The use of weather, water, ice, and climate (WWIC) information in the Polar Regions: What is known after the decade-long Polar Prediction Project?

Weather, Climate, and Society

Heinrich, Victoria; Stewart, Emma; Liggett, Daniela; Carrasco, Jorge; Dawson, Jackie et al

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The Use of Weather, Water, Ice, and Climate (WWIC) Information in the Polar Regions: What Is Known after the Decadelong Polar Prediction Project?

VICTORIA J. HEINRICH,[a] EMMA J. STEWART,[b] DANIELA LIGGETT,[c] JORGE F. CARRASCO,[d] JACKIE DAWSON,[e] MACHIEL LAMERS,[f] GITA J. LJUBICIC,[g] JELMER JEURING,[h] AND RICK THOMAN[i]

[a] *School of Psychological Sciences, University of Tasmania, Hobart, Tasmania, Australia*
[b] *Department of Tourism, Sport and Society, Lincoln University, Christchurch, New Zealand*
[c] *Gateway Antarctica, University of Canterbury, Christchurch, New Zealand*
[d] *Centro de Investigación Gaia Antártica, Universidad de Magallanes, Punta Arenas, Chile*
[e] *Department of Geography, Institute for Science, Society and Policy, University of Ottawa, Ottawa, Ontario, Canada*
[f] *Environmental Policy Group, Wageningen University and Research, Wageningen, Netherlands*
[g] *School of Earth, Environment and Society, McMaster University, Hamilton, Ontario, Canada*
[h] *Norwegian Meteorological Institute, Bergen, Norway*
[i] *Alaska Center for Climate Assessment and Policy, International Arctic Research Center, University of Alaska Fairbanks, Fairbanks, Alaska*

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ABSTRACT: The polar regions are facing a wide range of compounding challenges, from climate change to increased human activity. Infrastructure, rescue services, and disaster response capabilities are limited in these remote environments. Relevant and usable weather, water, ice, and climate (WWIC) information is vital for safety, activity success, adaptation, and environmental protection. This has been a key focus for the World Meteorological Organization's (WMO) Polar Prediction Project (PPP), and in particular its "Societal and Economic Research and Applications" (PPP-SERA) Task Team, which together over a decade have sought to understand polar WWIC information use in relation to operational needs, constraints, and decision contexts to inform the development of relevant services. To understand research progress and gaps on WWIC information use during the PPP (2013–23), we undertook a systematic bibliometric review of aligned scholarly peer-reviewed journal articles (n = 43), examining collaborations, topics, methods, and regional differences. Themes to emerge included activity and context, human factors, information needs, situational awareness, experience, local and Indigenous knowledge, and sharing of information. We observed an uneven representation of disciplinary backgrounds, geographic locations, research topics, and sectoral foci. Our review signifies an overall lack of Antarctic WWIC services research and a dominant focus on Arctic sea ice operations and risks. We noted with concern a mismatch between user needs and services provided. Our findings can help to improve WWIC services' dissemination, communication effectiveness, and actionable knowledge provision for users and guide future research as the critical need for salient weather services across the polar regions remains beyond the PPP.

SIGNIFICANCE STATEMENT: Every day, people in the Arctic and Antarctic use weather, water, ice, and climate information to plan and carry out outdoor activities and operations in a safe way. Despite advances in numerical weather prediction, technology, and product development, barriers to accessing and effectively communicating high-quality usable observations, forecasts, and actionable knowledge remain. Poorer services, prediction accuracy, and interpretation are exacerbated by a lack of integrated social science research on relevant topics and a mismatch between the services provided and user needs. As a result, continued user engagement, research focusing on information use, risk communication, decision-making processes, and the application of science for services remain highly relevant to reducing risks and improving safety for people living, visiting, and working in the polar regions.

KEYWORDS: Social science; Antarctica; Arctic; Numerical weather prediction/forecasting; Communications/decision-making; Societal impacts

1. Introduction

The polar regions, including the subarctic, subantarctic islands and oceans, are remote, isolated, and harsh environments. Weather conditions regularly limit travel and outdoor activities and can compromise safety across all polar communities and operations. People living, visiting, and working in these regions rely on weather, water, ice, and climate (WWIC) information and services for their everyday planning and decision-making, ranging from search and rescue, evacuations, aviation, tourism, logistics and resupply, shipping, science, and subsistence harvesting to fishing and resource extraction. Compared to more temperate zones, people in the polar regions face consistently greater safety risks and consequences through their exposure to more severe weather, constrained access to poorer environmental predictions, limited resources, communication and

Corresponding author: Victoria J. Heinrich, vicki.heinrich@utas.edu.au

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transport systems, and lack of easy access to emergency, rescue, medical, and environmental-disaster-mitigation equipment and services. Weather, ice conditions, and human error are the main contributors to incidents that result in the need for rescue, costly searches and evacuations, human injury, deaths, and environmental emergencies (Durkalec et al. 2014; Klein 2010; Panagiotidis et al. 2021; Transportation Safety Board of Canada 2014). Following Wiggins and O'Hare (1995) and Heinrich and Norris (2023b), we define successful weather-related decision-making as the utilization of the skills and knowledge that people need to identify and avoid weather hazards and safely execute their activities. This underscores that safety and risk mitigation are fundamental priorities for polar WWIC information users, in addition to the need to sustain and protect fragile polar ecosystems, and in the Arctic to support Indigenous communities and food security (van Luijk et al. 2022).

Arctic search and rescue incidents are increasing (Clark et al. 2016a; Kikkert and Lackenbauer 2021). Climate change in polar regions means that land, sea, and ice access is changing (Ford et al. 2019; van Luijk et al. 2022), ice is disappearing (Gudmundsson et al. 2019; Serreze and Meier 2019), precipitation intensity is increasing (Tebaldi et al. 2006), and globally, wind strengths are intensifying (Young and Ribal 2019). Additionally, the loss of sea ice has implications for coastal erosion (Brubaker et al. 2011; Reid and Massom 2022) and the stability of ice shelves (Reid and Massom 2022), which may lead to more sea ice hazards in regions that were previously iceberg free (J. Leiser 2023, personal communication). Thus, current local knowledge based on past polar experiences may rapidly become outdated and irrelevant. Greater uncertainty leads to an increased risk to human safety and likelihood of adverse weather incidents. Cumulatively, the risks, hazards, and negative impacts to humans and their activities are undoubtedly escalating. In uncertain conditions, aggravated by climate change, the need for high-quality weather services, training, and nontechnical skills to support proficient and safe decision-making and risk mitigation becomes more urgent. Therefore, providing effectively communicated, accurate, and quality weather information and warnings, along with the education, skills, and knowledge to correctly interpret and safely use this information and to assess risk and cope with severe and extreme weather events is critical to increasing safety and risk mitigation in the polar regions.

In addition to WWIC information—including conventional observations, automatic weather station data, satellite images, radar, forecasts, and numerical weather prediction (NWP) models—local and Indigenous knowledge, mentorship, information sharing, and past experience are vital for safe travel, activity planning, and successful operations (Heinrich and Norris 2023b; Lamers et al. 2018a; Simonee et al. 2021; Slats et al. 2019; Wilson et al. 2021a). People in the polar regions are highly reliant on their previous experience and their individual ability to find and correctly interpret weather information, which essentially amounts to self-briefing (Casner et al. 2012). As polar environments are changing around them, local knowledge and previous experience are no longer as dependable, and people in Arctic communities are losing confidence in the reliability of local and traditional Indigenous weather, climate knowledge, and forecasting skills (e.g., Baker 2021; Clark et al. 2016b; Simonee et al. 2021; Slats et al. 2019). With people less able to rely on traditional knowledge and forecasting skills, not surprisingly there is a growing use of weather forecasting services (Simonee et al. 2021) and a greater need for usable, context- and user-relevant WWIC services.

Forecasts and other WWIC information are only of value when they have utility to the users, that is, when they have the capacity to influence people's decisions (Murphy 1993). According to Murphy (1993), a "good forecast" has consistency, quality, and user value. A good forecast also requires useful and comprehensive data and the skillful translation of these data into trustworthy environmental forecasting services; in short, they rely on robust science which, in turn, must have salience, credibility, and legitimacy to be of relevance (Cash et al. 2002, 2006). The latter can only be achieved if we understand the context around people's decision-making and planning in order to discern which information and products are most useful and valuable and how services may be improved (Dilling and Lemos 2011; Dilling et al. 2021; McNie 2007). There are many different operating environments, activities, communities, and user sectors across the polar regions. Beyond the more apparent political, governance, geographic, resourcing, and cultural differences in and between the Arctic and Antarctic, there are also more nuanced and cross-cutting factors that diversify the realm of user contexts. Additionally, how WWIC information is sourced, comprehended, used, and applied in decision-making and risk mitigation is context dependent and unique to each user. Thus, while there are some similarities in the weather parameters needed in the polar regions, the context of people's WWIC information use and their resulting informational needs are highly variable.

Against this backdrop, since its inception in 2015, the Polar Prediction Project's (PPP) Societal and Economic Research Applications (SERA) Task Team has been examining the connections between service providers and polar WWIC users to create a deeper understanding of user decision-making contexts and needs. During the PPP decade, PPP-SERA expanded its membership and contributed multiple studies and projects on WWIC information use, user needs, decision-making, and service provision in the polar regions. In this review and research synthesis, we draw on findings from PPP-SERA work and a bibliometric metareview of the peer-based literature. In addition, the authors' insights and perspectives gained during their own research in the Arctic and Antarctic over the last two decades, as well as their collaborative work on WWIC service provision in the polar regions spanning a decade, informed the interpretation and discussion of the results and synthesis. We examine what we now know about WWIC information use and needs in the polar regions 10 years after the commencement of PPP and explore remaining research gaps.

2. Methods

The PPP-SERA work utilized an overarching transdisciplinary and multimethod approach and drew on several different social science disciplines and contributions from WWIC service delivery experts. PPP-SERA engagement with polar WWIC

service providers and users began with a series of open sessions linked to the group's annual meetings (Ottawa 2015, Christchurch 2016, Fairbanks 2017, The Hague 2018, Punta Arenas 2019, Montreal 2022, and Hobart 2023). See the Polar Prediction (2023) website for reports and further information. We undertook an inductive content analysis of the documents, notes, and summaries from these open sessions, workshops, and conversations with key stakeholders and identified themes, which were further discussed by the authors and refined in an iterative process until agreement was reached. In addition, numerous workshops, surveys, and interviews with polar WWIC users, including community groups, providers, and operators, were organized in the context of projects endorsed by the Year of Polar Prediction (YOPP) and led by various members of our team (e.g., Blair et al. 2020, 2022b; Carter et al. 2023; Carter and Ljubicic 2022; Heinrich and Norris 2023b; Jeuring et al. 2020; Jeuring and Lamers 2021; Jeuring and Knol-Kauffman 2019; Lamers et al. 2018b; Ljubicic and Carter 2023; Ljubicic et al. 2019). This review and research synthesis are informed by conclusions reached through the abovementioned content analysis and endorsed projects and other PPP-SERA research (e.g., Haavisto et al. 2020; Hooghiem 2019; Ljubicic and Carter 2023; Simonee et al. 2021; Stewart et al. 2020; Wilson et al. 2021a,b). In addition to this body of PPP-SERA work, we draw on our field experiences to inform and synthesize findings from a literature review on polar WWIC users to identify themes and research gaps and to develop our summary of the current polar WWIC user needs and services landscape.

Polar WWIC users' literature review

To identify the gaps and progress in our understanding of polar WWIC information use and users, we conducted a systematic search of the peer-reviewed literature produced during the PPP (2013–23). We purposefully restricted this literature search to peer-reviewed scientific articles to minimize subjectivity that is undesirable in selecting other publications (such as conference papers and book chapters). This is a common strategy adopted in other metareviews. Although unpublished and gray literature are included in the discussion and thematic review, only published peer-reviewed articles were included in the bibliometric analysis. Following premises from PPP-SERA workshops (2015–23), for this review, we focused on studies with polar WWIC users (actors/participants) who were living, working, visiting, or recreating in Arctic or Antarctic regions. For the purposes of this review, the polar regions are defined as regions 50°–90°S latitude and 50°–90°N latitude to include the Arctic, subarctic, Antarctic, subantarctic, and Southern Ocean.

1) DATABASE COMPILATION

A database of scholarly literature on the use of WWIC information in the Arctic or Antarctic (or both) (hereafter the "literature review database") was compiled by systematically searching the Scopus, Web of Science, and Arctic and Antarctic regions (AAR via EBSCOhost) databases for publications related to the use or provision of WWIC information in polar regions. The title, abstract, and keywords were searched using the search string shown in Table 1.

