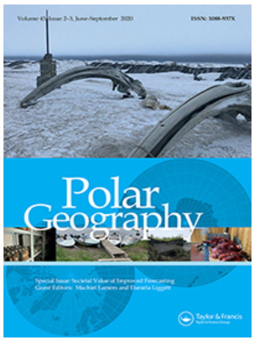


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# Characterizing polar mobilities to understand the role of weather, water, ice and climate (WWIC) information

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**ABSTRACT**

The Polar Regions are undergoing rapid environmental change while simultaneously witnessing growth and diversification of human activity. These changes call for more responsive, detailed and specialized weather, water, ice and climate (WWIC) information services so that the risks related to human activities can be minimized. Drawn from an extensive literature review this article provides an examination of selected sectors and their uses of WWIC information services in order to offer an initial understanding of diverse environmental forecasting needs. Utilizing a mobilities perspective we provide a characterization of mobility in the Polar Regions to help contextualize current WWIC uses and needs. Using four illustrative case studies of polar mobilities (community activities; cruise tourism; shipping; and government and research operations) the article explores two broad questions: (1) How are mobilities characterized in the Polar Regions? (2) What is known about the role of WWIC information in Polar mobilities? The findings suggest an incongruence between the information provided and the ways in which WWIC information is both used and needed by various sectors. Knowledge gaps are outlined that suggest more efforts are needed to understand the highly complex set of interconnections between WWIC users, providers, mobilities and decision-making across the Polar Regions.

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## Introduction

Improving access to, and quality of, climate relevant information is particularly pertinent to mobile actors and sectors operating in remote and dynamic polar marine and continental environments (Eicken, 2013; Thoman et al., 2017). The growth and diversity of activities in the Polar Regions call for more detailed and specialized weather, water, ice and climate (WWIC)[1] information services to be salient in the diversity of contexts and practices in which users engage (Lamers, Duske, & van Bets, 2018). The role of WWIC information in

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the Polar Regions is significant when considering socio-cultural factors, ethics, and costs related to search and rescue, as well as the impact of human activities on polar environments (Lamers, Pristupa, Amelung, & Knol, 2016). Human activities, from local transportation to shipping, tourism, and military and government initiatives, in the Polar Regions have inherent risks because of the remote geography and dynamic environmental conditions of the region, but can become exponentially risky because of the compounding limitations of current WWIC forecasting in and for the Polar Regions (Eicken, 2013).

Improving the ability to predict and forecast meaningful weather and sea-ice conditions in the Polar Regions depends on improving our understanding of how mobility sectors use such information in planning and operations (Dawson et al., 2017b). Mobility sectors are highly vulnerable to weather conditions, which can rapidly change and are affected by climate change over the longer term. In the Polar Regions, the main vulnerabilities arise from sea-ice and iceberg dynamics, rough seas (e.g. high waves, strong winds), icing events, and precipitation that affects visibility or ice conditions (Krupnik, Aporta, Gearheard, Holm, & Laidler, 2010; Lamers et al., 2018; Pizzolato, Howell, Dawson, Laliberté, & Copland, 2016). These vulnerabilities do not materialize independently; rather, they emerge through interactions between users, user characteristics (e.g. experience, mode of transportation, communication technology) and environmental factors. There is a need for research that considers the context in which mobile activities in the Polar Regions are undertaken and WWIC information services are used, including their different interests, constraints, abilities, routines and decision-making contexts (see also Lamers et al., 2018). In other words, for WWIC information services to become more relevant, they will have to be better tailored to decision practices of different users, not only in terms of content, but also in terms of format and interface (Thoman et al., 2017).

More work is needed to understand the type and extent of mobile activities in the Polar Regions in terms of their spatial and temporal characteristics. Most human activities in the Polar Regions, especially tourism, shipping and travel by members of local communities, are increasing in intensity, frequency or geographical extent (Nuttall, Christensen, & Siegert, 2018). Therefore, specialized and real-time weather and climate services are increasingly sought out in support of a greater diversity of contexts and practices (Dawson et al., 2017b; Lamers et al., 2018). Improving our understanding of various mobilities and diverse user needs for WWIC information services, along with considerations for opportunities and challenges associated with reliance on new technologies and communications networks, is important to inform improvements in WWIC service provision. The purpose of this article is to provide a review of selected sectors and their uses of WWIC information services in the Polar Regions in order to offer an initial understanding of diverse environmental forecasting needs.

Applying the mobilities paradigm (see Cresswell, 2010) to contextualize current WWIC uses and needs, we explore four illustrative case studies of polar mobilities focusing on two sets of questions:

(1) How are mobilities characterized in the Polar Regions?
    (a) Who are the main mobile actors?
    (b) What mobilities are prevalent?
(2) What is known about the role of WWIC information in Polar mobilities?
    (a) How is WWIC information used by polar mobile actors?
    (b) What are the WWIC needs of polar mobilities?

After presenting the regional environmental context as well as the theoretical framing of this article, we examine the characteristics of four key human mobility sectors in the Polar Regions and discuss how and why WWIC information is currently being used by these various sectors. We finish by articulating several priority research areas that could contribute to more tailored environmental forecasting services to meet user needs in the Polar Regions.

## Climate change in the Polar Regions and resulting risks

Our work is based on the premise that improving our understanding of user needs can encourage more targeted and specialized polar environmental forecasting, with the ultimate goal being to reduce risks for humans operating in the Polar Regions. Therefore, it is important to begin with a brief introduction of the link between rapid climatic changes currently being experienced in the Polar Regions and risks associated with these changes.

The Arctic and the Antarctic Peninsula have been experiencing an overall warming at a higher rate than any other region in the world (see e.g. Arctic Council, 2017; Graversen, Mauritsen, Tjernström, Källén, & Svensson, 2008; IPCC, 2013; Vaughan et al., 2003) resulting in profound environmental consequences, such as fast-ice formation and breakup with the potential of significant iceberg calving events in the coastal zone, ice-shelf collapse, permafrost degradation, extreme weather events combined with icing, and the opening and closing of coastal leads under anomalous atmospheric conditions. Warming in the Polar Regions causes continued decline and thinning of land (including permafrost regions) and sea ice in certain regions (e.g. IPCC, 2013; Paolo, Fricker, & Padman, 2015; Pritchard et al., 2012).

