding vulnerability processes, and addressing many of the research gaps requires such work. This needs to be complemented, however, by a greater emphasis on usable or applied science that fully engages northerners and seeks to inform policy, behaviors, and solutions to reduce vulnerability and enhance resilience. There have been notable developments in this area, including the growth in studies utilizing community-based participatory research and community-based adaptation approaches, along with federal funding targeted to communities (Ford et al, 2016). One example is *SakKijânginnatuk Nunalik*, or the Sustainable Communities Initiative of the Nunatsiavut Government, which adopts an holistic, integrative approach to address issues that are central to community wellbeing and sustainability in the context of a changing climate (Riedlsperger et al. 2017). At its core, the initiative incorporates Indigenous methodologies and Inuit Knowledge to inform good practices and provide guidance for community sustainability. Yet the evolution of such work is *ad hoc*, constrained by an absence of long term stable funding, and challenged by asymmetric power relationships between researchers and communities (Castleden et al., 2012; Ford et al., 2016; McClymont Peace and Myers, 2012). Research programs with an overarching fundamental science framing have benefited from large, multi-year investments through the Canada First Excellence Fund and Networks of Centres of Excellence, with similar investments needed to catalyze, support, and sustain applied decision orientated work focused on the north coast.

Finally, there is a need for enhanced communication of results of impacts, adaptation, and vulnerability research. While knowledge mobilization is increasingly being stressed and required by funders, little attention has been given to how to effectively communicate research to raise awareness and encourage behavioral change (Ford et al., 2016; Gearheard and Shirley, 2007; McDonald et al., 2016). Decision-makers involved in northern adaptation work interviewed in both Champalle et al (2013) and Labbe et al (2017), for instance, consistently noted poor communication of research results. Herein, the general scholarship highlights that effective knowledge mobilization is underpinned by process of social learning, involving collective action, reflection, and deliberation among stakeholders and scientists (Fazey et al., 2014; Fazey et al., 2013; Harvey et al., 2012; Harvey et al., 2013; Rodela et al., 2012). This process needs to go beyond just raising awareness about a problem, to encourage active engagement in the issue, create agents of change, and engender policy/behavioral change. This begins early in the project cycle, providing an opportunity for research priorities to be determined with input from knowledge users, to ensure that data collected is relevant for decision choices, and to engage all the relevant stakeholders. Such approaches are characterized by ongoing presentation, discussion, and reflection of results that are communicated in an accessible manner that recognizes the attitudes, worldview, experiences, and capabilities of those interested in the work often differ and need to be targeted appropriately. Region-to-region learning also offers significant promise in the north, involving community elders, leaders, and youth visiting other regions and communities to arise awareness and disseminate information on climate impacts and adaptation options (Gearheard et al., 2006; Huntington, 2011). It is also important that results are presented in an integrated way to limit the potential for confusion if contradictory results are presented – the communication of health issues around contaminants, for instance, offers a cautionary tale and learning opportunity for science communication more broadly in the north (Jardine et al., 2004).

7. Conclusion

The research landscape in northern Canada is developing rapidly. Climate change impacts, adaptation, and vulnerability studies are just one component of this, and we review and characterize the state of knowledge in this area, identify research needs, and outline cross-cutting themes for future work. A variety of issues relevant to the north coast are now at the forefront of the political agenda, including sustainable development, climate change, northern devolution, and tackling social and economic challenges facing many communities. Research has a central role in addressing many of these issues. Yet past (and current) research approaches have not always served the needs of northerners, and have often reflected the interests and worldviews of the scientific community. This is evident in growing researcher fatigue in the north, where communities report being overwhelmed with often overlapping projects seemingly asking the same questions and with limited local input or strategic direction. As the Pan-Northern Approach to Science argues—released in April 2016 by the three territorial premiers—a new approach to northern science is required that recognizes the importance of curiosity-driven or fundamental science but balances this with “solutions-driven, needs-oriented and partnership-based research,” (GN, GNWT, GY, 2016: p13). Strong community engagement and partnerships, respect for northern culture, and guidance from local and traditional knowledge need to underpin future impacts, adaptation, and vulnerability research on the north coast.

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