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PERSPECTIVE

Climate change, mass casualty incidents, and emergency response in the Arctic

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Abstract

Acute emergencies have been neglected in efforts to understand and respond to the transformational climatic changes underway in the Arctic. Across the circumpolar north, social-technological changes, extreme weather, and changing ice conditions threaten lives and infrastructure, increasing the risk of mass casualty incidents (MCIs), particularly as they impact transportation systems including global shipping, aviation, and community use of semi-permanent trails on the ice, land, and water. The Arctic is an inherently dangerous environment to operate in, and due to living in permanent settlements and the uptake of mechanised modes of transportation and navigation technologies, people's exposure to risks has changed. In responding to potential MCIs, emergency response systems face challenges due to remoteness, weather, and changing environmental conditions. We examine emergency response capacity in the Arctic, focusing on search and rescue and using examples from Canada and Greenland, identifying opportunities for enhancing emergency response as part of climate adaptation efforts.

1. Introduction

Average air temperatures have increased significantly in the Arctic over the past 40 years, a rate nearly four times the global average [1]. Such 'Arctic amplification' is well documented and has been accompanied by rapidly changing ice conditions, increasing storm intensity, permafrost thaw, rise in sea level, loss of sea ice, ecosystem shifts, opening new shipping routes, and changing weather patterns, affecting transportation systems [2]. The risks and opportunities posed by these changes to human activities is the focus of a growing body of scholarship [1, 3–5]. There is also evidence that governments across scales and the private sector are starting to invest in adaptation [6–9], and screening current policy and programming in-light of climate impacts (e.g. [10]).

Most Arctic research effort and policy attention has been directed to understanding and responding to risks and impacts of climate change that will evolve over the next 50–100 years. Important as such risks are, acute emergencies pose pressing and immediate—yet often overlooked—risks in many Arctic regions, where changing ice and weather conditions are increasing the potential for mass casualty incidents (MCIs) associated with transportation and disasters, and increasing demand for search and rescue (SAR). In this Perspective we examine how climate change might affect acute emergencies in the Arctic as mediated via impacts on transport systems, review current emergency preparedness for these risks, and argue that investing in emergency response is critical for enhancing preparedness for climate change in the Arctic. We draw upon examples from Canada and Greenland in particular, to illustrate the challenges and opportunities that confront such efforts.

Table 1. Shipping accidents in the Arctic (2005–2017).

Accident category	Count	Percentage
Collisions	115	4.36
Groundings	282	10.69
Equipment failure	634	24.03
Fire/Explosion	97	3.68
Flooding/Foundering	88	3.34
Pollution	605	22.93
Loss of control	150	5.69
Other	667	25.28
Total	**2638**	**100**

Data source: PAME, 2021.

2. An increasingly dangerous Arctic and people's activities

The climate and geography of the Arctic have always brought risks to those living, working, and travelling within and through the region. The Arctic climate poses severe risks due to extreme cold, which can lead to conditions ranging from frostbite to hypothermia. The human body struggles to retain heat in such conditions, exacerbated by factors like cold air, wind, and physical exertion, leading to frostbite and potentially gangrene in extremities [11, 12]. Cold weather can increase the risk of accidents and impair judgment, posing further dangers [11]. The combination of snow and wind create hazardous conditions such as limited visibility and avalanches [13, 14]. Extreme events impact the environment and activities like travel and herding and can lead to devastating effects on wildlife, including mass die-offs of species like reindeer, musk oxen, and caribou [15] and threats to shared food systems and cultural vitality [16]. Projected decrease in sea ice cover in the Arctic is anticipated to lead to increased wind speed and wave height, posing challenges to the safety of coastal communities and infrastructure development [17].

MCIs occur when the emergency response system of a given community and/or region is overwhelmed with the number and/or severity of injuries. In many remote and sparsely populated regions of the Arctic, as few as two qualifying trauma alert patients would overwhelm local and regional emergency resources and medical capacity [18], and thus be classified as an MCI. Climate change is exacerbating the potential for MCIs and environmental hazards, particularly those associated with transportation which is strongly influenced by ice and weather conditions. Examples of this include aviation, maritime transportation, and community use of semi-permanent trails on land, in the water, and on the ice [19, 20]. Significant disparities exist in emergency medical care, which is exacerbated by climate change to make emergency response situations more complex [18].