It is anticipated that there will be a seasonally sea-ice-free summer (sea-ice extent < 1.0 million km$^2$) in the Arctic as early as 2030 (AMAP, 2017), which will also have socio-economic consequences (Emmerson & Lahn, 2012). Reduced sea-ice coverage is likely to lead to increased navigability and open-water-season length for shipping activity in the Arctic and, in particular, may result in increased trade via the Northern Sea Route and the southern route of the Northwest Passage (e.g. Pizzolato, Howell, Derksen, Dawson, & Copland, 2014, 2016; Smith & Stephenson, 2013; Stephenson & Smith, 2015). There are, however, major challenges and constraints for a rapid growth of Arctic shipping, such as a shortage of infrastructure – in particular along the Northeast Passage, which is vital in terms of Search and Rescue or oil-spill preparedness and response. Furthermore, sea ice causes greater risks, lower predictability (which is important for container ships for just-in-time delivery) and additional costs (see Sander et al., 2016).

Until recently, in the Antarctic, sea-ice extent has been decreasing in some areas, in particular to the west of the Antarctic Peninsula, and increasing in most other areas, primarily in East Antarctica (King, 2014), which poses challenges for marine transportation and resupply of permanent bases. Since 2014, however, the mean Antarctic sea ice extent in September has been decreasing significantly and has stayed below the 1981–2010 average extent (National Snow and Ice Data Center, 2018). The upwelling of warm water under the ice shelves thins and weakens them from below (Pritchard et al., 2012), which has implications for shipping by affecting ocean currents and iceberg calving events. This upwelling may also potentially lead to the dramatic collapse of ice shelves, such as happened to Larsen B in 2002 (see e.g. Scambos, Bohlander, Shuman, & Skvarca, 2004) and more recently to Larsen C ice shelf in July 2017 (Hogg & Gudmundsson, 2017).

Of particular interest to this article is the expectation of growth in mobile activities, such as fishing, cargo and trade shipping, tourism, as well as mobile activities associated with communities and government operations. The Polar Regions, which have been traditionally used by outsiders, primarily for the purposes of resource exploitation (see, e.g. Avango, Hacquebord, & Wråkberg, 2014; Kock, 2007) are transitioning to a more routine use of the marine environment by those living outside the regions (Hillmer-Pegram & Robards, 2015), mainly in the Arctic. In this transitional phase, there is an urgent need for enhanced and reliable WWIC information services addressing physical events which are relevant to marine sectors, such as the timing and conditions related to freeze-up and break-up of fast ice, iceberg calving, extreme weather events and icing.

At the same time, there is growing concern about the risks involved in increased human activities in the Polar Regions. Risk generally refers to the probability and the consequences of an adverse weather event. As a measure for hazard (Keiler, 2004), risk represents 'a situation or event where something of human value (including humans themselves) has been put at stake and where the outcome is uncertain' (Rosa, 1998, p. 28). Risks result from exposure to direct biophysical changes and indirect socio-economic effects resulting in, e.g. increases in shipping activity. Various reports of maritime incidents in both the Arctic and the Antarctic region are calling for stricter regulations (e.g. the Polar Code) and stronger capabilities regarding maritime safety and search and rescue (SAR) (Dawson, Johnston, & Stewart, 2014; Dawson, Stewart, Johnston, & Lemieux, 2016; Jabour, 2014; Liggett, McIntosh, Thompson, Gilbert, & Storey, 2011; Marchenko, 2014; Swanson, Liggett, & Roldan, 2015). The marine insurance industry – whose collaboration is essential to the commercial viability of polar maritime activities – holds a host of safety and navigational concerns (Ghosh & Rubly, 2015; Jóhannsdóttir & Cook, 2015). The reduction in ice concentration and thickness outlined above could increase the risk to ships transiting the Polar Regions due to the presence of more hull-penetrating icebergs and bergy bits compared to larger ice islands of the past that are easier to navigate. Furthermore, the perception that the Polar Regions are becoming increasingly accessible could lead to a premature increase in activity and the entrance of new and unexperienced ship operators in the region (see Dawson et al., 2016, 2017a; Pizzolato et al., 2014, 2016; Stewart, Howell, Draper, Yackel, & Tivy, 2007).

As part of risk management, polar environmental forecasting services are an essential complement to navigational experience for individuals living or working in Arctic communities or in Antarctic research stations. WWIC information services contribute to the safe and efficient movement of people, goods, and services between places, as well as to access to homelands and country foods for community residents. Weather is notoriously challenging in the Polar Regions, with frequent low cloud ceilings, poor visibilities due to fog or blizzard, and rapid weather changes being commonplace. The variable nature of polar weather (Nakashima, Galloway McLean, Thulstrup, Ramos Castillo, & Rubis, 2012) means forecasts are generally reliable only up to about 48 h. It is widely recognized that, to realize the prospects and safety expectations of polar mobile sectors, there is a greater need for user-specific WWIC information services in the Polar Regions (EC-PHORS, 2015; Eicken, 2013; Knapp & Trainor, 2013, 2015; WMO WWRP PPP, 2013; WMO/WCP, 2015).

Although the above section considered the impacts of climatic change on the Polar Regions, this article is mainly concerned with short-term operational mobilities and hence places an emphasis on weather over climate. We acknowledge that changes in the climate will impact the weather in the polar regions in a non-linear fashion (Overland et al., 2016) and that we will consequently have to be aware of predicted climate changes in the

Arctic and Antarctic. For instance, changes in sea-ice cover are likely to affect temperatures, wind and wave height, all of which will be relevant for day-to-day mobilities. Yet, WWIC predictions for the Polar Regions are not as advanced as elsewhere in the world resulting, as outlined above, in increased risk for human wellbeing and assets, which could be reduced with improvements in WWIC information services.

## Conceptual framing of this review: mobilities

We draw on Cresswell's work (2010), which positions mobilities at the center of interdisciplinary research and investigation, countering prevailing notions of mobility as a secondary, or generic and static, process, quality or characteristic (Faulconbridge & Hui, 2016; Sheller & Urry, 2006). Constellations of mobilities are recognized as historically anchored and shaped constructs combining physical movements with narratives (or representations) and mobile practices (Cresswell, 2010). While Cresswell (2010) discusses six different components of mobilities (motive force, velocity, rhythm, route, experience, and friction), we view mobilities in an integrated fashion in this article whereby *mobile actors* or 'mobile subjective identities' (Cresswell, 2010, p. 26) might include tourists, migrant laborers, researchers, Indigenous hunters and so forth; and *mobile practices* constitute the form of movement, i.e. mobility.