TABLE 1. Search string used to retrieve relevant articles in Scopus, Web of Science, and EBSCOhost AAR databases.

weather OR water OR ice OR climate OR forecasting OR sea*
AND
Antarctic* OR Arctic OR Polar OR cryosphere OR circumpolar
AND
(information NEAR/3 use*) OR [(information* OR user* OR communit*) NEAR/5 need*] OR "decision-mak*" OR engagement OR rescue (Topic)
Abstract, title or keywords (timespan: 1 Jan 2013–12 Jul 2023)

The search terms were selected based on iterative practice searches and the first author's previous systematic review search experience. The searches were rerun in July 2023 to identify recent publications. Google Scholar was used to find additional papers, with the search being stopped after five pages of irrelevant results due to low probability of finding additional relevant literature. Additional papers were identified through examination of reference lists, the PPP Google Scholar page (https://scholar.google.de/citations?user=tbR5tOAAAAAJ&hl=en), and the literature and citation records individual PPP-SERA task-team members had on file, resulting in 2359 papers for screening. Papers were screened by title and abstract in "Covidence" by the first author. Microsoft Excel was used for the full text review and data extraction by the first three authors. Papers that did not include the descriptions of how, when, or why people source, use, or need WWIC information and services in the polar regions were excluded. Literature that was not peer-reviewed, English language, or published inside our 2013–23 timeframe was excluded, resulting in the inclusion of 43 papers in our literature review database. Differences on inclusion of papers were resolved through discussion among the first three authors to reach consensus.

2) ANALYSIS

Data extraction and analyses were completed using Microsoft Excel, NVivo, and VOSviewer (van Eck and Waltman 2010). Author networks and keywords and geographic and regional differences were examined in the bibliometric analysis. The collaboration relationships between authors were examined through social network analysis (SNA) and visualization of the coauthor network (Mali et al. 2012; Robins 2015). The coauthorship network was created, visualized, explored, and analyzed using VOSviewer, a software tool for visualizing bibliometric networks (van Eck and Waltman 2010, 2014). NVivo qualitative analysis software was used to analyze word frequencies, paper topics, and content analysis autocoding of themes. Bibliometrics and statistical frequencies were examined in Microsoft Excel. Key themes for the research synthesis and topics from the reviewed papers were thematically, deductively, and inductively analyzed by the first author following Braun and Clarke's (2013) reflective thematic analysis and expanding on themes generated in interviews with Antarctic weather information users (Heinrich and Norris 2023b).

TABLE 2. Number of articles on polar WWIC users published per journal (2013–23).

Polar Geography	9
Conference proceedings peer-reviewed	3
Weather, Climate, and Society	3
Arctic	2
Arctic Science	2
Frontiers in Earth Science	2
Polar Science	2
Bulletin of the American Meteorological Society	1

Research findings from the reviewed papers and literature review database analysis were synthesized, together with the knowledge and experience derived from the authors' and the broader PPP-SERA team's related projects.

3) LIMITATIONS

Limiting this review to English language and peer-reviewed literature means that unpublished studies and gray literature reports of polar WWIC users were not extensively examined. PPP-SERA did not consistently engage with sectors across the two polar regions. Comparative targeted engagement with sectors like tourism, aviation, emergency services, and fishers may provide additional case studies of user contexts and opportunities for citizen science collaborations and contributions to polar WWIC services and research (Meraldi et al. 2022; Robles et al. 2020; Taylor et al. 2020).

3. Results

a. *Bibliometric analysis*

The literature review database papers were published in a range of peer-reviewed journals and conference proceedings, most frequently in *Polar Geography* (special issue) and *Weather, Climate, and Society* (Table 2). In addition, single articles have been published in 20 other journals ranging from polar-specific journals (n = 16) such as *Polar Science* and *Polar Record* to climate-specific journals (n = 5) such as *Nature Climate Change* and *Climate Services* and sector-specific journals (n = 6) such as *Marine Policy* and the *Scandinavian Journal of Hospitality and Tourism*. As Fig. 1 reveals, the highest number of publications was made available in 2020 and 2021. Analyses show a limited spread in geographic locations, sectors, and topics. There were few transpolar studies (4), and only one paper was solely on the Antarctic (Fig. 2). Most papers were focused on the Arctic (38) and nearly half reported on Canadian locations (20). An emphasis on sea ice services over 30 papers (70%) dominated the decade's literature (Fig. 3).

NVivo word frequency count of the title, abstract, and keywords (Fig. 4), text searches, and content analysis autocoding of the paper's significant noun phrases revealed themes dominated by research on sea ice in the Arctic. Studies included participants from multiple roles and sectors, predominantly from communities, service providers, and operations (Fig. 5). Polar WWIC user sectors like aviation, search and rescue, land-based travel, and tourism were underrepresented. The most frequently used methods were interviews, focus groups, and reviews (Fig. 6). Papers that included a theoretical underpinning were limited (2). There were few experiments or studies of human cognition to understand how people process information, function, or think.

COAUTHORSHIP NETWORKS

The VOSviewer overlay visualization of the coauthor networks (Fig. 7) shows the total strength of the coauthorship links with 216 other authors across the literature review database from 2013 to 2023.

Over eight clusters, the largest set of 99 connected authors (48%) included PPP collaborators (centered around Dawson, Ljubicic, and Stewart). The second largest set of connected authors (e.g., Eicken, Bhatt, and Wiggins) reflects a larger body of literature focused on Arctic sea ice and satellite observation services for science. Examination of the author collaboration network across those who published two or more papers during the PPP decade shows 28 authors in three distinct, unconnected clusters, the largest representing 20 authors connected through PPP research (Fig. 8). Within the collaboration networks, Lamers, Ljubicic, Bell, Eicken, and Dawson had the most coauthorship links. PPP-SERA authors had multiple ties, forming a network core. The network visualizations show authors and groups (collaboration clusters) on the periphery of the network and that some authors were isolated with few collaboration ties (e.g., Finnis).

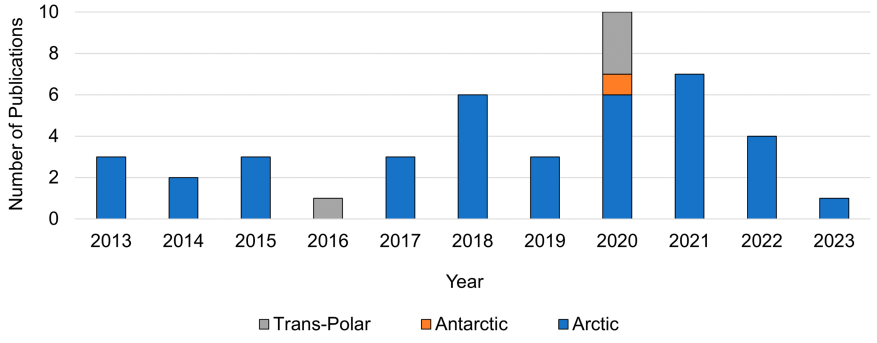

FIG. 1. Number of publications by year during the PPP decade (n = 43). Four discussed both Arctic and Antarctic regions and one was solely Antarctic; the remainder (88%) had an Arctic focus.

FIG. 2. Geographic study regions of the literature review database publications (an article may reference multiple geographic locations).

b. Thematic analysis

Building on Heinrich and Norris (2023b), PPP-SERA sessions, and the insights and expertise obtained by the authors over their careers in polar social science and WWIC services, our review of the polar WWIC users' literature has identified seven key themes around the information needs and factors that influence weather-related decision-making and planning in the polar regions (Fig. 9). We now examine these themes more closely and identify important research gaps.

1) ACTIVITY AND CONTEXT (RISKS, NEEDS, GOALS, PROCEDURES, PRIORITIES, COMFORT, AND SAFETY)

Of the literature review database papers, 30 discussed issues related to sea ice, of which 22 examined sea ice, travel safety, and related specific ice user needs of Arctic communities (e.g., Beaulieu et al. 2023; Bell et al. 2015; Eicken et al. 2014; Kettle et al. 2020; Segal et al. 2020; Wilson et al. 2021a) and sectors with an emphasis on the maritime industry (17) (e.g., Blair et al. 2022b; Rainville et al. 2020; Wagner et al. 2020), indicating limited diversity in the literature review database. Overall, 20 papers focused on WWIC information user needs or services' provision in Arctic communities (Carter et al. 2023; Fox et al. 2020; Panikkar et al. 2018; Simonee et al. 2021), fishing (Finnis et al. 2019; Rezaee et al. 2017), tourism operations (Denstadli and Jacobsen 2014; Lamers et al. 2018a) or in relation to hazard warnings (Abdel-Fattah et al. 2021; Engeset et al. 2018), decision-support tools (Abdel-Fattah et al. 2021; Boström 2018; Kettle et al. 2020; Rainville et al. 2020), terminology (Duerr et al. 2015), and Antarctic operations (Heinrich and Norris 2023b). The reviewed studies and PPP-SERA research highlight how accessibility of WWIC information varied between people (users) and that the knowledge generated, applied, and actioned depended on the context of people's activities and their goals as well as their operational and safety thresholds. Haavisto

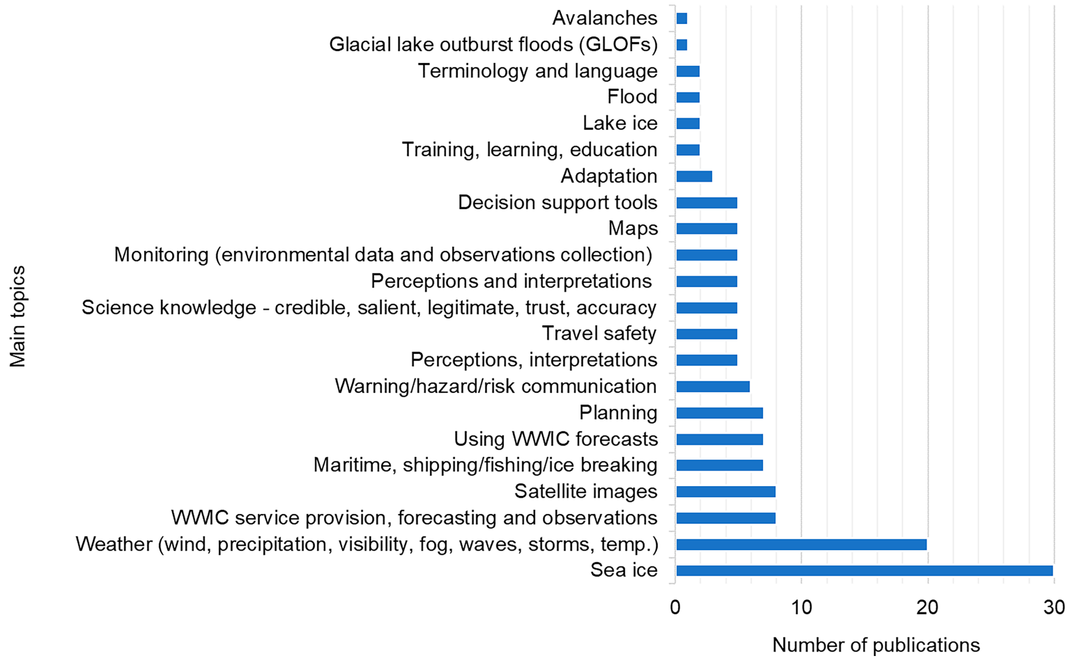

FIG. 3. Main topics of the literature review database publications (an article may discuss multiple topics).

et al. (2020) noted a dominance of WWIC provider focus on services for commercial users and activities, which may, at least in part, have necessitated the development of community-based monitoring approaches to data collection for national weather and climate services, the main topic discussed in other publications (e.g., Bell et al. 2015; Deemer et al. 2018; Eicken et al. 2014).

2) Human factors: Social, behavioral, and cognitive

The human factors theme comprised 31 papers that touched on human behavior, cognition, and individual differences. This included research that examined information use, formats, comprehension, experimental studies, and the influence of cognitive, social, and behavioral factors and nontechnical skills important to successful communication, information processing, and decision-making performance. Papers within this theme discussed avalanche risk factors (Engeset et al. 2018), fisher risk perceptions (Finnis et al. 2019), and community risk perceptions (Heinrich

FIG. 4. Exact matches of word frequency count examining title, abstract, and keywords from the literature review database publications (n = 43; abstracts n = 42, keywords n = 35). The dominant focus on sea ice research and Arctic WWIC users is visible.

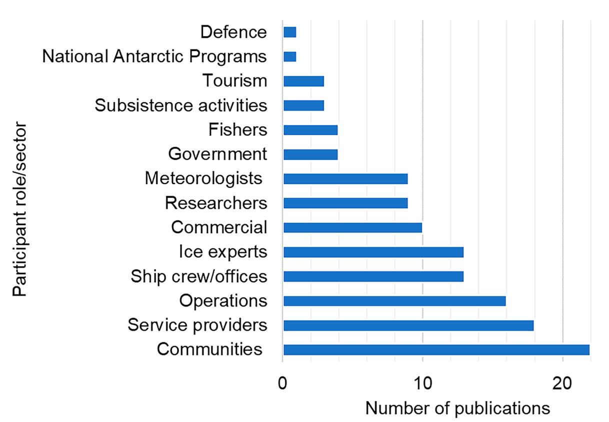

FIG. 5. Participant roles and sectors of the literature review database publications (an article may include participants from multiple roles or sectors).