One of the primary drivers of increasing risk of MCIs is the opening of the Arctic to maritime shipping with longer ice-free seasons. Arctic waters are risky for shipping due to the high likelihood of ice collisions, prevalent summer storms and fog, the scarcity of auxiliary vessels, and the inadequate provision of precise navigational charts [21, 22]. Such shipping is anticipated to increase rapidly with changing ice patterns, bringing with it ship crews unfamiliar with the region and cruise ships of 200–1000 passengers [23, 24]. Sailing in Arctic waters carries several risks due to factors such as unpredictable and extreme weather conditions, prolonged periods of darkness, and the lack of nearby infrastructure and emergency response services along the shipping routes. In case of accidents like grounding or fire, the cost of salvage and the environmental impact would be significantly higher compared to non-Arctic waters [25].

The distance sailed by bulk carriers in the Arctic rose by 160% between 2013 and 2019 [26], while ship traffic in the Canadian Arctic has nearly tripled over the past decade [27], with a 30% increase in recorded sailings in Greenland [28]. The annual number of ships transiting through the Northern Sea Route (NSR) increased from 228 in 2013–301 in 2017, reaching a peak of 317 in 2016 [29]. Shipping activity in the Arctic experienced a significant growth of 37% from 2013 to 2023 (1298–1782 ships), and the distance sailed by all the vessels increased by 75% [26], while the number of days when navigation is possible in Arctic Circle waters is expected to increase from around 70 d (currently) to 125 d in 2050 and as many as 160 d in 2100 [30]. Between 2005 and 2017, 2638 ship accidents occurred in the Arctic (see table 1 and figure 1) [31].

Between 2011 and 2020, a total of 520 casualties associated with shipping incidents were reported in the Arctic Circle [25], in which the operating environment resulted in machinery damage and failure, which stand out as the most frequent cause, accounting for nearly 48% of the total incidents. Shipping casualties, including incidents in the Bering Sea, Beaufort Sea, Chukchi Sea, and Canadian Arctic Archipelago, illustrate the region's challenging conditions for shipping. For instance, the sinking of the SS Islander in the Bering Sea in 1901—when the Canadian Pacific steamship struck an iceberg and sank off Alaska—resulted in the tragic