Following Sheller and Urry (2006), we define mobilities broadly as the movement or flow of people or information and/or knowledge. Mobility is a naturally integrating and organizing concept, whether used in everyday conversation or in academia. Taken literally, it is most frequently used in reference to the ability to physically move between two locations. The objects in motion could be people, animals and plants, raw materials, manufactured goods or a host of other things including ice, water and atmospheric phenomena (e.g. storms). As indicated above, when viewed more as a metaphorical social construct, mobility captures a broader range of transfer, including virtual travel, movements of capital, technology, images, ideas, opinions, knowledge and information.

In the Polar Regions, mobility is a fundamental concept, both from the perspective of individuals (e.g. residents and visiting scientists) and from the perspective of relevant mobile sectors (e.g. tourism, fisheries, resource development, and shipping). Human activities and mobility sectors vary widely in size and scope and are diverse in terms of their spatial–temporal context of operation and practices. Modes of travel, and hence mobilities, differ, depending on the environment they are occurring in and whether this environment is dominated by land, ice, snow or sea. Consequently, climate change impacts these environmentally-contingent mobilities differently, and while we are seeing a potential for increased marine traffic in the Arctic due to decreasing sea ice cover, travel on land and sea ice is likely to be negatively affected by climate change in the future (see, e.g. Sánchez & Njåstad, 2014; Stephenson, Smith, & Agnew, 2011).

Some travel occurs across vast geographic areas while others only cover small areas. Local residents in the Arctic regularly travel between and around communities to visit friends and relatives and to access country and subsistence food sources, with the latter applying particularly to Indigenous residents. Researchers engaging in field studies travel and undertake weather-dependent field operations. In addition to their own mobilities, individuals living in communities across the Arctic, as well as scientists, tourists or others visiting the Arctic and Antarctic, also rely on the mobility of goods and services from elsewhere to survive. Resource exploration and development in the Arctic, and fisheries and marine tourism in both the Arctic and Antarctic, are also examples of the various forms of mobility occurring across the Polar Regions today.

## Approach and methods

In 2012, World Meteorological Organization (WMO), through its World Weather Research Programme (WWRP), initiated the Polar Prediction Project (PPP). The primary goal of the PPP is to advance scientific knowledge such that society, both within and outside of Polar Regions, may benefit through applications of better WWIC information and improved services. Towards these ends, the PPP established a special committee of social and interdisciplinary researchers and service practitioners in 2015. This initiative led to the official establishment of the Polar Prediction Project's Societal and Economic Research and Applications (PPP-SERA) working group.[2]

The PPP-SERA working group notes that there is no consistent set of data on human activities, let alone human mobilities, within any sub-region of the Arctic or Antarctic (Dawson et al., 2017b). This lack of a comprehensive inventory makes it difficult to develop regional comparisons, characterize pan-Arctic or pan-Antarctic trends, or anticipate future developments with much confidence. To deal with data challenges and space constraints, we have drawn upon available literature (including peer-reviewed articles, reports, inventories and surveys) to illustrate human mobility trends across four key subsectors including: (a) community activities (local residents) in the Arctic, (b) cruise tourism in both Polar Regions, (c) shipping (cargo and goods) in the Arctic, and (d) government and research operations (search and rescue, military, science missions) in both Polar Regions. The full results of our scoping exercise are published as a report for the WWRP's Polar Prediction Project (Dawson et al., 2017b). This present article shares some of the key insights from this report and extends our literature review and analysis using a mobilities framework.

## Characterizing mobilities in the Polar Regions

The subsectors reviewed in this article are a selection of a much wider range of mobilities in the Polar Regions, including key marine or aerial transportation services. To avoid duplication in analysis, each of the subsectors reviewed focuses on particular mobility types (see Table 1). For example, the communities section focuses on WWIC information needs and uses of localized land, ice and sea-based mobility; the tourism section on dominant ship-based mobilities; the cargo and trade section on international marine-based mobilities; and the government and research operations section on the needs and uses associated mainly with air-based mobility.

While conventionally WWIC information services are environmental forecasting services provided by specialized service providers, such as national weather services, an important role is also played by informal and decentralized provision of WWIC information through interpersonal communication or private radio transmissions. As we will outline in the section on communities, WWIC information plays a significant role in the Arctic and often complements official WWIC information services with activity-relevant local information at a higher resolution than can be officially provided. Similarly, in the Antarctic, where low bandwidth might hinder access to high-resolution WWIC forecasting services, spatially-specific WWIC information is often relayed informally to vessels operating in the region via VHF radio or satellite phones and, while this information may be based on official forecasts, it is being informally interpreted and framed by the person relaying it.

**Table 1.** Summary of mobility characteristics, WWIC information uses and needs.

| | | Mobility Sector | | | |
|---|---|---|---|---|---|
| | | Community | Cruise tourism | Shipping | Government operations |
| Mobility characteristics | Location | Arctic | Arctic/Antarctic | Arctic | Arctic/Antarctic |
| | Mobility basis* **for the purposes of the paper* | Land and Marine-based | Marine-based | Marine-based | Air and Marine based |
| | Scale | Local/Regional | Regional/Cross-scale | International/Regional | Cross-scale |
| | Timeframe | Year-round | Seasonal (summer) | Seasonal (summer) | Year-round |
| WWIC information use | Information sources | • Local weather forecasts (on radio, TV, or Internet)<br>• Satellite imagery, and/or tide tables<br>• Local/Indigenous knowledge<br>• GPS technologies and navigational aids<br>• Social media for sharing information | • On-board instrumentation including meteorological instrumentation and radar<br>• Information services such as GRIB files or ice charts<br>• Communication tools such as internet, Iridium satellite telephone, VHF radio<br>• Experience levels of the captain and crew/various rule systems | • On-board instrumentation including meteorological instrumentation and radar<br>• Information services such as GRIB files or ice charts, satellite imagery<br>• Communication tools such as internet, Iridium satellite telephone, VHF radio<br>• Experience levels of the captain and crew and in some cases an ice pilot<br>• Specialized radar systems, and use of other innovations such as scouting drones | • On-board instrumentation including meteorological instrumentation and radar<br>• Information services, including both routine and specially developed forecasts.<br>• Communication tools such as internet, Iridium satellite telephone, VHF radio<br>• Route planning and storm sheltering |
| WWIC information | Information needs | Local weather conditions:<br>• wind speed and direction<br>• snow and rain fall<br>• cloud and fog conditions<br>Local sea-ice conditions:<br>• sea-ice and lake/river-ice formation and break-up processes<br>• ice thickness and stability<br>• floe-edge position<br>• Extreme events, seasonal trends and marine tidal cycles | Local weather conditions:<br>• wind speed and direction<br>• precipitation<br>• cloud and fog conditions<br>Local sea-ice conditions:<br>• periods of break or freeze up<br>• icing conditions<br>• ocean temperature | Local and regional weather conditions:<br>• wind speed and direction<br>• precipitation<br>• cloud and fog conditions<br>Local and regional sea-ice conditions:<br>• periods of break or freeze up<br>• ice coverage and thickness<br>• icing conditions | • Aviation: low level cloud heights and in-cloud icing potential. Airstrip (primary and backup) forecasts<br>• Marine: wave and swell heights and directions. Detailed sea ice conditions and short-term forecasts. Superstructure icing potential. |

## Communities

This section focuses on the activities associated with daily community-life in Arctic settlements. Issues related to Antarctica's science-based communities are discussed in the section on government and research operations.