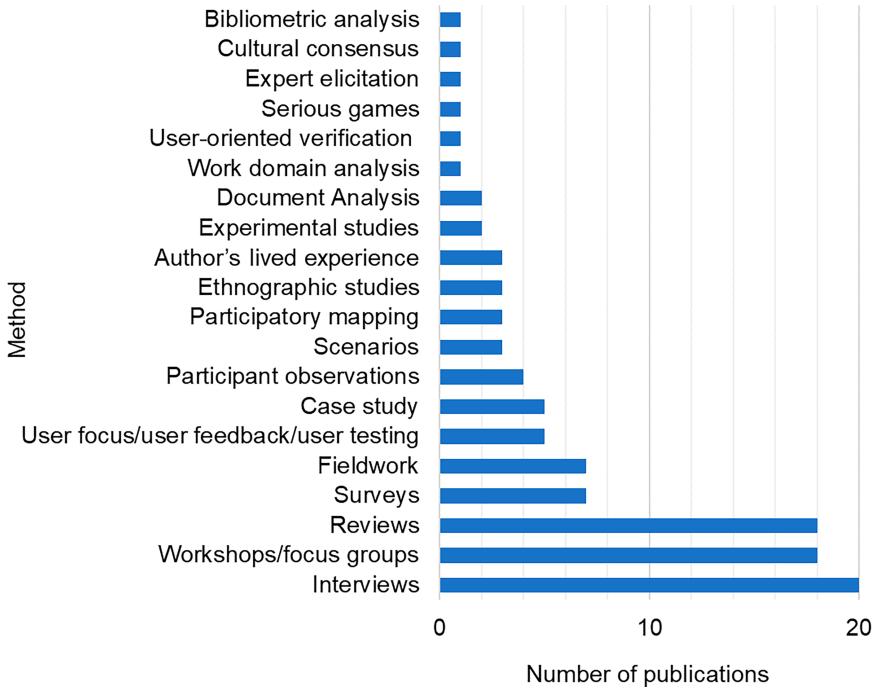

FIG. 6. Methods of the literature review database publications (an article may include multiple methods).

and Norris 2023a; Sawatzky et al. 2021; Simonee et al. 2021). Information content, product format, interpretation, and comprehension were examined by Blair et al. (2022b), Engeset et al. (2018), Segal et al. (2020), and Wilson et al. (2021a,b). Other studies within this theme considered ice terminology, language, and standard format challenges (e.g., Beaulieu et al. 2023; Blair et al. 2022a; Duerr et al. 2015; Fox et al. 2020; Segal et al. 2020; Wilson et al. 2021a); community members' perceptions of climate science (Baztan et al. 2017), cost-benefit, performance, and trust (Blair et al. 2022a); tourists' weather perceptions (Denstadli and Jacobsen 2014; Duerr et al. 2015); and vulnerability (Spinney and Pennesi 2013). Spinney and Pennesi (2013) provide an enlightening case study of why understanding different cultural and community perceptions is important and how misunderstandings may influence perceptions of vulnerability to weather events, media and government actions, and recovery resourcing.

3) INFORMATION SHARING, ADVICE FROM TRUSTED OTHERS, AND DECISION-MAKING AUTHORITY

The 27 papers in the information sharing theme show that in polar communities and operations, the sharing of observations, knowledge, and experience is key to people's ability to adapt to changing conditions and to adjust travel plans and routes to maintain safety and access (Carter et al. 2023; Heinrich and Norris 2023b; Lamers et al. 2018a; Panikkar et al. 2018; Sawatzky et al. 2020; Segal et al. 2020; Simonee et al. 2021; Wilson et al. 2021a). The reviewed papers also illustrate how, within Arctic Indigenous communities, the sharing of environmental observations is culturally significant and a part of the process of passing knowledge from one generation to the next, with information shared for everyone's benefit (Carter et al. 2023; Sawatzky et al. 2021; Wilson et al. 2021a). In the Antarctic, informal mentorship and a culture of safety were identified as realms where more experienced expeditioners, guides, and leaders passed on local knowledge, activity-specific guidance, and hazard information to novices in these transient populations (Heinrich and Norris 2023b). More experienced community members were perceived as more knowledgeable and sought as trusted sources of information and advice (Heinrich and Norris 2023b; Sawatzky et al. 2021). Furthermore, trust was important in the uptake of products, information source choice, advice seeking, knowledge sharing, relationship building, and cooperation for successful outdoor activities and coping with weather events (Baker 2021; Blair et al. 2022a; Finnis and Reid-Musson 2022; Heinrich and Norris 2023b; Sawatzky et al. 2021; Simonee et al. 2021; Spinney and Pennesi 2013; Wilson et al. 2021a). The loss or potential loss of these information and experience-sharing practices, related knowledge, skills, and normative and preventative safety behaviors, along with inexperience and any lack of training or education to make up deficits, increases the risks to people in polar regions, with implications for increased search and rescue incidents and negative community impacts (Boström 2018; Heinrich and Norris 2023b; Kikkert and Lackenbauer 2021; Simonee et al. 2021).

4) SITUATIONAL AWARENESS AND USE OF PERSONAL ENVIRONMENTAL OBSERVATIONS

All polar travel is impacted by and subject to the weather. Therefore, as the 13 papers under this theme showed, situational

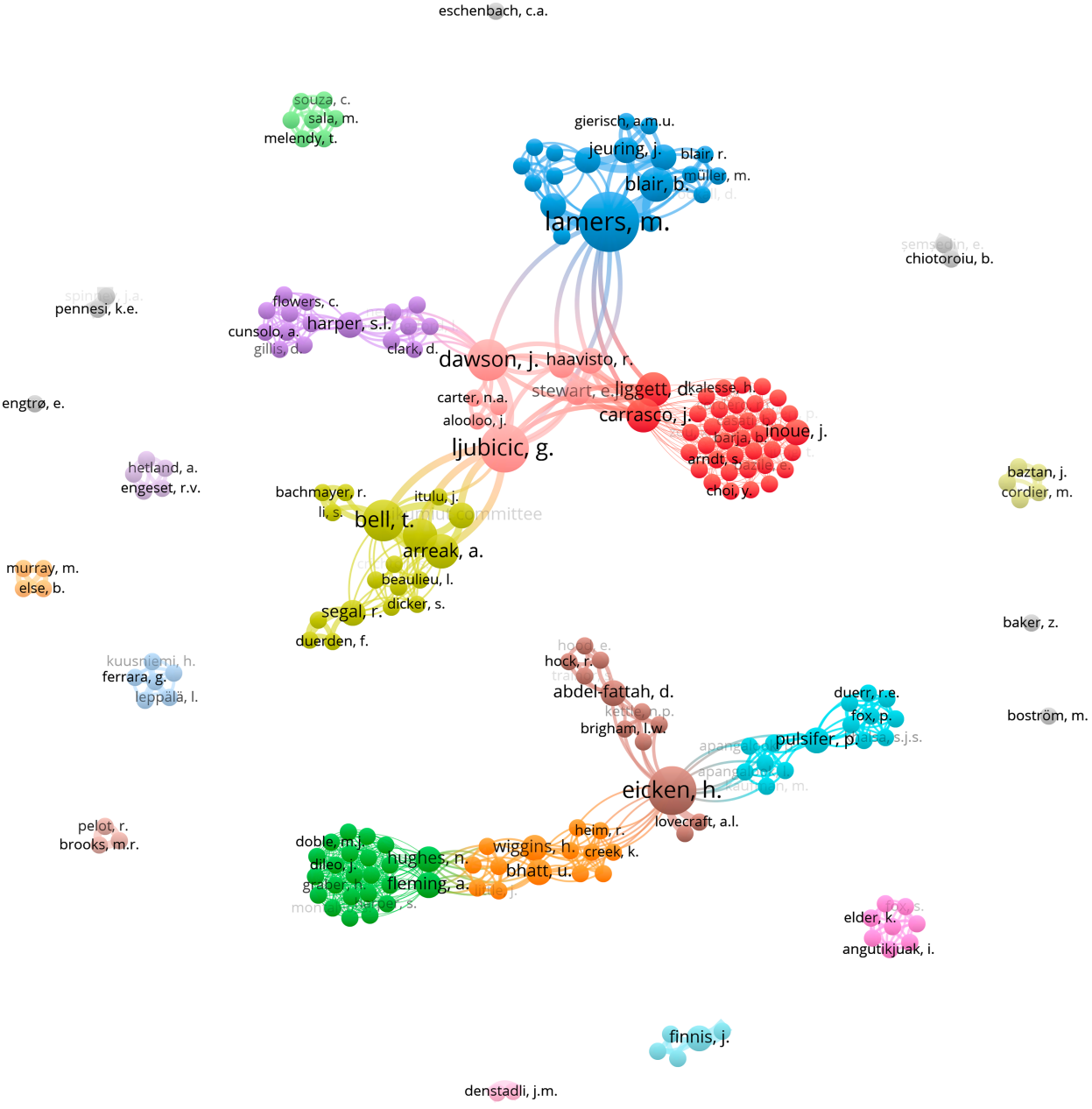

FIG. 7. VOSviewer network visualization of the literature review database coauthorship network; $n = 216$ authors, 99 connected authors, and 24 clusters. Network analysis by number of links (fractionalized weighting) and documents. Individual authors (nodes) are represented by a circle. The curved lines between the circles represent the edges or network ties and show when two authors have coauthored a publication. A thicker line represents a stronger collaboration link. More lines emerging from an author indicate more coauthorship collaborations and greater centrality within the network. Weakly related authors are placed further away from each other, and strongly related authors are located close to each other. A cluster indicates a set of closely related authors. Colors indicate to which research cluster an author belongs. For further explanation of VOSviewer and network visualization features, see van Eck and Waltman (2010, 2014).

awareness (Endsley 1995), i.e., being cognizant of and able to anticipate changing conditions, is important for hazard identification, outdoor activity risk mitigation, comfort, and travel safety in the polar regions (Carter et al. 2023; Heinrich and Norris 2023b; Kettle et al. 2020; Leppala et al. 2019; Rainville et al. 2020; Wilson et al. 2021a,b). For example, proficient situational awareness enables the enactment of protective decisions like being equipped and prepared for adverse (deteriorating) conditions, proactively changing travel routes, undertaking alternative "safer" activities, or stopping early and returning to shelter (Baker 2021; Heinrich and Norris 2023b; Lamers et al. 2018a; Simonee et al. 2021). To inform their situational

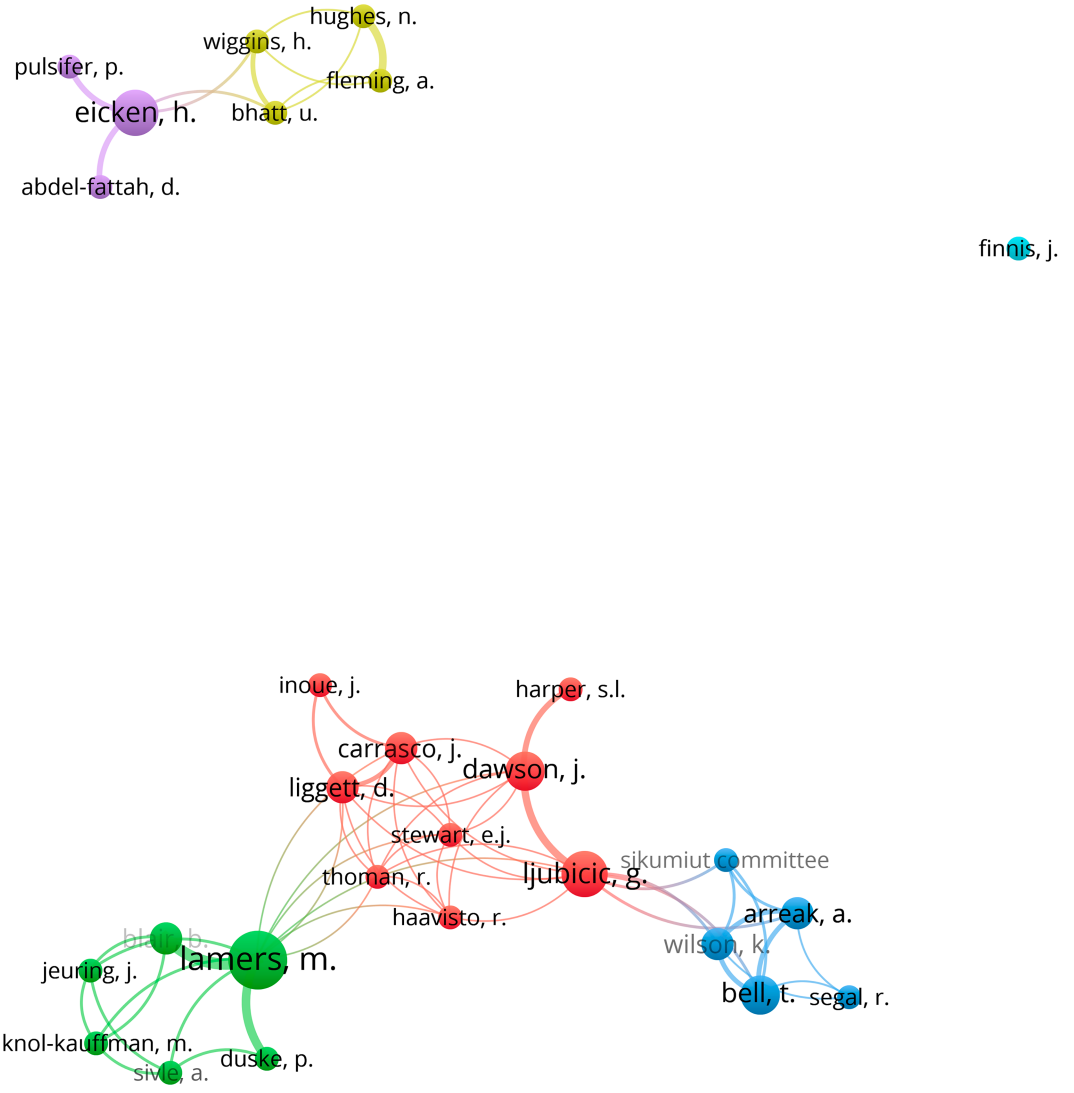

FIG. 8. VOSviewer coauthor network visualization of 28 authors who have two or more publications in the literature review database. The largest set of 20 connected authors reflects the PPP collaboration network. Colors indicate clusters. Larger circles and labels indicate higher author weight (more publications and coauthorship links). Network analysis by number of links (fractionalized weighting) and documents.

awareness, people drew on multiple WWIC information sources, including current real-time weather data, satellite imagery, radar, forecasts, NWP models, ice charts, their experience, personal environmental observations, local knowledge, advice, and observations from others (Carter et al. 2023; Heinrich and Norris 2023b; Panikkar et al. 2018; Rainville et al. 2020; Wagner et al. 2020; Wilson et al. 2021a). For example, in Arctic communities, people use their Indigenous knowledge, community-based monitoring services, and regionally specific, locally generated information [e.g., the mittimatalik siku asijjipallianinga (sea ice climate atlas and sea ice terminology booklet)] to inform their risk assessments, situational awareness, and travel safety (Eicken et al. 2014; Panikkar et al. 2018; Wilson et al. 2021a,b). Studies by Beaulieu et al. (2023), Bell et al. (2015), Blair et al. (2022b), Fox et al. (2020), and Wilson et al. (2021a) among others demonstrate collaborative projects, and training can be successfully developed to provide education and products aimed at improving people's safety.