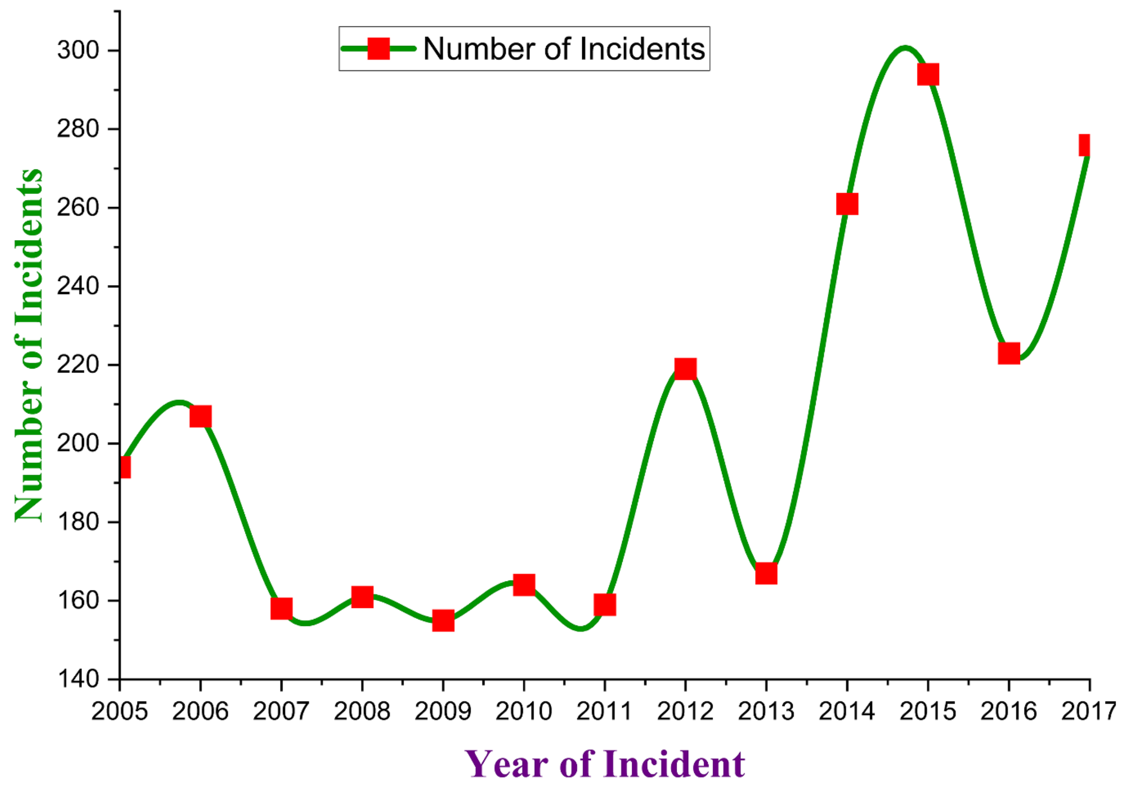

Figure 1. Yearly trend in shipping incidents in the Arctic (2005–2017).

loss of forty lives. Similarly, the sinking of the USCGC Polar Sea in the Chukchi Sea in 2010 and HMS Breadalbane in the Canadian Arctic Archipelago in 1853, and grounding of the MV Arctic in 2010 highlight the risks posed by treacherous ice, severe storms, and narrow channels [32, 33].

Between 1990 and 2015, the distance travelled by vessels increased by over 150% in the Canadian Arctic [34]. Inland shipping on navigable rivers and lakes is also increasing with a longer ice-free season, particularly in Russia, with dangers associated with changing hydrology and shallow waters in rivers [35]. Climate change is shifting trade routes to the Arctic, enhancing shipping prospects for Polar Class 7 vessels, designed for extreme Arctic conditions having high ice-class certification and reinforced hulls, yet risks remain due to persistent mobile ice, with up to two additional months of operation possible for routes like the Arctic Bridge [36]. Although warming of 2 °C–4 °C could improve ship navigation in the Arctic by the end of the century, the future of shipping in the region may be influenced more by unpredictable socio-economic factors—such as the impact of global events like pandemics (e.g. COVID-19) and cost of insuring vessels for operating in polar waters [36]. Studies have shown that shifts in Arctic shipping activity are often linked to broader developments in infrastructure, the economy, and natural resource extraction [34]. Increased shipping could improve resupply frequency for Arctic communities, but this benefit is tempered by the drawback of shorter seasons of stable coastal ice, which disrupts intercommunity travel, traditional hunting accesses, and food security [37].

Aviation also brings potential for MCIs. Air transport is the sole means of year-round transport access for many remote communities, with an average increase of 10.8% per year in commercial air flights across the Arctic since 2008, over twice the growth rate of global air traffic, with over 14 000 flights annually [38–40]. While most of these flights cross the region without incident, there are sizable number of transatlantic flights that need to make unplanned stops in Arctic communities due to medical or mechanical incidents [41]. Additionally, increase in transcontinental flights crossing the Arctic brings additional risk of a low-probability, yet high-consequence disaster if a plane were to crash.

While transatlantic flights are exposed to turbulence and large storms (e.g. post tropical cyclones), local air travel is more exposed to the changing climate across the Arctic. Air travel in the Arctic is highly sensitive to weather conditions, especially turbulence and extreme weather events [42], which were a determining factor in 44 crashes in Newfoundland and Labrador, 36 in the Northwest Territories, and 27 in Nunavut, accounting for several lives lost between 2011 and 2021 [43] with examples of crashes like 32 people killed in 1974 in Nunavut [44]. Particularly in remote regions, airports are often small, serviced by small propeller planes, and have limited infrastructure [45] (e.g. deficiencies in the runway lighting systems and power supply, which are essential for safe operations in low-visibility conditions, and a lack of weather radar coverage across the Arctic [46, 47]).