### Characteristics of community mobilities

In large parts of the Arctic, small, remote settlements are predominantly Indigenous communities, which maintain strong ties to land- and marine-based subsistence activities as part of the mixed economy (BurnSilver, Magdanz, Stotts, Berman, & Kofinas, 2016; Harder & Wenzel, 2012; Larsen & Huskey, 2015; Poppel & Kruse, 2009). Accordingly, community mobilities in Polar Regions are unique in their use of sea ice as a travel platform, overland mobility mainly being in winter and spring with sufficient snow cover and permafrost stability, and open-water travel with small crafts in the summer (or off the ice edge in the winter or spring) (Gearheard, Holm, Hunting, Leavitt, & Mahoney, 2013; Krupnik et al., 2010). Indigenous peoples have survived and thrived in Arctic regions for generations, and while many communities are interconnected with the global economy, they are still closely connected to seasonal cycles of harvesting country foods (AMAP, 2009; Donaldson et al., 2010; Fondahl, Filippova, & Mack, 2015; ICC, 2015). This includes gathering (e.g. berries, mushrooms, roots) in the terrestrial environment, hunting and fishing in both terrestrial and marine environments, and reindeer husbandry (Bartsch, Kumpula, Forbes, & Stammler, 2010; Rattenbury, Kielland, Finstad, & Schneider, 2009; Rees, Stammler, Danks, & Vitebsky, 2008). Such activities occur as part of cultural and family practices, to support dietary needs and preferences, or as part of local commercial enterprises (e.g. adventure tourism, sport hunting or fishing, ecotourism, arts and crafts, reindeer herding) (AMAP, 2009; Berner et al., 2016; Donaldson et al., 2010; Kenny & Chan, 2017; Nilsson & Evengård, 2015).

All these activities depend on transportation, which in turn is defined by the activity and by the time of year. Travel for hunting, fishing or gathering can range from a few to hundreds of kilometers away and to places accessed typically by snow machine, all-terrain vehicles (ATV) or open motor boat. Movement between communities is also important and takes place using the same modes of transport as for subsistence activities as well as commercial small aircraft operations. Movement on foot is also common. The use of dog teams is a less common practice but remains important for cultural activities, recreation, and some outfitting operations.

### Role of WWIC information for community mobilities

In support of the kinds of travel outlined above, much attention is paid to weather conditions and extreme events, seasonal trends, wind speed and direction, sea ice and lake/river ice formation and break-up processes, ice thickness/roughness and stability, floe edge position, snow and rain fall, cloud and fog conditions, and marine tidal cycles (Aporta, 2002; Druckenmiller, Eicken, Johnson, Pringle, & Williams, 2009; Eicken et al., 2014; Ford et al., 2008; Gearheard et al., 2006; Gearheard, Pocernich, Stewart, Sanguya, & Huntington, 2010; George et al., 2004; Laidler et al., 2009, 2011; Laidler, Dialla, & Joamie, 2008; Meier, Stroeve, & Gearheard, 2006; Nickels, Furgal, Buell, & Moquin, 2005; Weatherhead, Gearheard, & Barry, 2010). Nuanced WWIC indicators are all considered, in particular place-based contexts to inform community mobility decisions around travel destinations, timing, and safety (see Table 1).

In order to prepare for land-based, sea-ice, or water travel, it is common for residents to consult weather forecasts, tide tables, and satellite imagery of sea ice conditions, among other information, by listening to community radio, watching TV, or using the Internet (Ford et al., 2008; Gearheard et al., 2010; ICC, 2008, 2014; Laidler et al., 2008, 2011; Meier et al., 2006). However, significant importance is placed on local/Indigenous knowledge derived from long-term observation and experience that includes intergenerational knowledge transfer and information gained from informal, often inter-personal knowledge sharing networks (Gearheard et al., 2013; Krupnik et al., 2010). Weather is part of a daily conversation and is shared in person with family members or other community members, as well as over the local community radio and via short-wave radio or satellite phone while traveling. Social media is also increasingly being used for sharing information of all kinds of information, including environmental indicators and safety warnings (ICC, 2008, 2014; Larsen & Fondahl, 2015; Rasmussen, Olsen, Hansen, Hátún, & Larsen, 2014).

GPS technologies are increasingly used as navigational aids, especially for younger or less experienced hunters and travelers (Aporta & Higgs, 2005; Durkalec, Furgal, Skinner, & Sheldon, 2014; Ford et al., 2008; ICC, 2008, 2014). However, in assessing travel safety, Indigenous and local weather, water and ice indicators and tools (e.g. using a harpoon to test the thickness of ice) are predominantly relied upon to make decisions on the fly. Nevertheless, Elders and experienced hunters worry that the younger generations may not be spending enough time on the land, water, or ice to gain sufficient weather-related knowledge to use as forecast indicators (Aporta & Higgs, 2005; Ford et al., 2008; George et al., 2004; Laidler et al., 2008). Concerns have also been expressed in relation to observed environmental changes, and greater uncertainties associated with rapidly changing weather events, ice dynamics and increasingly unreliable traditional indicators (Alessa et al., 2015; Durkalec et al., 2014; Ford & Pearce, 2012; Gearheard et al., 2006; George et al., 2004). Because of this, some communities have begun to initiate their own community-based monitoring programs to track weather and ice conditions in locations and at scales that are most relevant to local decision-making (Alessa et al., 2015; Druckenmiller et al., 2009; Gearheard et al., 2010; Johnson et al., 2015; Kouril, Furgal, & Whillans, 2016; Mahoney, Gearheard, Oshima, & Qillaq, 2009).