5) EXPERIENCE, LOCAL KNOWLEDGE, AND TRAINING

The 27 papers under the experience theme highlight the importance of expertise gained through personal experience and local knowledge for risk assessment, decision-making, activities, and safety in polar regions (e.g., Abdel-Fattah et al. 2021; Baker 2021; Beaulieu et al. 2023; Bell et al. 2015; Boström 2018; Engtrø 2022; Finnis and Reid-Musson 2022; Finnis et al. 2019; Heinrich and Norris 2023b; Lamers et al. 2018a; Panikkar et al. 2018; Sawatzky et al. 2021; Stewart et al. 2020; Wilson et al. 2021a) and support similar findings from PPP-SERA

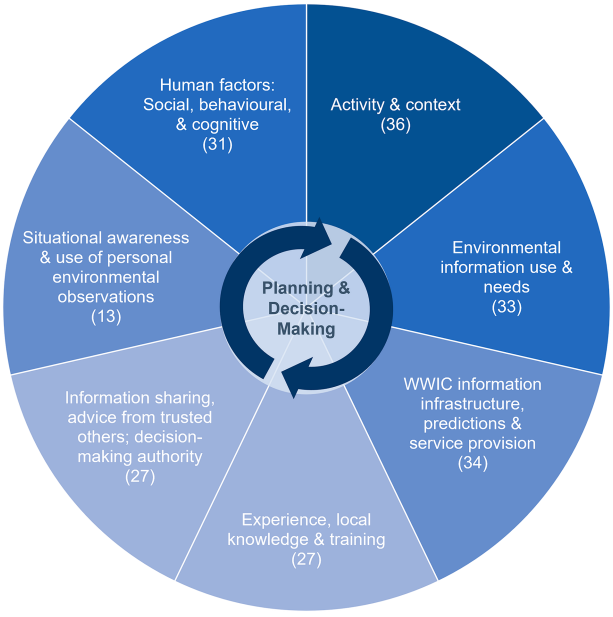

FIG. 9. Key themes, factors, and influences on WWIC information use and related decision-making, cognitions, and behavior in polar regions. Numbers in parentheses indicate the number of publications from the literature review database classified under each theme. Note that papers ($n = 43$) may be classified under multiple themes.

sessions. Furthermore, Kikkert and Lackenbauer (2021), Segal et al. (2020), Simonee et al. (2021), and Villemain and Godon (2017) among others discuss the vulnerability of people who lack the experience (knowledge and skills) to stay safe and successfully problem solve during unexpected events, such as when technology or machinery fails or during adverse conditions. Collectively, the reviewed papers highlight people's needs for actionable risk information, the transfer of local knowledge, skills, and training to develop expertise and support safe activities and to reduce adverse incidents.

6) Environmental information use and needs

Summarizing research from the 33 papers under the environmental information use and needs theme, and supporting findings from PPP-SERA sessions, the most useful weather parameters in the polar regions included wind, visibility, low cloud, precipitation, and sea ice information from forecasts, satellite imagery, and real-time data. Weather-related planning and decision-making occur before and during outdoor activities. This decision-making may be multistaged, use multiple information sources, and be a part of an ongoing, repetitive, and reactive process that accounts for changing conditions, risks, and other pertinent factors (Heinrich and Norris 2023b; Regnier and Feldmeier 2022). Forecasts were often used for planning and scheduling of activities and for finding weather windows, i.e., when conditions were suitable for a long enough time period to conceivably complete specific tasks (Baker 2021; Bromwich et al. 2020; Finnis et al. 2019; Heinrich and Norris 2023b; Inoue 2021; Panikkar et al. 2018; Rainville et al. 2020). However, real-time automatic weather station (AWS) data, personal environmental observations and, when available, satellite imagery and ice charts were equally important and desired for planning, forming and maintaining situational awareness, decision-making, and adapting to changing conditions and safety thresholds (Baker 2021; Carter et al. 2023; Fox et al. 2020; Heinrich and Norris 2023b; Kettle et al. 2020; Knol et al. 2018; Lamers et al. 2018a; Leppala et al. 2019; Panikkar et al. 2018; Segal et al. 2020; Shoop et al. 2015; Simonee et al. 2021; Stewart et al. 2020; Wagner et al. 2020). During PPP-SERA sessions and interviews (Heinrich and Norris 2023b), some polar WWIC users commented that current forecast models and tailored services were "good enough" for their decision-making and planning needs. However, the results of our bibliometric metareview and our joint PPP-SERA experience show that many services were not fit for purpose, with users citing concerns about accessibility, time scales, timeliness, frequency, resolution, data gaps, and the spatial extent of NWP models and real-time observations (see Fig. 10).

From a transpolar perspective, and across different sectors, user needs and activities, wind information (predictions and real-time data) were critically important for safety, forecasting services, risk mitigation, planning, and decision-making (Bromwich et al. 2020; Carter et al. 2023; Heinrich and Norris 2023b; Simonee et al. 2021; Stewart et al. 2020; Wagner et al. 2020). Furthermore, with climate change impacts and wind, ice, and extreme event regime changes, accurate and reliable wind information may become more important to avoiding hazards that negatively impact human safety across many polar activities (Burrows and Mooney 2021; de Freitas and Symon 1987; Ford et al. 2019; Fox et al. 2023; Gultepe et al. 2019; Panagiotidis et al. 2021; Reid and Massom 2022; Rezaee et al. 2017; van Luijk et al. 2022; Waseda et al. 2018; Young and Ribal 2019). Therefore, improving and tailoring wind information provision and services, including real-time automatic weather station data, NWP models, and forecasts to meet actionable knowledge needs, may bring the greatest benefits to many polar WWIC users and service providers.

7) WWIC information infrastructure, predictions, and service provision

WWIC information infrastructure, predictions, and service provision are addressed by 34 papers in our database. The studies underline that, for most polar WWIC users, creators, and providers, the internet is critical for creating, disseminating, sourcing, and sharing WWIC information. However, barriers include knowing where to find information, low bandwidths that limit/slow internet and network data transmission speeds and volumes, no or unreliable internet access, difficulty with interpretability, complexity, formats, languages, and nonpublic availability/commercial constraints, lack of real-time data and maintenance, and need for more frequent updates, weather stations, satellite data, and costs (Boström 2018; Carter et al. 2023; Fox et al. 2023; Heinrich and Norris 2023b; Kettle et al. 2020; Knol et al. 2018; Lamers et al. 2018a; Leppala et al. 2019; Segal et al. 2020; Simonee et al. 2021).

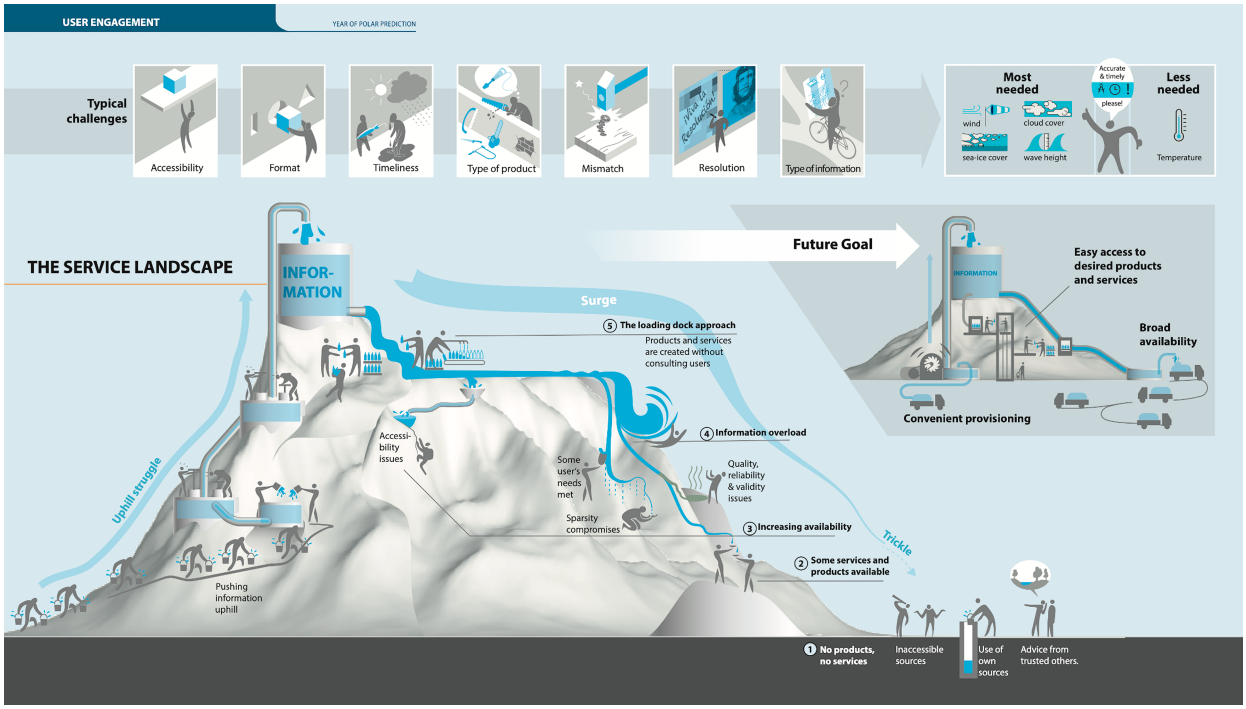

FIG. 10. The current polar WWIC user needs and services landscape: challenges for weather information accessibility and usability (WMO 2022b). Research focused on local engagement and user needs is limited, contributing to a gap and mismatch between the services provided and the services users need and an arguable perpetuation of loading dock approaches (Cash et al. 2006) to science and services' provision that results in a lack of operational WWIC services and ongoing challenges to effective communication, accessibility, and WWIC information use. In the current landscape, weather information and services vary from no products or available services (1) to increasing product availability as we climb the service mountain (2, 3). Near the peak of the mountain (4), despite the many choices and product options, some user needs are still not met, a result of the traditionally applied top-down loading dock approach to service provision (5) (Cash et al. 2006).

Nine studies included meteorologists as participants and offer viewpoints from weather service providers (e.g., Baker 2021; Blair et al. 2022b; Duerr et al. 2015; Finnis and Reid-Musson 2022; Finnis et al. 2019; Jeuring et al. 2020; Kettle et al. 2020). Subthemes included papers describing new decision support tools and systems (e.g., Abdel-Fattah et al. 2021; Inoue 2021; Kettle et al. 2020; Rainville et al. 2020) and Indigenous community–led research projects to develop skills, maps, information, observations, weather station installations, and training to meet local decision-making and travel safety needs (e.g., Beaulieu et al. 2023; Bell et al. 2015; Carter et al. 2023; Fox et al. 2020, 2023; Segal et al. 2020; Simonee et al. 2021; Wilson et al. 2021a,b). Baztan et al. (2017) highlight how sometimes the science produced in the polar regions serves the needs of researchers and academics, not the knowledge requirements of local communities.

4. Discussion

Most of the literature from the last decade focused on sea ice and related polar WWIC user needs and almost entirely explored Arctic contexts, with a scarcity of reported Antarctic research. This aligns with the initial focus of the PPP on economic benefits and service needs of commercial shipping, aviation, and industry users (WMO 2013), and patterns of greater Arctic investment and research publication output (Aksnes and Hessen 2009). Most papers we analyzed were descriptive and discussed specific polar WWIC user activities and information-use contexts and catalogued important weather parameters, decisions, or user needs. Experience, local knowledge, situational awareness, and information sharing were important for decision-making and risk assessments. A few Arctic studies reported one-off user engagement, coproduction, or service development. Other Arctic studies provided in-depth examination of ongoing community research programs developed to meet WWIC user planning, navigation, and travel safety needs and to support traditional ways of life under changing climates.