Climate change impacts ground stability, weather patterns, and runway maintenance at Arctic airports [48]. These changes have implications for the stability and functionality of the aeronautical infrastructure, appearance of crevasses in runway areas, as well as the demand for air transportation services, such as medical travel, medevac, and SAR [46, 49, 50]. Canada's northern territories for instance, have 11 paved and 75 gravel runways, but most planes need paved runways to operate. Gravel runways are also vulnerable to weather changes, affecting the efficiency and safety of aviation [46, 51, 52]. Increasing storminess, more variable wind and weather, and changes in the predominant direction of the wind documented in many regions, pose particular risks [53, 54].

While the potential for MCIs associated with shipping and aviation typically receive the most attention among decision makers and the public, in many regions more pervasive dangers face individuals traveling on unmaintained trails on the ice, land, and water for accessing communities and/or participating in traditional hunting, fishing, and herding activities [55]. In the North American Arctic in particular [54], the majority of SARs involve responding to emergencies involving use of such trails, where individuals have become stranded due to a mechanical breakdown or sudden change in ice or weather conditions, have had an accident (e.g. fallen through the ice), or have become lost [56–58]. On average, more than 1000 people across the Canadian north require SAR assistance each year, a rate 16.4 times the Canadian average (7.81/1000 people) [59]. Increasing incidence of SAR associated with the use of these trails has been documented in some regions as changing ice and weather conditions make travel more dangerous, compounded by changes in how people travel, a weakening of environmental knowledge among some trail users, and prohibitive cost of safety equipment [35, 59–62]. While data are sparse, between 2007–2017 SAR doubled in the Canadian territory of Nunavut [63], with a significant increase in Alaska [64] and increased winter SAR events in a warming climate across the Arctic, resulting in a higher risk of SAR events on ice [65].

3. Preparedness

The Arctic is poorly prepared for MCIs due to a combination of socioeconomic and environmental factors. It is a challenging environment in terms of emergency prevention, preparedness, and response due to remoteness, limited and under-developed infrastructure, communication challenges, and severe weather conditions [66, 67]. The region's increasing human activity, driven by natural resource development and the opening of new transportation routes, has heightened the risk of disasters [68, 69]. This is compounded by the lack of adequate SAR facilities and navigational aids, particularly in shallow, uncharted waters [68]. Climate change is affecting Arctic infrastructure like roads, airports, railways, buildings, pipelines, industrial facilities, and ports [70, 71], and compromises the safety of infrastructure making transportation of goods and services challenging and reducing predictability of access [72]. The rapid environmental changes, including shorter ice seasons, have further exacerbated these challenges, particularly affecting the transport infrastructure [73]. Transport infrastructure in the Arctic is unevenly developed, provides poor transport connectivity and accessibility [74, 75], with concerns related to the lack of or outdated infrastructure [75] to ensure safety of the NSR as a main transport artery in the Arctic [76, 77], which is affected by climate change that is increasing vulnerabilities and disrupting transport connectivity and threatening sustainability of ecosystems and livelihoods [78, 79].

In the case of a shipload of passengers needing food, shelter, and evacuation, emergency response would be severely challenged in most regions of the Arctic, and health systems impacted for a period of weeks to months [80]. Competence standards for SAR operations are crucial, particularly in the context of large-scale emergencies on passenger ships [81]. However, the use of unmanned aerial vehicles (UAVs) in emergency response in the Arctic, while potentially beneficial for hazard monitoring, is limited by legal and weather restrictions [59], local capacity, and extreme environment, including airframe and carburettor icing [82]. Despite these limitations, UAVs have been successfully used for glacier research, atmospheric observation, and ecosystem monitoring [83, 84] but are yet to be extensively used to enhance emergency response in the Arctic.

The response to First Air crash near Resolute Bay, Nunavut, in 2011 was hampered by inclement weather and the remote location of the crash site [85]. These challenges can make it difficult for ground and airborne SAR operations to locate the crash site quickly. These challenges are further complicated by the nature of the disaster, such as the presence of hazardous materials [86], and the need for effective coordination of multiple resources, including UAVs [87]. The human factor is also crucial, with the need for effective checklists and human performance considerations in high-stress situations [88].

MCIs have received limited focus by researchers or decision makers in a climate change context, and here we use the examples from northern Canada and Greenland to examine capacity to manage emergency events associated with transportation in the Arctic.