## *Cruise tourism*

Despite land-based tourism opportunities (such as adventure tourism), most tourism to the Polar Regions is ship-based and supported by air travel to gateway ports. Ship-based tourism is dominated by cruise vessels, with many of the same vessels operating both in the Arctic and Antarctic (Lück, Maher, & Stewart, 2010). Increasingly, private and commercial yachts, i.e. vessels with a capacity of up to 12 passengers, are also visiting the Polar Regions (Johnston, Dawson, De Souza, & Stewart, 2017). Due to the prominence of marine-based mobilities in the polar tourism sector, this section focuses on the activities associated with ship-based tourism.

### *Characteristics of cruise tourism mobilities*

Cruise tourism is an economic sector with growing significance in both Polar Regions. Total tourism numbers in the Polar Regions have increased over the past decade but continue to fluctuate annually. The overall number of tourists visiting the Arctic is greater than the number of tourists visiting the Antarctic, but tourism represents the primary and largest commercial activity in Antarctica (Stewart & Liggett, 2016). The total number of Antarctic visitors in 2017–2018 was recorded as 51,707 persons and was 17% greater than in the previous season (IAATO, 2018). Visitation across the Arctic varies dramatically by country, with approximately a million cruise passengers to Alaska, approximately 75,000 to Svalbard, approximately 25,000 to Greenland and almost 5,000 to the Canadian Arctic (Dawson et al., 2014; Lasserre & Têtu, 2015; Van Bets, Lamers, & van Tatenhove, 2017).

Growing numbers of cruise passengers travel to and through the Polar Regions on increasing numbers of vessels of differing sizes, levels of ice-strengthening and technological capabilities. Moreover, cruise travel is undertaken in increasingly diverse forms, from trips on large cruise ships with thousands of passengers to expedition-style cruises and yacht excursions (Johnston et al., 2017). In most regions (except Alaska), ship-based tourism is dominated by expedition-cruise vessels, with many of the same vessels operating both in the Arctic and Antarctic (Lück et al., 2010). Expedition cruising is characterized by small vessels (between 20 and 500 passengers), shore landings and exploration using rubber boats, quality interpretation, exclusive wilderness experience, minimal environmental and social impact, human safety and flexibility due to dynamic weather and sea ice conditions. During expedition cruises, passengers engage in a variety of land-based and marine activities including hiking, camping, climbing, and skiing (Lamers & Gelter, 2012) (see Table 1).

Ship-based tourism in the Polar Regions is typically concentrated in the summer season (approximately four months, depending on the region) due to unfavorable weather and sea-ice conditions as well as limited opportunities to view wildlife in colder seasons. Expedition-cruise trips of one week in Svalbard and eleven days in the Antarctic Peninsula are scheduled back-to-back to allow for optimal cost-efficiency in the short tourism season. In both Polar Regions, dramatic changes in sea-ice extent and thickness and, in particular, diminishing sea-ice cover in the Arctic and around the Antarctic Peninsula region (see e.g. Meredith et al., 2017; Stroeve, Markus, Boisvert, Miller, & Barrett, 2014) allow expedition-cruise and yacht operators to move into even higher latitudes and to extend the lengths of their operating season from earlier in the spring into later in the summer (see Bender, Crosbie, & Lynch, 2016; Tejedo, Pertierra, & Benayas, 2014).

The need for WWIC information services grows as risks and stakes are increasing, as itineraries are becoming more standardized and regularized, and as operational experience of captains, expedition leaders and guides is becoming diluted due to growth. Overall, there is a spectrum of mobilities from larger cruise vessels with limited operational flexibility (standardized routes), high technological capabilities and a propensity for low-risk thresholds, to smaller passenger vessels with high operational flexibility, lower technological capabilities and higher risk thresholds. The sinking of the M/V *Explorer* in Bransfield Strait in 2007 has highlighted the risks of operating in ice-strewn waters (Republic of Liberia, 2009; Stewart & Draper, 2008). Given the diversity in mobility types and their operational characteristics, WWIC information services are playing an increasingly important role in both planning and operating ship-based tourism in the Polar Regions.

### *Role of WWIC information for cruise tourism mobilities*

WWIC information services are an important source of information available to the captain and the expedition leader in safely navigating vessels and conducting shore excursions (see also Lamers et al., 2018). For example, operators use on-board instruments, including barometers and barographs, information services such as GRIB[3] files or ice charts and communication tools such as internet, Iridium satellite telephone and VHF radio. Their use is integrated into complex operational practices that predominantly depend on the experience of captains and expedition leaders, their expertise interpreting weather/ice charts and their ability to communicate (Duske, 2016). Depending on the conditions and the activities planned, different information sources and systems are being consulted, for example sea-ice in combination with wind condition or ocean temperature in periods of break- or freeze-up (see Table 1).

Internet connectivity is very weak in the higher latitudes, which makes data-heavy formats difficult to download, particularly for smaller expedition-cruise vessels. This results in the greater use of satellite telephones and VHF radios for communication with company headquarters and other expedition vessels in the vicinity about weather and sea-ice conditions. With improved internet connectivity, additional information sources can be used in decision-making, such as e-navigation services to develop route planning, individualize and combine different sources of information, including weather and sea ice data, and to reduce data volume transfers (Lamers et al., 2018).

## Shipping

Shipping is a fundamental industry that involves the movement of goods, including raw materials and manufactured items, by cargo ships, tankers, re-supply vessels, tug and barge operations and others. The shipping industry is responsible for between 80% and 90% of trade globally and the movement of over four trillion USD in goods annually and is therefore a fundamental industry that supports modern day society (WSC, 2019). The majority of shipping activities occur in the lower latitudes, where there is a long history of trade, highly developed maritime infrastructure, and less harsh weather conditions than in the Arctic (Ng, Andrews, Babb, Lin, & Becker, 2018; WSC, 2019). However, the rapid loss in sea ice as a result of climate change is opening up the Arctic Ocean to shipping opportunities (Eguíluz, Fernández-Gracia, Irigoien, & Duarte, 2016; Pizzolato et al., 2014, 2016). For almost five centuries, nations around the world have aspired to first discover and then exploit Arctic sea routes for the purpose of international trade considering the Arctic Ocean offers the shortest distance by sea between the Pacific and Atlantic Oceans. Harsh weather and thick multi-year sea ice has, in the past, prevented reliable maritime routes through the Arctic, but climate change and revolutionary technological developments in ship design are making maritime trade through the north an increasing reality.