The coauthorship networks show that the PPP-SERA authors have served as knowledge brokers and connectors. The centrality of the PPP-SERA authors reflects the influence of the PPP as an important initiative facilitating collaboration and that the PPP was influential in launching several key projects such as Enhancing the Saliency of Climate Services for Marine Mobility Sectors in European Arctic Seas (SALIENSEAS) (Blair et al. 2022b), Heinrich's Ph.D., and peer-reviewed publications produced during the PPP decade (e.g., Simonee et al. 2021; Stewart et al. 2020; Wilson et al. 2021a). Some of the authors not connected

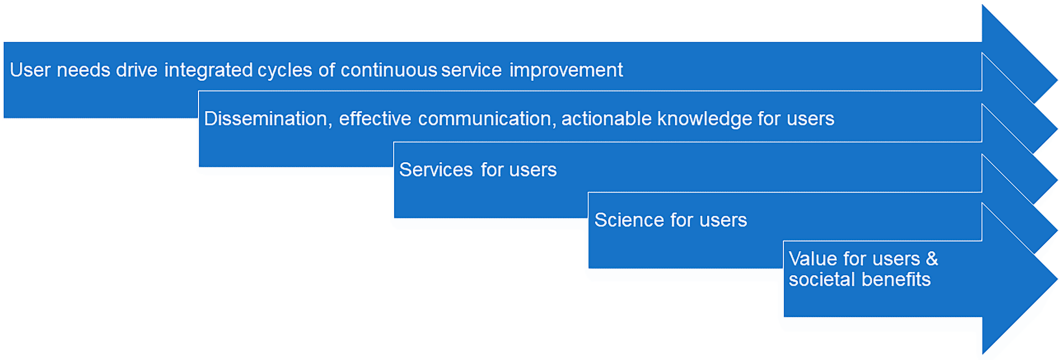

FIG. 11. Ensuring polar WWIC user needs drive resourcing, service improvements, research priorities, and knowledge generation. We reverse the traditional linear value-chain perspective with the purpose of highlighting the importance of starting with an understanding of user needs to inform services and improvements. This is followed by identifying the operational and science/research requirements needed to deliver services that meet these established user needs, such as improved forecasts and real-time data, the flow-on value for users and societal benefits.

to the PPP (e.g., Finnis) represent the knowledge and understandings of user needs from stakeholder groups (e.g., fishers and aviators) whose work was not affiliated with the PPP and emerged in parallel and, to at least some extent, preceded the PPP. Further investigation is required, but unconnected collaboration clusters and isolated authors may indicate where there may be communication challenges within a network and knowledge may not be shared sufficiently (Mali et al. 2012; Robins 2015). These unconnected authors and clusters may provide opportunities for future engagement.

The literature on polar weather information users is in an exploratory phase of development. Our understanding of polar WWIC information use, challenges, barriers, and user needs is growing, but it is geographically incomplete, inconsistent, and lacking depth across locations, sectors, user groups, activity contexts, and topic scope, which we will explore thematically in the following sections.

a. Mismatch of polar WWIC services and user needs

For more than two decades, PPP-SERA research and experiences of PPP-SERA (e.g., Dawson et al. 2017; Stewart et al. 2020), other polar studies (e.g., Council of Managers of National Antarctic Programs 2015; Eicken et al. 2021; Ford et al. 2013; Parsons et al. 2017; Tietsche et al. 2020; Wagner et al. 2020), and the broader weather and climate services literature (e.g., Cash et al. 2002; Dewulf et al. 2020; Lemos et al. 2012; Pielke and Carbone 2002) have highlighted a gap and mismatch between the science, products, and services provided by WWIC researchers and services and the applications and needs of polar WWIC users. Multiple PPP-SERA studies and user-engagement sessions have recurrently found similar themes around the need for incorporating the polar WWIC user context and needs into service provision for planning, decision-making, efficiency, and safety in the polar regions. Synthesizing our findings from PPP-SERA sessions, broader research insights in the field, and the literature review database, we provide a conceptualization of the current polar WWIC user needs and services landscape (Fig. 10), noting that some providers are also users of polar WWIC information (Dawson et al. 2017; Stewart et al. 2020).

The current polar WWIC services landscape includes many users, each with different and individual perceptions, risk tolerances, goals, decision thresholds, and information needs. Service providers are facing challenges to obtain data to produce WWIC information and services, just as polar WWIC users are struggling to access appropriate and usable information and services. Furthermore, Baztan et al. (2017), Ford et al. (2013), and Hooghiem (2019) demonstrated that many polar studies lack local engagement, collecting data primarily for science and research needs. From our experience and associated PPP-SERA work, and supported by findings from the literature review, the experience of many polar WWIC users aligns with top-down or "loading dock approaches to service provision" (Cash et al. 2006). However, we have not yet been able to empirically test this. In the loading dock approach, products and services are developed and "dumped" indiscriminately on polar WWIC users without consultation. There is an unspoken, tacit assumption that new products or services will be salient. In addition, while there may be some consultations with stakeholders, users may still have the perception that they are not involved or that things are dumped on them—i.e., user engagement may be experienced differently by researchers/providers compared to how it is experienced by users.

Reviewed papers detailing successful polar WWIC service development show, in line with recommendations from Cash et al. (2006), Fleming et al. (2023), Gruntfest (2018), Morss et al. (2011), and others, that coproduction methods, engagement, and consultation with users and stakeholders can be integrated into developing new and enhanced observations systems and forecasting services to give the greatest value and benefit to users (public good), especially when spending public funds. Therefore, continuous effort and service improvements are needed, along with a focus on user needs and an understanding of user contexts and value-chain cycles (Dawson et al. 2017; Haupt et al. 2018) (see Fig. 11) to help overcome current top-down models of science and service delivery in pursuit

of the desired future goal of broadly available and easily accessible WWIC information in the polar regions. For most users, WWIC information needs to be readily available to be used in modeling and forecasting or planning and decision-making, and to be accessible, relevant, location-specific, and provided at varying resolutions and time scales across different terminologies, languages, and platforms, at low bandwidth, from verified, transparent sources, and in centralized websites/applications/sources.

b. Need for actionable knowledge

Across the polar regions, individuals, their activities, their goals, and their decision-making processes differ significantly, requiring different types of environmental forecasting information. Products and services that provide actionable knowledge contain information applicable to the different users' contexts (Argyris 1996; Mach et al. 2020). Consequently, actionable knowledge assists users in planning and preparing for their activities as well as informing their risk assessments and hazard avoidance. Environmental forecasting information should be useful, usable, actionable (Lemos 2015; Lemos et al. 2012), timely, and of suitable spatial and temporal scales (Cash et al. 2003; McNie 2007, 2013). Further, it should be perceived as salient, legitimate, and credible (Cash et al. 2002). Additionally, Dewulf et al. (2020) suggest that it is important to include the concepts of consequentiality, appropriateness, and meaningfulness in understanding decision-making support and user needs. Information and services that do not meet user requirements are not delivering their full benefit and value to society (Cash et al. 2006; Murphy 1993; Pielke and Carbone 2002) and could cause more harm than public good (Dilling et al. 2021; McGovern et al. 2022; Pielke 1999).

c. Education and training needs

Heinrich and Norris (2023b) found that there is limited weather-specific training and education of people deployed to Antarctica and training may be focused on topics that are less relevant to learning how to correctly interpret weather information, manage others, and stay safe during outdoor activities (Heinrich and Norris 2023b; Nielsen and Roldan 2023). A reliance on word of mouth, informal mentorship, implicit learning, and previous experience to educate novices dominates. These practices of education and information sharing are unreliable, ad hoc, and subject to corporate knowledge loss in transient populations. The lack of policies and procedures on the gathering, retention, and teaching of organizational and local knowledge specific to a polar location means that novices, unaware of safety norms and local indicators, may be at a greater risk of being ill-equipped and unprepared in dangerous conditions.

Similarly, in the Arctic, a lack of local knowledge and education is implicated in adverse incidents that required search and rescue services (Durkalec et al. 2014). Some Arctic communities have successfully expanded environmental monitoring to meet community information needs (Beaulieu et al. 2023; Bell et al. 2015; Fox et al. 2020) and have established programs for developing relevant decision-support tools, training, and education for travel safety, traditional practices, and subsistence hunting (Beaulieu et al. 2023; Carter et al. 2023; Fox et al. 2020; Panikkar et al. 2018; Sawatzky et al. 2021; Segal et al. 2020; Simonee et al. 2021; Wilson et al. 2021a). Under growing impacts from climate change and prolonged severe weather events, preparedness, training, WWIC services, and capacity building are critical to community resilience and adaptation (Fox et al. 2023). Simonee et al. (2021) recommended formalized training of community members to develop local, tailored meteorological services that are relevant and inclusive of local communities, their activities, and contexts.

d. Importance of tailored services

Polar WWIC users can feel overloaded with information and choices and may become overstretched and time-constrained in trying to balance information needs, safety, and daily tasks (Jeuring et al. 2020; Lamers et al. 2018b), underscoring the importance of providing tailored services. An inaccurate source that is trusted and used, or information that is incorrectly interpreted or misunderstood, may lead to accidents and incidents when conditions, hazards, and associated risks are not as the user expected (Pielke and Carbone 2002; Pielke 1999). In the circumstances of too many products and choices, knowledge brokers such as local, trusted meteorologists or other forecast service providers can help curate and select the most suitable and usable information sources (Heinrich and Norris 2023b; Simonee et al. 2021). Another role of meteorologists when providing tailored (often in-person) weather briefings includes conveying and discussing the likelihood of different weather forecast scenarios for specific activities and the variation or uncertainty in the forecast and NWP models (V. J. Heinrich 2013, 2015, 2019, personal observation). However, most polar WWIC users do not have access to tailored products, decision-support services, or a local meteorologist. When local knowledge brokers are not present, concerns around quantifying uncertainty, contradictory information sources, inconsistency, and trust may emerge, and questions of quality, reliability, and validity and safety, value, and public good are likely to arise.

e. Gaps and future research directions

There is a gap in the diversity of studies needed to broadly understand the complex WWIC needs of polar communities and their activities including the related decision-making, cognitions, and behaviors, as well as their regional focus, with a dearth of Antarctic knowledge. Although some national Antarctic programs receive tailored WWIC services, little is known about the sufficiency, efficacy, and usability of these services, or the needs of other users and sectors (e.g., tourism, fisheries, search and rescue) operating in these high-risk environments (Dawson et al. 2017; Heinrich and Norris 2023b). Furthermore, not all types of polar communities, sectors, or activities were subject to examination in the reviewed scholarly literature or engaged by PPP. Research to inform our understanding of WWIC information needs, use, and decision-making in warning systems, risk communication, disaster risk reduction, aviation, or land-based transport and activities were limited.

Future studies investigating the expertise, skills, and knowledge required for safe and successful activities, people's education needs, and related training requirements and suitable programs, are needed.

Experience, risk perception, social norms, and trust, along with other psychosocial factors may help explain why people use (or do not use) a particular weather information source and their choices, behaviors, and decision errors in response to WWIC information and warnings (Demuth et al. 2016; Paton 2019; Weinstein 1989; Wiggins and O'Hare 1995). However, few publications examined cognitive, social, or behavioral factors that influenced comprehension, use, decision-making, preparedness, information sharing, and situational awareness or related processes. The role played by new technologies, formats, accessibility, and psychosocial (human) factors on information use, planning, and decision-making remains largely unclear in polar contexts, and more research is needed. These gaps contribute to the challenges experienced by polar WWIC users and negatively impact providers' capabilities to effectively disseminate and communicate WWIC information, provide actionable knowledge, or support improved decision-making, operational efficiency, and safety.

Competing provider and stakeholder interests and existing territorial boundaries and institutional constraints mean that without strategic governance, there may be a lack of motivation or incentives to share environmental data that may service multiple interests or users (Lovecraft et al. 2013). Thus, there is a need for further research to understand international and regional provider–user landscapes, governance, and barriers to equitable and accessible service provision and to support United Nations (UN) initiatives like Early Warning Services for All (WMO 2022a). Additionally, limited cross- or interdisciplinary collaborations (Taylor 2002; Tejedo et al. 2014) and funding structures (Overland and Sovacool 2020) may impact research output and require further exploration in the polar WWIC services' context.

The coauthorship networks examined in this review contribute to knowledge of the collaborative social structure of science in the polar regions and the PPP, and they help to understand the processes of knowledge creation and flow (Mali et al. 2012). However, we still do not fully understand the full value of targeted research programs, such as the PPP, longitudinal research, community-based research partnerships, and collaborative research groups.

Future research could build on Cash et al.'s (2006) loading dock framework of service provision to study processes of user-oriented WWIC services and to inform successful and sustainable service infrastructures. More research is needed to understand the contexts in which providing access in real time to weather observations adds value, and where a lack of observations negatively impacts polar WWIC users, operators, and service providers, beyond considerations of modeling verification and reanalysis improvements (e.g., Sandu et al. 2021) or biological monitoring foci (e.g., Cary and Cummings 2020). In addition, future research could further investigate polar value chains and the value of multipurpose data, such as the use of automatic weather station data in real-time decision-making, NWP model assimilation, and forecasting services, if maintained, long-term climate and research datasets.