Example 1: Canada

In 2011, Canada signed the Arctic SAR Agreement, agreeing to 'promote the establishment, operation and maintenance of an adequate and effective SAR capability' within the Canadian Arctic [89]. While the agreement has been a benchmark for successful international cooperation by the Arctic Council and has led to inter-agency knowledge sharing, it has not markedly improved SAR coverage or response for those living in the Canadian Arctic [69]. Over the past few years, for example, SAR rates have continued to rise across the region while communities have increasingly been burdened by a lack of SAR resources and funding [18, 58, 90]. The surge in maritime traffic, particularly in the NSR and Northwest Passage, linked to climate change and melting polar ice, has led to an increase in incidents [91].

SAR operations face unique difficulties due to complex coastlines, uncharted traffic routes, and extreme conditions. The SAR response relies heavily on equipment like aircraft, helicopters, and icebreakers, but recent drastic climate change impacts and increased maritime traffic reveal safety gaps [92]. In the Canadian Arctic, the inherent limitations to response time stem from geographical remoteness, a lack of ports, and multilevel SAR resources. The far southern location of all Joint Rescue Coordination Centres (JRCCs) contributes to an average response time of approximately 10 h during the open water navigation season. Specific incidents, such as the Akademik Ioffe grounding in 2018, highlight the challenges faced by SAR flights and ships. Helicopters, while crucial, have limited capacity and require frequent refuelling stops [92–94].

SAR response across the Canadian Arctic is provided by numerous actors and agencies. The Canadian Air Force is responsible for aeronautical incidents; the Canadian Coast Guard is responsible for marine incidents; Parks Canada is responsible for incidents within national parks; and provincial and territorial governments are responsible for searches for missing persons including those who are lost or overdue on land or inland waters—commonly known as ground SAR (GSAR). While GSAR responses may involve RCAF and CCG or even Royal Canadian Mounted Police resources based on territorial Emergency Management Office discretion and availability, most incidents across the region rely on ground searchers, nearly always community volunteers [63] and community-based organizations, who face challenges like equipment shortage, training gaps, support, funding, and volunteer burnout [95].

Most communities across Inuit Nunangat—the Inuit homelands of northern Canada—are minimally prepared and resourced for the current SAR demands [59]. The system is largely dependent on volunteers with high rates of burnout reported [90]. While the system benefits from the strong land knowledge and skills of volunteers, volunteers often have to use their own equipment for SAR missions with only gas and oil reimbursements provided. While the push for more Canadian Coast Guard Auxiliary units has increased resources and tools, formal training available to most communities remains minimal. Training that volunteers have observed as lacking includes first aid training, emergency management training, training on how to work with RCMP, and practice conducting multi-agency responses [96].

Providing additional training, resources, and support for volunteer SAR groups across the region is critical as they are nearly always the first responders and are an invaluable resource in ensuring quick and efficient response. However, additional support and presence from RCAF and the CCG is also essential to ensure backup is readily available to ground searchers and for rapid response to mass-casualty incidents that would soon overwhelm community response procedures. Inequitable coverage of air support across northern Canada from RCAF is anticipated to be exacerbated when the C-295 Kingfisher replaces the CC-130 Hercules unless aircraft are stationed farther north [97] because the C-295's has a shorter range and may require more frequent refuelling stops, affecting its ability to cover large areas efficiently. The CC-130 has a longer range and endurance compared to the C-295 and can cover greater distances without refuelling, making it better suited for long-range SAR missions.

Many communities are responding to increasing SAR incidents with prevention programs that emphasize providing avenues for youth to learn traditional land, survival, navigation skills from Elders, such as Inuit Qaujimajatuqangit programs in Nunavut, youth mentorship programs in the Northwest Territories, and cultural camps in Yukon [98, 99]. Communities and territories are also promoting safety by lending out satellite beacons and subsidizing equipment and gasoline costs through hunter support programs. Research has indicated, however, that additional efforts are needed and may lead to substantial cost savings [16]. Prevention may include further reducing financial barriers for purchasing safety gear, building marine-band and CB repeater towers near communities, continuing to subsidize satellite beacon use, and funding programs that allow youth to learn traditional land skills.