### Characteristics of shipping (cargo and goods) in the Arctic

Over the past decade, ship traffic throughout the global Arctic has increased, albeit not with any uniformity. The most dominant ship types operating in the Arctic are re-supply, research, and survey vessels, followed by fishing, cargo, and tankers (AMAP, 2017; Eguíluz et al., 2016). Traffic is highest in the Norwegian and Barents Seas and tends to access the region via the eastern route of the Northern Sea Route. The spatial distribution of shipping traffic in the Arctic is very concentrated compared to shipping in the lower latitudes, likely because of the limited hydrographic charting, infrastructure, and services available to support safe navigation that force ships onto certain known corridors (Christensen, Lasserre, Dawson, Guy, & Pelletier, 2017; Doyon et al., 2016; Lasserre, 2018; Lasserre, Beveridge, Fournier, Têtu, & Huang, 2016; Rompkey & Cochrane, 2008; Schmied et al., 2017;

also see Chénier, Abado, Sabourin, & Tardif, 2017; Porta, Abou-Abssi, Dawson, & Mussells, 2017). Compared to the European and Russian Arctic areas, there is significantly less ship traffic in Canada and through the Northwest Passage. Overall, the region is less navigable because of higher variability in ice conditions, limited maritime and navigational infrastructure, and simply because it is remote (Mussells, Dawson, & Howell, 2017). Despite lower overall traffic in Arctic Canada, the region is still experiencing rapid increases, with the total kilometers traveled by ships in Arctic Canada more than tripling over the past decade (Dawson, Pizzolato, Howell, Copland, & Johnston, 2018). Due to thick multi-year sea ice, the transpolar route over the top of the Arctic via the North Pole, is not currently feasible for Arctic maritime trade, although some authors claim that the route could be open during the summer as soon as mid-century (Aksenov et al., 2017; Smith & Stephenson, 2013). The Arctic shipping season is getting longer with increased ice-free periods. The majority of traffic is concentrated between July and October, correlated to seasonal dynamics and ice coverage. However, the amount of traffic occurring in the shoulder seasons, including in June and November, is increasing (Eguíluz et al., 2016; Pizzolato et al., 2014).

Additional changes in shipping traffic are expected in the future as climate change continues to impact sea-ice extent and thickness (AMAP, 2017; Haas & Howell, 2015; Pizzolato et al., 2016). It has been forecasted that by 2050, the Arctic Ocean may be largely ice-free during the summer and that many regions of the Arctic, including the Northwest Passage, will be accessible to even non-ice-strengthened vessels (Stephenson & Smith, 2015). Modeling specific future traffic volumes for 2050 is very challenging considering the range of factors beyond climate change that influence ship traffic, such as commodity prices, global economic trends, insurance regimes, geopolitics and regulation (Dawson et al., 2014; Hodgson, Russell, & Megannety, 2013; Ng et al., 2018). However, it is fairly certain that the Arctic will experience increased shipping traffic in the future. Perhaps most telling is fact that China has declared their intention to develop the 'Polar Silk Road' (PRC, 2018), the United States has introduced the 'SEAL' Act (Shipping and Environmental Arctic Leadership) (United States Senate, 2019), and Russia announced it will resume fighter patrols over the North Pole for the first time in over 30 years (Weber, 2019). Investment in the Arctic is expected to be in the hundreds of billions of dollars over the next decade (AMAP, 2017; Mikkola & Käpylä, 2013) as climate change and technological innovations combine to enhance access to the Arctic Ocean, for which there are also increasing motivations from international trade and global resource demands to use the region's shipping routes.

### *Role of WWIC information for shipping*

WWIC information is fundamental for safe and sustainable Artic shipping operations. Ship captains need access to reliable and real-time information on potentially hazardous and changing weather and ice conditions for navigational and operational decision-making. Operating a ship in the Arctic, where there are additional weather-related hazards such as, sea ice, ice bergs, landfast ice, pressured ice, freezing spray, and rapid changes in weather and wind conditions[4], requires quick and responsive decisions. Having access to accurate and timely WWIC data is one of the most important tools for a ship operator. Changing temperatures and increased incidences of extreme precipitation and temperature events are challenging for ship operators, but it is the rapid and sudden changes in wind conditions that cause some of the greatest concern. For example, fuel re-supply ships servicing Canadian Arctic communities anchor off shore due to the lack of infrastructure around communities and lay out as much as 100 meters of floating fuel hose between the ship and the shore. If there is a sudden and unexpected change in wind that blows multi-year ice towards the hose, a fuel spill could occur. Changing wind conditions have also regularly and unexpectedly 'iced in' vessels throughout the Arctic requiring Coast Guard rescue. There are significant WWIC needs for ship operations in the Arctic and operators would benefit from improved services, in particular access to real-time and higher resolution data on wind, ice thickness and ice pressure (see Mussells et al., 2017) (see Table 1).

## Government and research operations

The Polar Regions are not only seen as bellwethers of climate change and, consequently hot spots for climate research, but are also strategically and geopolitically significant areas a range of states maintain active presence in.

### Characteristics of mobilities in government and research operations

In the Arctic, government and research vessels undertake surveying, oceanographic research, vessel escort in ice, salvage, pollution response, naval and military exercises and search-and-rescue (SAR) operations (Arctic Council, 2009; Dawson et al., 2017a). Terrestrial research and permanent research stations by governments in the Arctic typically require air or marine support, whether for resupply or simply access. An increasing number of icebreakers and research vessels have been conducting geological, geophysical, oceanographic, and environmental research throughout the central Arctic Ocean to establish the limits of the extended continental shelves (Arctic Council, 2009) and support increased economic interests in the region.

In the Antarctic, government activities are dominated by research, building and maintenance of research stations, refuges or field camps and any other activities in support of research. The latter can include the use of the military, private companies or national operators to provide transport to and from the Antarctic and deploy and maintain field camps and field bases, as well as provide air, land and sea support of these field camps from the main research stations. Research activities and research support in the Antarctic is generally characterized by a high level of cooperation between different states, as encouraged by the 1959 Antarctic Treaty. Antarctic programs with sufficient motivation or funds may utilize cutting-edge and high-cost technologies to ensure the safety of personnel and the efficiency of operations.

SAR mobilities can be air-, marine- and land-based in the Arctic (Canadian National Search and Rescue Secretariat, 2016) and in the Antarctic. Incidents in the Arctic are increasing due to changing weather and ice conditions, limited SAR assets, and the vast geographic areas needing coverage (Clark et al., 2016). The increase in frequency of extreme weather events requires changes to the deployment of SAR resources (Canadian National Search and Rescue Secretariat, 2016). Furthermore, increased commercial and tourist activity is demanding a deeper awareness of the requirements and responsibilities for successful SAR in the region while the development of new technologies (such as the international Medium Earth Orbit SAR System), together with supporting regulation, presents opportunities for improving SAR through enhanced communications, detection, and so forth. Conversely, new technologies have the potential to create a false sense of security in the general public. This, in combination with a loss of land-based knowledge, increases the potential for SAR incidents. Implementation of the international code for ships operating in Polar waters, known as the Polar Code (see: IMO, 2017) and other Arctic Council agreements are promising multi-lateral approaches to dealing with the increasing probabilities of Arctic incidents, but only in marine areas.