Overall, there is a continued need for greater interdisciplinarity, more specific science, and for collaborations to develop services that meet polar WWIC user needs, are fit for purpose, and overcome ongoing service challenges and gaps. Opportunities, resourcing (funding), and mechanisms are needed for social scientists and local communities to engage in ongoing research with different sectors and providers. Future research could promote the translation of science into user services, focusing not just on "science to operations" (e.g., Calhoun et al. 2021; Serafin et al. 2002) but delivering science for services that meet user needs. Thus, we support recommendations that research and services development be prioritized from the perspective of the user and their WWIC information and actionable knowledge needs, particularly for future research programs like the WMO's World Weather Research Programme's (WWRP) new Polar Coupled Analysis and Prediction for Services (PCAPS) project. Bringing this together in Fig. 11, we depict how a focus on outcomes for users may help to overcome challenges in the current WWIC services landscape and more broadly guide significant service improvements for all polar WWIC users.

5. Conclusions

This synthesis of the last decade's literature on polar WWIC users, informed by our PPP-SERA knowledge, helps to build our understanding of polar weather information use and the current polar WWIC user needs and services landscape and clarifies where gaps remain. Our research shows that some polar WWIC services are presently not fit for purpose in all contexts, and in many instances, there is a mismatch between user needs and the services provided.

Our findings show that reliable and usable weather and sea ice services are highly desired by polar WWIC users and are increasingly important to climate change–impacted communities. Extension of forecast lead times, along with subseasonal and seasonal outlooks, may be useful to polar WWIC users, but due to the uncertainty and errors in models, with a few exceptions, these are still in the purview of researchers rather than routine services provided to users (Blair et al. 2022b; Inoue 2021; Jung et al. 2016; Wagner et al. 2020). As ice and seasonal models become more reliable, accurate, and usable for operational and tactical decision-making, early engagement with users and strategic application of coproduction methods will be valuable in developing these products and services in a way that meets WWIC user needs and applications across polar contexts.

PPP-SERA has built on the polar work initiated with THORPEX (Parsons et al. 2017) and joins calls over the last 30 years to draw on social and behavioral science approaches for a greater understanding and application of WWIC services to user needs (Demuth et al. 2007; Morss et al. 2008, 2011; Murphy 1993; National Academies of Sciences, Engineering, and Medicine 2018; Parsons et al. 2017; Pielke 1997). During the PPP, we have shown the applicability and depth of understanding that can be developed through using transdisciplinary studies utilizing multiple methods to better understand polar WWIC use and needs.

While this paper is an assessment of achievements during the PPP decade, it is also a reflection on the challenges, barriers, and constraints that users and providers still face in providing, accessing, and using fit for purpose polar WWIC information services. We have a robust understanding about the information and services needed by polar WWIC users, but more investment, work, and collaboration are needed. We are only beginning to shift the focus to the tailoring of polar WWIC services to meet user needs and the production of context-sensitive information, and there is still a long way to go to provide improved services. There is a clear need and requirement to facilitate the translation of PPP-SERA findings and related research to operations and weather service providers and to build links for codesign and coproduction efforts.

To reiterate Serafin et al. (2002), in moving forward to realize the legacy of PPP, it is important to ensure that knowledge is transferred and research is integrated into WWIC services and forecasting operations in a timely manner. Next steps for national service providers, the WMO, and stakeholder communities include developing and maintaining observational monitoring networks, a deeper understanding of user contexts, and products and services that meet these diverse polar WWIC user needs. This may be achieved through investment, cross-disciplinary research collaboration, cofunding, and continued user engagement partnerships. Polar WWIC user needs will continue to expand and shift under climate change and as activities and operations intensify and diversify, whether they are government, scientific research, community or commercial, and whether they relate to Antarctic, Arctic, or transpolar operations. Meaningful polar WWIC user engagement is required to understand, adapt, and tailor services to evolving user needs. Ongoing improvement of polar WWIC services and generating broader knowledge of weather-related decision-making through research across many different disciplines, methods, actors, decision contexts, locations, and case studies are therefore warranted.

As we consolidate PPP and implement WMO's WWRP PCAPS, we once more highlight the priority for interaction and coproduction between researchers, providers, and users to ensure usable, actionable knowledge for WWIC services in our fragile polar regions. We hope that such efforts will continue to develop and inspire the tailoring of much-needed WWIC services for people who call the polar regions home and for people who travel there for work or pleasure.

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Data availability statement. Data are available on request from the authors.

REFERENCES

Abdel-Fattah, D., S. Trainor, E. Hood, R. Hock, and C. Kienholz, 2021: User engagement in developing use-inspired glacial lake outburst flood decision support tools in Juneau and the Kenai Peninsula, Alaska. *Front. Earth Sci.*, **9**, 635163, https://doi.org/10.3389/feart.2021.635163.

Aksnes, D. W., and D. O. Hessen, 2009: The structure and development of polar research (1981–2007): A publication-based approach. *Arct. Antarct. Alp. Res.*, **41**, 155–163, https://doi.org/10.1657/1938-4246-41.2.155.

Argyris, C., 1996: Actionable knowledge: Design causality in the service of consequential theory. *J. Appl. Behav. Sci.*, **32**, 390–406, https://doi.org/10.1177/0021886396324004.

Baker, Z., 2021: Anticipatory culture in the Bering Sea: Weather, climate, and temporal dissonance. *Wea. Climate Soc.*, **13**, 783–795, https://doi.org/10.1175/WCAS-D-21-0066.1.

Baztan, J., M. Cordier, J.-M. Huctin, Z. Zhu, and J.-P. Vanderlinden, 2017: Life on thin ice: Insights from Uummannaq, Greenland for connecting climate science with Arctic communities. *Polar Sci.*, **13**, 100–108, https://doi.org/10.1016/j.polar.2017.05.002.

Beaulieu, L., and Coauthors, 2023: Indigenous self-determination in cryospheric science: The Inuit-led *Sikumik Qaujimajjuti* ("tools to know how the ice is") program in Inuit Nunangat, Canada. *Front. Earth Sci.*, **11**, 1076774, https://doi.org/10.3389/feart.2023.1076774.

Bell, T., R. Briggs, R. Bachmayer, and S. Li, 2015: Augmenting Inuit knowledge for safe sea-ice travel—The SmartICE information system. *2014 Oceans–St. John's*, St. John's, NL, Canada, Institute of Electrical and Electronics Engineers, 1–9, https://doi.org/10.1109/OCEANS.2014.7003290.

Blair, B., O. A. Lee, and M. Lamers, 2020: Four paradoxes of the user-provider interface: A responsible innovation framework for sea ice services. *Sustainability*, **12**, 448, https://doi.org/10.3390/su12020448.

——, A. M. U. Gierisch, J. Jeuring, S. M. Olsen, and M. Lamers, 2022a: Mind the gap! A consensus analysis of users and producers on trust in new sea ice information products. *Climate Serv.*, **28**, 100323, https://doi.org/10.1016/j.cliser.2022.100323.

——, M. Müller, C. Palerme, R. Blair, D. Crookall, M. Knol-Kauffman, and M. Lamers, 2022b: Coproducing sea ice predictions with stakeholders using simulation. *Wea. Climate Soc.*, **14**, 399–413, https://doi.org/10.1175/WCAS-D-21-0048.1.

Boström, M., 2018: Breaking the ice: A work domain analysis of icebreaker operations. *Cognit. Technol. Work*, **20**, 443–456, https://doi.org/10.1007/s10111-018-0482-2.

Braun, V., and V. Clarke, 2013: *Successful Qualitative Research: A Practical Guide for Beginners*. SAGE Publications, 400 pp.

Bromwich, D. H., and Coauthors, 2020: The Year of Polar Prediction in the Southern Hemisphere (YOPP-SH). *Bull. Amer. Meteor. Soc.*, **101**, E1653–E1676, https://doi.org/10.1175/BAMS-D-19-0255.1.

Brubaker, M. Y., J. N. Bell, J. E. Berner, and J. A. Warren, 2011: Climate change health assessment: A novel approach for Alaska Native communities. *Int. J. Circumpolar Health*, **70**, 266–273, https://doi.org/10.3402/ijch.v70i3.17820.

Burrows, W. R., and C. J. Mooney, 2021: Blizzard conditions in the Canadian Arctic: Observations and automated products

for forecasting. *Wea. Forecasting*, **36**, 1113–1129, https://doi.org/10.1175/WAF-D-20-0077.1.

Calhoun, K. M., K. L. Berry, D. M. Kingfield, T. Meyer, M. J. Krocak, T. M. Smith, G. Stumpf, and A. Gerard, 2021: The Experimental Warning Program of NOAA's Hazardous Weather Testbed. *Bull. Amer. Meteor. Soc.*, **102**, E2229–E2246, https://doi.org/10.1175/BAMS-D-21-0017.1.

Carter, N., and G. J. Ljubicic, 2022: Weather and society workshop report: October 2022. 72 pp., https://straightupnorth.files.wordpress.com/2022/10/weather-society_oct2022-report.pdf.

——, C. Buttle, G. J. Ljubicic, R. Sinclair, and E. Paquette, 2023: Nunavut results of a community survey on environmental forecasting uses and needs. 93 pp., https://straightupnorth.files.wordpress.com/2023/12/english_2023_nunavut-wwic_report_dec5.pdf.

Cary, C., and V. Cummings, 2020: Antarctic Near-shore and Terrestrial Observation System (ANTOS) 2018–2020 report. 6 pp., https://scar.org/~documents/scar-meeting-papers/xxxvi-scar-delegates-2021-online/sub-group-reports-2021/antos-expert-group-report-2020?layout=default.

Cash, D., W. C. Clark, F. Alcock, N. M. Dickson, N. Eckley, and J. Jäger, 2002: Salience, credibility, legitimacy and boundaries: Linking research, assessment and decision making. KSG Working Papers Series RWP02-046, 26 pp., http://nrs.harvard.edu/urn-3:HUL.InstRepos:32067415.

Cash, D. W., W. C. Clark, F. Alcock, N. M. Dickson, N. Eckley, D. H. Guston, J. Jäger, and R. B. Mitchell, 2003: Knowledge systems for sustainable development. *Proc. Natl. Acad. Sci. USA*, **100**, 8086–8091, https://doi.org/10.1073/pnas.1231332100.

——, J. C. Borck, and A. G. Patt, 2006: Countering the loading-dock approach to linking science and decision making. *Sci. Technol. Hum. Values*, **31**, 465–494, https://doi.org/10.1177/0162243906287547.

Casner, S. M., M. P. Murphy, E. C. Neville, and M. R. Neville, 2012: Pilots as weather briefers: The direct use of aviation weather products by general aviation pilots. *Int. J. Aviat. Psychol.*, **22**, 367–381, https://doi.org/10.1080/10508414.2012.718241.

Clark, D. G., J. D. Ford, L. Berrang-Ford, T. Pearce, S. Kowal, and W. A. Gough, 2016a: The role of environmental factors in search and rescue incidents in Nunavut, Canada. *Public Health*, **137**, 44–49, https://doi.org/10.1016/j.puhe.2016.06.003.

——, ——, T. Pearce, and L. Berrang-Ford, 2016b: Vulnerability to unintentional injuries associated with land-use activities and search and rescue in Nunavut, Canada. *Soc. Sci. Med.*, **169**, 18–26, https://doi.org/10.1016/j.socscimed.2016.09.026.

Council of Managers of National Antarctic Programs, 2015: COMNAP sea ice challenges workshop. COMNAP Workshop Rep., 37 pp., https://www.comnap.aq/s/COMNAP_Sea_Ice_Challenges_BKLT_Web_Final_Dec2015.pdf.

Dawson, J., and Coauthors, 2017: Navigating weather, water, ice and climate information for safe polar mobilities. WMO Tech. Rep. WWRP/PPP 5-2017, 84 pp., https://epic.awi.de/id/eprint/46211/1/012_WWRP_PPP_No_5_2017_11_OCT.pdf.

Deemer, G. J., and Coauthors, 2018: Broadening the sea-ice forecaster toolbox with community observations: A case study from the northern Bering Sea. *Arct. Sci.*, **4**, 42–70, https://doi.org/10.1139/as-2016-0054.

de Freitas, C. R., and L. V. Symon, 1987: A bioclimatic index of human survival times in the Antarctic. *Polar Rec.*, **23**, 651–659, https://doi.org/10.1017/S0032247400008354.

Demuth, J. L., E. Gruntfest, R. E. Morss, S. Drobot, and J. K. Lazo, 2007: WAS*IS: Building a community for integrating meteorology and social science. *Bull. Amer. Meteor. Soc.*, **88**, 1729–1738, https://doi.org/10.1175/BAMS-88-11-1729.

——, R. E. Morss, J. K. Lazo, and C. Trumbo, 2016: The effects of past hurricane experiences on evacuation intentions through risk perception and efficacy beliefs: A mediation analysis. *Wea. Climate Soc.*, **8**, 327–344, https://doi.org/10.1175/WCAS-D-15-0074.1.

Denstadli, J. M., and J. K. S. Jacobsen, 2014: More clouds on the horizon? Polar tourists' weather tolerances in the context of climate change. *Scand. J. Hospitality Tourism*, **14**, 80–99, https://doi.org/10.1080/15022250.2014.886096.