Of the roughly 1000 individuals that require SAR across the Canadian Arctic, nearly 20% are facing medical emergencies [100]. It is likely that the case load as well as severity will increase in the coming decade. While Canada has been fortunate that few disasters have occurred in the Arctic, national security policy and health care systems need to be prepared for future eventualities. Building resilience and improving safety for both exogenous incidents and ongoing community SAR needs can and should be done in tandem.

Example 2: Greenland

Greenland has experienced a rise in SAR operations due to an increase in shipping activity over the last decade with an expected 24% rise in maritime traffic from 2013 to 2027, with notable spikes: 100% for cruise ships, 20% for passengers, and a staggering 2543% for bulk carriers, totalling 205 940 nautical miles [101]. Rescue efforts face a critical time constraint to reach survivors before succumbing to exposure, and it is unlikely that any assistance would arrive sooner than 12 h after an emergency call [102]. Assets can reach Greenland within a time frame of 12–36 h following a request for assistance [103]. Whether it is an emergency landing of a transpolar flight on Greenland's ice cap or evacuating passengers from a sinking cruise ship to a remote island or the ice, the task may involve sustaining over a thousand people for up to five days until rescue assets arrive [102]. Parachuting rescue equipment and personnel into the disaster area is possible but would potentially be hindered by Greenland's extreme weather conditions. Unlike several other Arctic coastal nations, Denmark does not operate a dedicated coast guard service in Greenland [104]. The risk of mass casualties looms large, especially with the frequent visits of large cruise ships carrying 1000 of passengers and crew.

The Danish Ministry of Defence holds the responsibility for sea and air SAR operations in Greenland. This includes regulating both sea and air rescue efforts, coordinating across these domains, managing air rescue operations, overseeing sea rescue operations, and establishing SAR helicopter contingencies. The management of Greenland's SAR service is shared between the Joint Arctic Command's (JACO) JRCC and the Greenland Police. The JACO is specifically responsible for JRCC Greenland, which means it oversees both air and sea rescue services in Greenland. This encompasses SAR efforts for vessels enrolled in the compulsory ship-reporting system known as 'GREENPOS', rescuing individuals in distress from aircraft and ships, regardless of whether relief measures are executed at sea, in the air, or on land [105, 106].

JACO deploys assets in the region, including four large Thetis class inspection ships with helicopters and three smaller Knud Rasmussen class vessels equipped for helicopter landing and refuelling. Typically, one of each vessel is on duty in Greenlandic waters, performing patrols, bathymetry, and fishery inspections. Additionally, JACO operates a CL-604 Challenger surveillance aircraft from Kangerlussuaq, approximately 190 miles from Nuuk. Air Greenland provides an S-61N SAR helicopter in Kangerlussuaq or Nuuk and a BELL 212 helicopter in South Greenland. However, none of the helicopters possess all-weather or night capabilities, nor can they refuel from Danish navy vessels. The S-61N helicopter features a rescue hoist but lacks a rescue diver [102, 107]. The Greenland Police are tasked with SAR operations on land, including coastal areas, emphasizing the critical role of local knowledge and Indigenous knowledge and expertise in navigating Greenland's rugged terrain for rescue mission [105].

Greenland's limited infrastructure, including airports, heliports, and harbours, with limited facilities at Nuuk, Ilulissat, and Qaqortoq, presents challenges for SAR operations [108]. The unique climate and geography, such as permafrost and subglacial lakes, further complicate these efforts [109]. The convergence of vast distances, inadequate infrastructure, limited navigational data, and frequent severe weather conditions pose formidable challenges for SAR operations. These same risks also impact commercial endeavours in the region due to the intricate coordination required, the absence of robust communication infrastructure, uncertain bathymetric information, and the ever-changing local sea ice conditions [77, 110]. In sectors where demand for Arctic-specific solutions is low and economic margins are tight, there is little incentive to adopt existing technologies or create bespoke solutions. Additionally, the current SAR coverage is subject to debate regarding its effectiveness [110]. While there are robust assets off the coast of Norway, the coast of Greenland lacks similar infrastructure to respond to emergencies, especially for passenger ships in distress. Shortages exist in essential SAR response resources, including long-range, heavy-lift helicopters. The effectiveness of these assets is frequently constrained by weather conditions and other operational factors [111, 112]. Due to the fatigue of the limited human resources, JACO cannot run a large-scale SAR operation for more than 24 h [102]. While efforts are underway to enhance SAR infrastructure, significant challenges persist such as geographical extremes, harsh weather conditions, sparse population density, and logistical constraints.