In the Antarctic, over the past decade, states have shown significant interest in increasing their presence on the continent by expanding their facilities or adding new stations or camps. States that have recently joined the Antarctic Treaty System (e.g. Mongolia, Kazakhstan, Iceland), and other states such as Malaysia, Iran, Thailand and Turkey, are working towards increasing their profiles in Antarctic research. Thus, there is likely to be continued and increased international research and government activity in the region.

### Role of WWIC information for government and research operations

Mobility decisions related to Government and Research Operations may happen on the fly as is often the case with SAR and on-site research activities, but there is also a long-term perspective when the operations and protocols for different situations are planned. As the form of mobility may be land-, marine- or air-based, there are several WWIC-related aspects to consider. However, to avoid duplication with earlier sections, here we mainly address air-based mobilities. While modern aviation activities worldwide are less weather-impacted now than in the past, due to significantly improved technologies and weather-numerical prediction, the Polar Regions have not benefitted to the same extent by infrastructure modernization programs.

Long-term changes occurring in polar environments bring a variety of risks and opportunities for governmental and research operations in the Polar Regions. For instance, increasing demand for SAR activities needs both increasing aviation and marine activities, sometimes in dangerous conditions. Surface-related changes will also have important consequences for activities in some polar areas as, for example, stable sea ice for seasonal airstrip construction on snow and ice have very short seasons. This seasonality of activities can greatly increase the time required and cost of the shipment of goods and services by air. At some small research stations or communities, seasonal and permanent airstrips are unusable during spring thaw and autumn freeze, and climate change will potentially impact the timing, frequency and duration of thaw/freeze cycles. The timing of the transition from wheeled to ski-equipped aircraft (and back again) is likely to change (Dawson et al., 2017b).

In the Antarctic, aircraft activity is almost entirely limited to the austral summer, although night flights in winter have been trialed and are likely to become more common in the future. It is also noteworthy that access to some field sites is highly limited even during the austral summer period, with soft snow conditions preventing access after late November or early December. Ice runways in the Antarctic are equally susceptible to change as they are in the Arctic. Airfields constructed on ice shelves are vulnerable to degradation and ice-stream movement and require significant maintenance or relocation when the ice shelf becomes unstable.

Overall, environmental changes are likely to continue to impact inflight aviation conditions, the navigability of research vessels and the safety of personnel working in research stations. In particular, changes in the seasonality and potential intensity of low-level icing can also be expected from, e.g. decreasing sea-ice coverage, warming air temperatures and increase lower-atmospheric moisture. These changes will also likely lead to increased fog intensity in some areas and will challenge ice-based landing areas as well as navigation. Thawing permafrost and warmer summers will continue to impact landing strips across the Polar Region (see Table 1).

## Discussion: WWIC information needs

Mapping human activities and mobilities in the Polar Regions is a challenging task (Freeman, 1976; Hughes, Fretwell, Rae, Holmes, & Fleming, 2011; Pertierra, Hughes, Vega, Olalla-Tárraga, & Peter, 2017). It is clear that we do not have a sufficiently detailed understanding of what specialized polar environmental forecasting services should look like to ensure that the current actors in these regions – from communities residing in the Arctic to commercial operations in polar waters (shipping, fishing, tourism, government operations) to research support in the Antarctic – receive timely and targeted information that can assist them in navigational and other decision-making. In some cases, the availability of WWIC information at a sufficient resolution to be helpful for operators yet packaged in file sizes small enough to be downloadable in areas of low bandwidth can prevent a major environmental disaster or even death (Dawson et al., 2017b).

The WWIC-related issues and challenges identified for the four mobility sectors reviewed in this paper are, to some degree, attributable to the harsh, demanding, and changing aspects of the polar environment. In addition, many of these conditions are exacerbated or complicated by a growing demand for resources, associated increased levels of activity and greater access to and use of new technologies (Nuttall et al., 2018). Users generally exhibit a greater dependency on technology, but require specialized services due to the breadth of contexts and practices involved.

While the affected actors are numerous and wide-ranging (e.g. individual Arctic residents, cruise-ship operators, scientific-expedition logistics coordinators, etc.), all of them make decisions that involve some consideration and understanding of WWIC conditions. The mobility sectors we have discussed require WWIC information, albeit at different scales, timeframes, and resolutions (for a summary see Table 1). Each sector requires focused attention to tailor data products for their unique needs and requirements.

Despite the difference identified in terms of information use and needs across the mobility sectors reviewed in this article, there are some universal understandings related to many user groups in the Polar Regions (Dawson et al., 2017b):

- A need exists for real-time observations and related products (e.g. short-term forecasts). The operational seasons are short, and weather conditions can change quickly, real-time or near-real-time data are essential for operators in any sector outlined here to make risk-reducing decisions.
- Sometimes an indication of data directionality and tendency (e.g. is the wind increasing or decreasing; is it from the West or the East?) is most useful.
- Operators and community members rely heavily on past experience, and WWIC data are just one piece of information used in their decision-making processes.
- Effective data interpretation is essential. There is a need for communicating data simply, efficiently, and effectively in a language that is understandable for the users.
- Nuanced WWIC indicators that are based on local, including Indigenous, knowledge need to be better communicated to – and documented by – service providers to identify potential scales, thresholds, and frequency of products that could be better tailored to user needs.
- Wind is one of the most important weather variables for navigation in the Polar Regions (i.e. in terms of extreme events, rapid movement of ice, etc.), and there is a lack of good wind prediction and forecasting tools.

- It is challenging for data users to stay current with new weather data portals and products. Users may prefer a single information source for WWIC information, but this is not the current convention.
- Ice data in the Antarctic are lacking compared to what is available for the Arctic.
- The limited communications infrastructure and, in particular, the limited bandwidth available for Internet transmissions is a challenge when trying to access data.
- Some providers offer data via sophisticated dynamic interfaces which are inaccessible to most community users. WWIC information services are rarely tailored to address locally relevant indicators, at appropriate spatial and temporal scales.