Dewulf, A., N. Klenk, C. Wyborn, and M. C. Lemos, 2020: Usable environmental knowledge from the perspective of decision-making: The logics of consequentiality, appropriateness, and meaningfulness. *Curr. Opin. Environ. Sustainability*, **42**, 1–6, https://doi.org/10.1016/j.cosust.2019.10.003.

Dilling, L., and M. C. Lemos, 2011: Creating usable science: Opportunities and constraints for climate knowledge use and their implications for science policy. *Global Environ. Change*, **21**, 680–689, https://doi.org/10.1016/j.gloenvcha.2010.11.006.

——, ——, and N. Singh, 2021: Commentary: First, do no harm: Scaling usable knowledge for just and equitable outcomes. *Global Environ. Change*, **71**, 102404, https://doi.org/10.1016/j.gloenvcha.2021.102404.

Duerr, R. E., and Coauthors, 2015: Formalizing the semantics of sea ice. *Earth Sci. Inform.*, **8**, 51–62, https://doi.org/10.1007/s12145-014-0177-z.

Durkalec, A., C. Furgal, M. W. Skinner, and T. Sheldon, 2014: Investigating environmental determinants of injury and trauma in the Canadian north. *Int. J. Environ. Res. Public Health*, **11**, 1536–1548, https://doi.org/10.3390/ijerph110201536.

Eicken, H., M. Kaufman, I. Krupnik, P. Pulsifer, L. Apangalook, P. Apangalook, W. Weyapuk, and J. Leavitt, 2014: A framework and database for community sea ice observations in a changing Arctic: An Alaskan prototype for multiple users. *Polar Geogr.*, **37**, 5–27, https://doi.org/10.1080/1088937X.2013.873090.

——, and Coauthors, 2021: Connecting top-down and bottom-up approaches in environmental observing. *BioScience*, **71**, 467–483, https://doi.org/10.1093/biosci/biab018.

Endsley, M. R., 1995: Measurement of situation awareness in dynamic systems. *Hum. Factors*, **37**, 65–84, https://doi.org/10.1518/001872095779049499.

Engeset, R. V., G. Pfuhl, M. Landrø, A. Mannberg, and A. Hetland, 2018: Communicating public avalanche warnings—What works? *Nat. Hazards Earth Syst. Sci.*, **18**, 2537–2559, https://doi.org/10.5194/nhess-18-2537-2018.

Engtrø, E., 2022: A discussion on the implementation of the Polar Code and the STCW Convention's training requirements for ice navigation in polar waters. *J. Transp. Secur.*, **15**, 41–67, https://doi.org/10.1007/s12198-021-00241-7.

Finnis, J., and E. Reid-Musson, 2022: Managing weather & fishing safety: Marine meteorology and fishing decision-making from a governance and safety perspective. *Mar. Policy*, **142**, 105120, https://doi.org/10.1016/j.marpol.2022.105120.

——, J. W. Shewmake, B. Neis, and D. Telford, 2019: Marine forecasting and fishing safety: Improving the fit between forecasts and harvester needs. *J. Agromedicine*, **24**, 324–332, https://doi.org/10.1080/1059924X.2019.1639576.

Fleming, A., and Coauthors, 2023: Perceptions of co-design, co-development and co-delivery (Co-3D) as part of the co-production process—Insights for climate services. *Climate Serv.*, **30**, 100364, https://doi.org/10.1016/j.cliser.2023.100364.

Ford, J. D., M. Knight, and T. Pearce, 2013: Assessing the 'usability' of climate change research for decision-making: A case study of the Canadian international polar year. *Global Environ. Change*, **23**, 1317–1326, https://doi.org/10.1016/j.gloenvcha.2013.06.001.

——, D. Clark, T. Pearce, L. Berrang-Ford, L. Copland, J. Dawson, M. New, and S. L. Harper, 2019: Changing access to ice, land and water in Arctic communities. *Nat. Climate Change*, **9**, 335–339, https://doi.org/10.1038/s41558-019-0435-7.

Fox, S., E. Qillaq, I. Angutikjuak, D. J. Tigullaraq, R. Kautuk, H. Huntington, G. E. Liston, and K. Elder, 2020: Connecting understandings of weather and climate: Steps towards co-production of knowledge and collaborative environmental management in Inuit Nunangat. *Arct. Sci.*, **6**, 267–278, https://doi.org/10.1139/as-2019-0010.

——, A. Crawford, M. McCrystall, J. Stroeve, J. Lukovich, N. Loeb, J. Natanine, and M. Serreze, 2023: Extreme Arctic weather and community impacts in Nunavut: A case study of one winter's storms and lessons for local climate change preparedness. *Wea. Climate Soc.*, **15**, 881–892, https://doi.org/10.1175/WCAS-D-23-0006.1.

Gruntfest, E., 2018: *Weather and Society: Toward Integrated Approaches*. Wiley, 232 pp.

Gudmundsson, G. H., F. S. Paolo, S. Adusumilli, and H. A. Fricker, 2019: Instantaneous Antarctic ice sheet mass loss driven by thinning ice shelves. *Geophys. Res. Lett.*, **46**, 13 903–13 909, https://doi.org/10.1029/2019GL085027.

Gultepe, I., and Coauthors, 2019: A review of high impact weather for aviation meteorology. *Pure Appl. Geophys.*, **176**, 1869–1921, https://doi.org/10.1007/s00024-019-02168-6.

Haavisto, R., M. Lamers, R. Thoman, D. Liggett, J. Carrasco, J. Dawson, G. Ljubicic, and E. Stewart, 2020: Mapping weather, water, ice and climate (WWIC) information providers in polar regions: Who are they and who do they serve? *Polar Geogr.*, **43**, 120–138, https://doi.org/10.1080/1088937X.2019.1707320.

Haupt, S. E., and Coauthors, 2018: Building the Sun4Cast System: Improvements in solar power forecasting. *Bull. Amer. Meteor. Soc.*, **99**, 121–136, https://doi.org/10.1175/BAMS-D-16-0221.1.

Heinrich, V. J., and K. Norris, 2023a: Is it cold? Is it windy? Is it dangerous? Exploring people's perceptions of risk in extreme environments. School of Psychological Sciences, University of Tasmania, 49 pp.

——, and ——, 2023b: Situational awareness and safety: Using weather information to inform decision-making in extreme environments. School of Psychological Sciences, University of Tasmania, 44 pp.

Hooghiem, M., 2019: User-engagement in developing improved weather information, predictions and forecasting services in the Arctic: Conceptualizing users, identifying levels of user-engagement and conceptualizing challenges in user-engagement in the context of the Year of Polar Prediction. M.S. thesis, Dept. of Environmental Policy, Wageningen University, 80 pp., https://edepot.wur.nl/504777.

Inoue, J., 2021: Review of forecast skills for weather and sea ice in supporting Arctic navigation. *Polar Sci.*, **27**, 100523, https://doi.org/10.1016/j.polar.2020.100523.

Jeuring, J., and M. Knol-Kauffman, 2019: Mapping weather, water, ice and climate knowledge & information needs for maritime activities in the Arctic. Survey Rep., 44 pp., https://hdl.handle.net/10037/16508.

——, and M. Lamers, 2021: Towards useful forms of co-production in metocean services for the European Arctic: PPP-SERA Special Services Workshop Rep., 32 pp., https://www.polarprediction.net/fileadmin/user_upload/www.polarprediction.net/Home/Meetings/Reports/Towards_useful_forms_of_co-production_in_metocean_services_for_the_European_Arctic.pdf.

——, M. Knol-Kauffman, and A. Sivle, 2020: Toward valuable weather and sea-ice services for the marine Arctic: Exploring user–producer interfaces of the Norwegian Meteorological Institute. *Polar Geogr.*, **43**, 139–159, https://doi.org/10.1080/1088937X.2019.1679270.

Jung, T., and Coauthors, 2016: Advancing polar prediction capabilities on daily to seasonal time scales. *Bull. Amer. Meteor. Soc.*, **97**, 1631–1647, https://doi.org/10.1175/BAMS-D-14-00246.1.

Kettle, N. P., D. Abdel-Fattah, A. R. Mahoney, H. Eicken, L. W. Brigham, and J. Jones, 2020: Linking Arctic system science research to decision maker needs: Co-producing sea ice decision support tools in Utqiaġvik, Alaska. *Polar Geogr.*, **43**, 206–222, https://doi.org/10.1080/1088937X.2019.1707318.

Kikkert, P., and P. W. Lackenbauer, 2021: "A great investment in our communities": Strengthening Nunavut's whole-of-society search and rescue capabilities. *Arctic*, **74**, 258–275, https://doi.org/10.14430/arctic73099.

Klein, R. A., 2010: Cruises and bruises: Safety, security and social issues on polar cruises. *Cruise Tourism in Polar Regions*, 1st ed. M. Luck, P. T. Maher, and E. J. Stewart, Eds., Routledge, 83–100.

Knol, M., P. Arbo, P. Duske, S. Gerland, M. Lamers, O. Pavlova, A. D. Sivle, and S. Tronstad, 2018: Making the Arctic predictable: The changing information infrastructure of Arctic weather and sea ice services. *Polar Geogr.*, **41**, 279–293, https://doi.org/10.1080/1088937X.2018.1522382.

Lamers, M., P. Duske, and L. van Bets, 2018a: Understanding user needs: A practice-based approach to exploring the role of weather and sea ice services in European Arctic expedition cruising. *Polar Geogr.*, **41**, 262–278, https://doi.org/10.1080/1088937X.2018.1513959.

——, M. Knol, M. Müller, B. Blair, J. Jeuring, T. Rasmussen, and A. Sivle, 2018b: Enhancing the Saliency of climate services for marine mobility sectors in European Arctic Seas (SALIENSEAS). Stakeholder Advisory Group Workshop Rep., 28 pp., https://salienseas.com/wp-content/uploads/2021/06/SALIENSEAS_Report_SAG_coscoping.pdf.

Lemos, M. C., 2015: Usable climate knowledge for adaptive and co-managed water governance. *Curr. Opin. Environ. Sustainability*, **12**, 48–52, https://doi.org/10.1016/j.cosust.2014.09.005.

——, C. J. Kirchhoff, and V. Ramprasad, 2012: Narrowing the climate information usability gap. *Nat. Climate Change*, **2**, 789–794, https://doi.org/10.1038/nclimate1614.

Leppala, L., S. Honkala, G. Ferrara, M. Kirkko-Jaakkola, H. Kuusniemi, and S. Miettinen-Bellevergue, 2019: Challenges in Arctic navigation: The user perspective. *2019 European Navigation Conf.*, Warsaw, Poland, Institute of Electrical and Electronics Engineers, 1–8, https://doi.org/10.1109/EURONAV.2019.8714187.

Ljubicic, G., and N. Carter, 2023: Weather and society: Tailoring weather, water, ice, and climate services to Northern community needs. Weather and Society Workshop Rep., 21 pp., https://straightupnorth.files.wordpress.com/2023/08/weather-society_2023-report.pdf.

Ljubicic, G. J., N. Carter, and S. Tagalik, 2019: Understanding Inuit community uses and needs for weather, water, ice and climate information and services. https://straightupnorth.ca/community-wwic-uses-and-needs/.

Lovecraft, A. L., C. Meek, and H. Eicken, 2013: Connecting scientific observations to stakeholder needs in sea ice social–environmental systems: The institutional geography of northern Alaska. *Polar Geogr.*, **36**, 105–125, https://doi.org/10.1080/1088937X.2012.733893.

Mach, K. J., and Coauthors, 2020: Actionable knowledge and the art of engagement. *Curr. Opin. Environ. Sustainability*, **42**, 30–37, https://doi.org/10.1016/j.cosust.2020.01.002.

Mali, F., L. Kronegger, P. Doreian, and A. Ferligoj, 2012: Dynamic scientific co-authorship networks. *Models of Science Dynamics: Encounters Between Complexity Theory and Information Sciences*, A. Scharnhorst, K. Börner, and P. van den Besselaar, Eds., Springer, 195–232, https://doi.org/10.1007/978-3-642-23068-4_6.

McGovern, A., I. Ebert-Uphoff, D. J. Gagne II, and A. Bostrom, 2022: Why we need to focus on developing ethical, responsible, and trustworthy artificial intelligence approaches for environmental science. *Environ. Data Sci.*, **1**, e6, https://doi.org/10.1017/eds.2022.5.

McNie, E. C., 2007: Reconciling the supply of scientific information with user demands: An analysis of the problem and review of the literature. *Environ. Sci. Policy*, **10**, 17–38, https://doi.org/10.1016/j.envsci.2006.10.004.

——, 2013: Delivering climate services: Organizational strategies and approaches for producing useful climate-science information. *Wea. Climate Soc.*, **5**, 14–26, https://doi.org/10.1175/WCAS-D-11-00034.1.

Meraldi, V., T. Morgan, A. Lynnes, and Y. Grams, 2022: Collection of valuable polar data and increase in nature awareness among travellers by using Expedition Cruise Ships as platforms of opportunity. *EGU General Assembly 2022*, Vienna, Austria, European Geosciences Union, EGU22-12972, https://doi.org/10.5194/egusphere-egu22-12972.

Morss, R. E., J. K. Lazo, B. G. Brown, H. E. Brooks, P. T. Ganderton, and B. N. Mills, 2008: Societal and economic research and applications for weather forecasts: Priorities for the North American THORPEX program. *Bull. Amer. Meteor. Soc.*, **89**, 335–346, https://doi.org/10.1175/BAMS-89-3-335.