In 2012, Greenland conducted its first live Arctic search and rescue exercise (SAREX 2012). This exercise involved personnel, authorities, airplanes, helicopters, and ships from all eight Arctic states. The motivation behind this major-scale exercise was to launch a SAR mission in the High North, driven by factors such as the melting ice and the opening of new land and sea areas [113, 114]. Collaboration on an international scale is a fundamental aspect of Greenland's SAR strategy. This commitment is evident in exercises like Exercise Argus and SAREX 2012. These exercises serve as powerful demonstrations of the dedication to improving SAR preparedness and capabilities through cooperation among multiple nations. Exercise Argus, which brings together resources from the United States, Denmark, Greenland, and France, emphasizes joint SAR efforts and marine environmental response, highlighting the significance of interoperability among global partners [115].

To enhance its SAR capabilities, Air Greenland has recently upgraded its helicopter fleet by acquiring two Airbus H225 heavy helicopters. These helicopters are renowned for their exceptional performance in extreme conditions and are set to replace the aging S-61 models. This upgrade represents a significant advancement in Greenland's aerial SAR resources. The inclusion of the H225 helicopters, backed by a comprehensive maintenance and training package from Airbus, ensures greater operational readiness and safety for SAR missions across Greenland's challenging maritime and terrestrial environment [116, 117].

4. Discussion

In the Arctic, robust research, community leadership and engagement, and informed policy decisions are crucial given the rapidly emerging risks posed by climate change. Key areas include understanding environmental risks, promoting community well-being, sustainable resource management, and fostering research cooperation. Better collection of SAR and MCI data is important, with such data currently available only in an *ad hoc* manner. For better SAR data, focus on technological solutions, standardized reporting, and interagency coordination are important. Regarding MCIs, prioritizing triage systems, resource dispatching, on-site medical assistance, and integrated response policies are important. These efforts will enhance safety, resilience, and preparedness in the Arctic.

Collaborative efforts between SAR organizations and communities are important in ensuring the seamless integration of traditional knowledge with SAR techniques. In the face of climate change challenges, SAR organizations operating in the Arctic need to invest in cutting-edge technologies and equipment, such as satellite imagery, remote sensing, and unmanned aerial systems (UAS). These advancements can enhance situational awareness, reduce response times, and facilitate effective SAR operations. The utilization of such technologies provides real-time data on critical factors like ice conditions, weather patterns, and vessel movements. Armed with this information, SAR teams can make informed decisions and allocate resources efficiently. Moreover, UAS enable aerial surveillance and the delivery of essential supplies to distressed individuals, further bolstering SAR capabilities in the Arctic. However, achieving effective responses necessitates the thoughtful design and implementation of SAR management policies and programs, complemented by the presence of appropriate transportation and physical infrastructure and a well-trained personnel base.

The recent Adaptation Actions for a Changing Arctic assessment by the Arctic Council contains only limited mention of SAR and emergency response. The Arctic lacks basic SAR capabilities, and variations in SAR capabilities across Arctic nations persist. To address this, the Council could enhance the agreement by establishing a common operating procedure (SAR COP) database and facilitating regular meetings and exercises for improved coordination and preparedness. Climate change has significantly impacted SAR operations in the Arctic. The melting of sea ice and increased human activities have resulted in more frequent SAR incidents, necessitating adaptations in strategies and capabilities. The challenging factors include remoteness, extreme weather conditions, and shifting ice dynamics. To address these risks, collaborative efforts between SAR organizations and Indigenous communities, along with the integration of advanced technologies, are crucial. Continued research and investment in SAR capabilities are essential for improving transportation sectors and effectively responding to emergencies in this rapidly changing Arctic environment.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary information files).

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Author contributions

All the authors conceptualised the framework and contributed to the writing of the article.

Conflict of interest

The authors declare no conflict of interest.

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