WWIC information is important in addressing user needs in the context of a changing climate and in supporting critical services (e.g. community re-supply, resource harvesting) and preparedness for the environment (e.g. SAR, emergency response to environmental disasters, safe navigation in shipping and aviation, and national security). As indicated in the bullet points above and in the preceding sections, we observe a mismatch or incongruence between the WWIC information currently provided and the ways in, and extent to, which current WWIC information is used and is needed by various mobile actors and sectors (Dawson et al., 2017b).

## Conclusion

The availability and utility of accurate and relevant WWIC prediction services to local residents, researchers and industry stakeholders are fundamental for local and regional polar mobility and, in many instances, can mean the difference between life and death. However, the way information services are used and how they influence relevant decision-making and operational practices is largely unknown. Different end-users seem to have very different needs and capabilities with regard to WWIC information services, depending on their objectives, mobilities, experience or available technologies as well as their access to, and comprehension of, WWIC products. A wide range of WWIC information is available but, out of the array of available information, only a small subset of services is being selected by individual users, usually based on familiarity, convenience and accessibility (free of cost). The mere availability of information, or the fact that actors access certain information, does not say much about if and how this information is actually used in decision-making.

There is a need to identify and assess relevant human activities and mobilities in the Polar Regions and to undertake in-depth systematic and sector-specific analyses to characterize and synthesize what is currently known about these activities, the kinds of WWIC used or identified as necessary to support decision-making at different spatial and temporal contexts. Currently, no comprehensive information is available on human activities in the Polar Regions. We encourage research, industry, and government efforts to develop approaches to effectively and systematically identify and track the diverse mobilities taking place in the Polar Regions.

Work is also needed to understand how risks are dealt with in practice by various mobile actors, including how risks are perceived, how decisions are taken by different actors, and how risks are influenced by constraining or facilitating factors (e.g. policies). Competence and experience are key factors in the safe conduct of activities in dynamic polar environments, regardless of whether these are local communities or ship operators. A pertinent issue emerges with new actors or operators entering these environments. How can we ensure that they have sufficient experience or access to the best information to make sensible decisions?

We need to improve our collective understanding of human activities in the Polar Regions, their related mobilities, WWIC needs and decision-making behaviors. Consequently, we recommend the following work to be undertaken:

- Extensive descriptive research collating trans-regional information and statistics on human activities in the Polar Regions across all sectors, but with a particular focus on tourism, fishing, the transport sector, research activities and community-based activities;
- A survey of key actors to understand the breadth of 'information user needs';
- Assessments of information needs for WWIC information services among different user categories; and
- Ethnographies detailing decision-making processes among actors in the Polar Regions and their use of WWIC-related information.

An evaluation of the relevance, accessibility, ease of use, and effectiveness of communication of current WWIC forecasts or modeling products considering the perspectives of target users is critical. Currently, there is a paucity of research on the provider-user interface and on the usefulness and effectiveness of WWIC information services despite the obvious need to tailor products or formats to specific user needs and assess the relative levels of success in this respect. Work is required to explore user preferences for certain sources or formats of information and users' habits related to using and accessing WWIC information to assess the kinds of interface characteristics or channels for accessing WWIC information that users find more useful or challenging. Here, we also need to ask what makes certain providers trusted sources, and how institutional, legal or other factors that may constrain access to, or provision of, WWIC information services impact provider ability to respond to user needs and feedback. On a practical level, we encourage the development of additional opportunities and mechanisms for user feedback of data services/technologies offered by providers.

Finally, it is essential to understand the role of local WWIC observations, citizen-science and operational forecasters, which is increasingly recognized as contributing important WWIC information. These groups are often considered as 'users', but the boundary between 'users' and 'providers' of WWIC forecasting is no longer dualistic or clearly defined. Consequently, we need to assess to what extent WWIC information and forecasts can be co-produced, and what infrastructure and communication pathways are needed to connect community-based or research-driven monitoring with larger formalized WWIC-service providers, such as national WWIC service providers.

This article has highlighted what information is available on human activities and decision-making in the Polar Regions but, more importantly, what information we are currently lacking. Environmental forecasting services for the Polar Regions are still lagging behind those in the more temperate regions, due to a lower density of observations or models not properly presenting the atmospheric and physical phenomena in the Polar Regions (Jung & Matsueda, 2016), but some progress has been made to close the gaps. During the Year of Polar Prediction (YOPP) more in-situ observations, from buoys, weather balloons, additional automatic weather stations, research cruises, etc., along with considerable efforts in improving models, ensemble forecasts and data reanalyzes have resulted in greater accuracy in forecasts, with errors being reduced further as the models are being further strengthened and verified over the next few years (Sato et al., 2017).

Furthermore, new technology such as the Visible Infrared Imaging Radiometer Suite (VIIRS) on board a recently launched environmental satellite, the Suomi National Polar-orbiting Partnership (S-NPP), allows the collection of visible and infrared images that can track vessels whose decks are illuminated (Straka et al., 2015). This VIIRS technology has permitted a crab-catching vessel operating in the Bering Sea in February 2013 to be located amidst closing sea ice and poor visibility and guided to safety (Ibid). As technologies continue to evolve in tandem with improved environmental forecasting, more targeted assistance and WWIC information will be able to be provided in the future.

However, it is beyond doubt that, to improve environmental forecasting services in the Polar Regions, we need to better understand user needs. This in turn requires a better grasp of the scale and scope of human activities in the Polar Regions, and the characteristics and mobilities of individual actors. The Societal and Economic Research and Applications subcommittee of the Polar Prediction Project, and scholars focussing on the Polar Regions more broadly, can contribute to addressing some of the knowledge gaps outlined in this article. We invite others to contribute further information to enable an informed discussion on the highly complex set of interconnections between users, providers, mobilities and decision-making across the Polar Regions.

## Notes

1. A differentiation between 'weather' and 'water' in WWIC is made to highlight aspects such as wave height and wave action, which could be otherwise easily forgotten.
2. The authors of this paper are all members of PPP-SERA and this paper aims to provide a foundation to the work of the group.
3. GRidded Information in Binary (GRIB) files are a special binary format of weather data and are regarded as a useful and cost effective forecasting tool, particularly for short-term forecasts.
4. We acknowledge that different types of hazard are associated with different risk profiles, depending on the type of mobility and the environment it is undertaken in. It is out of the scope of this paper to explore individual hazards, their risk profiles, and related WWIC information separately, and we refer readers to a host of publications exploring this topic (see e.g. Eicken & Mahoney, 2015; Stewart, Tivy, Howell, Dawson, & Draper, 2010).

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