——, O. V. Wilhelmi, G. A. Meehl, and L. Dilling, 2011: Improving societal outcomes of extreme weather in a changing climate: An integrated perspective. *Annu. Rev. Environ. Resour.*, **36**, 1–25, https://doi.org/10.1146/annurev-environ-060809-100145.

Murphy, A. H., 1993: What is a good forecast? An essay on the nature of goodness in weather forecasting. *Wea. Forecasting*, **8**, 281–293, https://doi.org/10.1175/1520-0434(1993)008<0281:WIAGFA>2.0.CO;2.

National Academies of Sciences, Engineering, and Medicine, 2018: *Integrating Social and Behavioral Sciences within the Weather Enterprise*. National Academies Press, 198 pp.

Nielsen, H., and G. Roldan, 2023: Polar policy in practice: Tour guiding in Antarctica. *Yearb. Polar Law Online*, **14**, 145–166, https://doi.org/10.1163/22116427_014010008.

Overland, I., and B. K. Sovacool, 2020: The misallocation of climate research funding. *Energy Res. Soc. Sci.*, **62**, 1–13, https://doi.org/10.1016/j.erss.2019.101349.

Panagiotidis, P., K. Giannakis, N. Angelopoulos, and A. Liapis, 2021: Shipping accidents dataset: Data-driven directions for assessing accident's impact and improving safety onboard. *Data*, **6**, 129, https://doi.org/10.3390/data6120129.

Panikkar, B., B. Lemmond, B. Else, and M. Murray, 2018: Ice over troubled waters: Navigating the Northwest Passage using Inuit knowledge and scientific information. *Climate Res.*, **75**, 81–94, https://doi.org/10.3354/cr01501.

Parsons, D. B., and Coauthors, 2017: THORPEX research and the science of prediction. *Bull. Amer. Meteor. Soc.*, **98**, 807–830, https://doi.org/10.1175/BAMS-D-14-00025.1.

Paton, D., 2019: Disaster risk reduction: Psychological perspectives on preparedness. *Aust. J. Psychol.*, **71**, 327–341, https://doi.org/10.1111/ajpy.12237.

Pielke, R. A., Jr., 1997: Asking the right questions: Atmospheric sciences research and societal needs. *Bull. Amer. Meteor. Soc.*, **78**, 255–264, https://doi.org/10.1175/1520-0477(1997)078<0255:ATRQAS>2.0.CO;2.

——, 1999: Who decides? Forecasts and responsibilities in the 1997 Red River flood. *Appl. Behav. Sci. Rev.*, **7**, 83–101, https://doi.org/10.1016/S1068-8595(00)80012-4.

——, and R. E. Carbone, 2002: Weather impacts, forecasts, and policy: An integrated perspective. *Bull. Amer. Meteor. Soc.*, **83**, 393–406, https://doi.org/10.1175/1520-0477(2002)083<0393:WIFAP>2.3.CO;2.

Polar Prediction, 2023: Polar Prediction Project Societal and Economic Research Application (PPP-SERA). Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research (AWI), accessed 12 July 2023, https://www.polarprediction.net/organization/yopp-task-teams/polar-prediction-project-societal-and-economic-research-applications-ppp-sera/.

Rainville, L., and Coauthors, 2020: Improving situational awareness in the Arctic Ocean. *Front. Mar. Sci.*, **7**, 581139, https://doi.org/10.3389/fmars.2020.581139.

Regnier, E. D., and J. W. Feldmeier, 2022: D minus months: Strategic planning for weather-sensitive decisions. *Decis. Anal.*, **19**, 1–20, https://doi.org/10.1287/deca.2021.0434.

Reid, P. A., and R. A. Massom, 2022: Change and variability in Antarctic coastal exposure, 1979–2020. *Nat. Commun.*, **13**, 1164, https://doi.org/10.1038/s41467-022-28676-z.

Rezaee, S., M. R. Brooks, and R. Pelot, 2017: Review of fishing safety policies in Canada with respect to extreme environmental conditions and climate change effects. *WMU J. Marit. Aff.*, **16**, 1–17, https://doi.org/10.1007/s13437-016-0110-z.

Robins, G. L., 2015: *Doing Social Network Research: Network-Based Research Design for Social Scientists*. SAGE Publication Limited, 266 pp.

Robles, M. C., and Coauthors, 2020: Clouds around the world: How a simple citizen science data challenge became a worldwide success. *Bull. Amer. Meteor. Soc.*, **101**, E1201–E1213, https://doi.org/10.1175/BAMS-D-19-0295.1.

Sandu, I., and Coauthors, 2021: The potential of numerical prediction systems to support the design of Arctic observing systems: Insights from the APPLICATE and YOPP projects. *Quart. J. Roy. Meteor. Soc.*, **147**, 3863–3877, https://doi.org/10.1002/qj.4182.

Sawatzky, A., and Coauthors, 2020: "The best scientists are the people that's out there": Inuit-led integrated environment and health monitoring to respond to climate change in the Circumpolar North. *Climatic Change*, **160**, 45–66, https://doi.org/10.1007/s10584-019-02647-8.

——, and Coauthors, 2021: "It depends…": Inuit-led identification and interpretation of land-based observations for climate change adaptation in Nunatsiavut, Labrador. *Reg. Environ. Change*, **21**, 54, https://doi.org/10.1007/s10113-021-01772-4.

Segal, R. A., R. K. Scharien, F. Duerden, and C.-L. Tam, 2020: The best of both worlds: Connecting remote sensing and Arctic communities for safe sea ice travel. *Arctic*, **73**, 405–550, https://doi.org/10.14430/arctic71896.

Serafin, R. J., A. E. MacDonald, and R. L. Gall, 2002: Transition of weather research to operations: Opportunities and

challenges. *Bull. Amer. Meteor. Soc.*, **83**, 377–392, https://doi.org/10.1175/1520-0477(2002)083<0377:TOWRTO>2.3.CO;2.

Serreze, M. C., and W. N. Meier, 2019: The Arctic's sea ice cover: Trends, variability, predictability, and comparisons to the Antarctic. *Ann. N. Y. Acad. Sci.*, **1436**, 36–53, https://doi.org/10.1111/nyas.13856.

Shoop, S. A., T. Melendy, B. Tracy, J. Stanley, C. Souza, M. Sala, and R. Thivierge, 2015: Expedient Skiway reconnaissance and operations near Resolute Bay, Canada. *16th Int. Conf. on Cold Regions Engineering*, Salt Lake City, UT, American Society of Civil Engineers, 476–487, https://doi.org/10.1061/9780784479315.042.

Simonee, N., J. Alooloo, N. A. Carter, G. Ljubicic, and J. Dawson, 2021: Sila qanuippa? (how's the weather?): Integrating Inuit Qaujimajatuqangit and environmental forecasting products to support travel safety around Pond Inlet, Nunavut, in a changing climate. *Wea. Climate Soc.*, **13**, 933–962, https://doi.org/10.1175/WCAS-D-20-0174.1.

Slats, R., and Coauthors, 2019: Voices from the front lines of a changing Bering Sea. *Arctic Report Card 2019*. M. L. Druckenmiller, R. Daniel, and M. Johnson, Eds., NOAA, 88–94, https://arctic.noaa.gov/report-card/report-card-2019/voices-from-the-front-lines-of-a-changing-bering-sea/.

Spinney, J. A., and K. E. Pennesi, 2013: When the river started underneath the land: Social constructions of a 'severe' weather event in Pangnirtung, Nunavut, Canada. *Polar Rec.*, **49**, 362–372, https://doi.org/10.1017/S0032247412000320.

Stewart, E. J., D. Liggett, M. Lamers, G. Ljubicic, J. Dawson, R. Thoman, R. Haavisto, and J. Carrasco, 2020: Characterizing polar mobilities to understand the role of weather, water, ice and climate (WWIC) information. *Polar Geogr.*, **43**, 95–119, https://doi.org/10.1080/1088937X.2019.1707319.

Taylor, A. J. W., 2002: Interdisciplinary developments in hazardous environment research: A silent tribute to general systems theory? *Int. J. Circumpolar Health*, **61**, 216–223, https://doi.org/10.3402/ijch.v61i3.17455.

Taylor, A. R., Þ. Barðadóttir, S. Auffret, A. Bombosch, A. L. Cusick, E. Falk, and A. Lynnes, 2020: Arctic expedition cruise tourism and citizen science: A vision for the future of polar tourism. *J. Tourism Futures*, **6**, 102–111, https://doi.org/10.1108/JTF-06-2019-0051.

Tebaldi, C., K. Hayhoe, J. M. Arblaster, and G. A. Meehl, 2006: Going to the extremes. *Climatic Change*, **79**, 185–211, https://doi.org/10.1007/s10584-006-9051-4.

Tejedo, P., B. Gutiérrez, L. R. Pertierra, and J. Benayas, 2014: Analysis of published scientific research from Deception Island, South Shetland Islands. *Antarct. Sci.*, **27**, 134–149, https://doi.org/10.1017/S0954102014000455.

Tietsche, S., M. Mueller, L. Bertino, G. Garric, H. Goessling, L. T. Pedersen, P. Wagner, and T. Lavergne, 2020: Recommendations for more user-relevant sea-ice forecasts. KEPLER Deliverable Rep. 33 pp., https://doi.org/10.5281/zenodo.5761695.

Transportation Safety Board of Canada, 2014: Aviation investigation report A13F0011. Tech. Rep. A13F0011, 15 pp., http://www.tsb.gc.ca/eng/rapports-reports/aviation/2013/a13f0011/a13f0011.asp.

van Eck, N. J., and L. Waltman, 2010: Software survey: VOSviewer, a computer program for bibliometric mapping. *Scientometrics*, **84**, 523–538, https://doi.org/10.1007/s11192-009-0146-3.

——, and ——, 2014: Visualizing bibliometric networks. *Measuring Scholarly Impact: Methods and Practice*, Y. Ding, R. Rousseau, and D. Wolfram, Eds., Springer, 285–320.

van Luijk, N., N. A. Carter, J. Dawson, C. Parker, K. Grey, J. Provencher, and A. Cook, 2022: Community-identified risks to hunting, fishing, and gathering (harvesting) activities from increased marine shipping activity in Inuit Nunangat, Canada. *Reg. Environ. Change*, **22**, 24, https://doi.org/10.1007/s10113-022-01894-3.

Villemain, A., and P. Godon, 2017: Toward a resilient organization: The management of unexpected hazard on the polar traverse. *Saf. Sci.*, **95**, 210–218, https://doi.org/10.1016/j.ssci.2016.03.008.

Wagner, P. M., and Coauthors, 2020: Sea-ice information and forecast needs for industry maritime stakeholders. *Polar Geogr.*, **43**, 160–187, https://doi.org/10.1080/1088937X.2020.1766592.

Waseda, T., A. Webb, K. Sato, J. Inoue, A. Kohout, B. Penrose, and S. Penrose, 2018: Correlated increase of high ocean waves and winds in the ice-free waters of the Arctic Ocean. *Sci. Rep.*, **8**, 4489, https://doi.org/10.1038/s41598-018-22500-9.

Weinstein, N. D., 1989: Effects of personal experience on self-protective behavior. *Psychol. Bull.*, **105**, 31–50, https://doi.org/10.1037/0033-2909.105.1.31.

Wiggins, M., and D. O'Hare, 1995: Expertise in aeronautical weather-related decision making: A cross-sectional analysis of general aviation pilots. *J. Exp. Psychol. Appl.*, **1**, 305–320, https://doi.org/10.1037/1076-898X.1.4.305.

Wilson, K. J., A. Arreak, J. Itulu, Sikumiut Community Management Committee, G. J. Ljubicic, and T. Bell, 2021a: "When we're on the ice, all we have is our Inuit Qaujimajatuqangit": Mobilizing Inuit knowledge as a sea ice safety adaptation strategy in Mittimatalik, Nunavut. *Arctic*, **74**, 418–583, https://doi.org/10.14430/arctic74212.

——, ——, Sikumiut Committee, T. Bell, and G. Ljubicic, 2021b: The Mittimatalik Siku Asijjipallianinga (Sea Ice Climate Atlas): How Inuit knowledge, earth observations, and sea ice charts can fill IPCC climate knowledge gaps. *Front. Climate*, **3**, 715105, https://doi.org/10.3389/fclim.2021.715105.

WMO, 2013: WWRP polar prediction project implementation plan. WMO Tech. Rep. WWRP/PPP 2-2013, 72 pp., http://www.polarprediction.net/fileadmin/user_upload/www.polarprediction.net/Home/Documents/WWRP-PPP_IP_Final_12Jan2013_v1_2.pdf.

——, 2022a: Early warnings for all: The UN global early warning initiative for the implementation of climate adaptation, executive action plan 2023–2027. WMO Tech. Rep., 56 pp., https://library.wmo.int/index.php?lvl=notice_display&id=22154#.Y41vIn1BxhF.

——, 2022b: Year of the polar prediction: Achievements and impacts. WMO Tech. Rep., 48 pp., https://library.wmo.int/idurl/4/58100.

Young, I. R., and A. Ribal, 2019: Multiplatform evaluation of global trends in wind speed and wave height. *Science*, **364**, 548–552, https://doi.org/10.1126/science.aav9527.