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Arctic Science

OPEN ACCESS | Introduction

Terrestrial geosystems, ecosystems, and human systems in the fast-changing Arctic: research themes and connections to the Arctic Ocean

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Abstract

In parallel to rapid sea-ice loss and other climate impacts in the Arctic Ocean, large-scale changes are now apparent in northern landscapes and associated ecosystems. Arctic communities are increasingly vulnerable to these changes, including effects on food security, water quality, and land-based transport. The project "Terrestrial Multidisciplinary distributed Observatories for the Study of Arctic Connections" (T-MOSAiC) was conducted under the auspices of the International Arctic Science Committee over the period 2017–2022. The aim was to generate multiauthored syntheses, protocols, and observations toward an improved understanding of Arctic terrestrial change, and to identify priorities for northern research, monitoring, and policy development. This special collection of *Arctic Science* covers a broad range of these themes, including limnological insights into northern lakes and rivers, a set of protocols for permafrost and vegetation monitoring, an integrated perspective on Arctic roads and railways to bridge the social and natural sciences, snow and ice studies at the coastal margin of the Last Ice Area, and Indigenous perspectives on Arctic and global conservation. The contributions summarized in this introductory article to the T-MOSAiC special collection include recommendations for the future, and they illustrate the immense value of Arctic collaborations that bring together researchers across disciplines, nations, and cultures.

Key words: climate change, snow and ice, permafrost, multidisciplinary, Indigenous

Introduction

The Arctic is warming at rates up to four times more rapidly than the global mean (Rantanen et al. 2022), and many regions are likely to experience average annual air temperatures that are several degrees above current conditions by the end of this century (IPCC 2018). Attention has focused on the implications of this massive climate change for the Arctic Ocean, and an almost complete loss of summer sea ice is projected within the next few decades (Newton et al. 2021). Less attention has been given to evaluating how sea ice decline may affect Arctic terrestrial systems (including lakes and rivers), yet lands, freshwaters and seas are intimately connected throughout the North Polar region, and there is already evidence of wide-ranging impacts on coastlands, inland waters, and climate (Post et al. 2013; Bintanja and Andry 2017; Buchwal et al. 2020).

Changing sea ice conditions directly impact the Indigenous communities that live on northern coasts, and that depend on marine ecosystems for traditional foods and culture (Steiner et al. 2021). Diminished ice conditions are also opening up the region to increased marine transport, providing new opportunities for tourism and other commercial shipping activities across Arctic seas and at coastal ports, but with an increasing risk of accidents (Mudryk et al. 2021; Vincent et al. 2023). Terrestrial changes may also have reciprocal effects on the Arctic Ocean, for example, by increasing river

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discharge and heat fluxes that accelerate the melting of sea ice (Park et al. 2020) and by increasing coastal erosion and inputs of sediment to the ocean due to greater wave exposure combined with warmer temperatures (Fritz et al. 2017).

Recognizing the need for improved understanding of Arctic ocean–land interactions alongside climate change impacts on Arctic terrestrial systems, the International Arctic Science Committee (IASC) sponsored a series of workshops to formulate an IASC-endorsed project entitled “Terrestrial Multidisciplinary distributed Observatories for the Study of Arctic Connections” (T-MOSAiC). This project ran over the period 2017–2022 and involved measurements and observations at many land-based sites around the circumpolar North (see, for example, the map given in Figure 1 of Povoroznyuk et al. 2023), with the overarching goal of connecting observations among locations and disciplines of Arctic terrestrial change. The project ran in parallel to a large-scale ocean/sea ice/atmosphere project over the winter of 2019/20 in the central Arctic Ocean, also under the auspices of IASC, named “Multidisciplinary drifting Observatory for the Study of Arctic Climate” (MOSAiC; Nikolaus et al. 2022). T-MOSAiC extended from the northern coasts to inland regions, and a systems-level approach was applied to connect diverse studies at multiple scales, with attention to themes such as connectivity, extreme events, emergent properties, threshold effects, and feedback mechanisms.

This special collection of *Arctic Science* brings together 16 papers on different aspects of T-MOSAiC research activities. The authors represent diverse disciplines and northern expertise, and are from 15 countries. Land–ocean interactions were of particular interest in the Last Ice Area (LIA) at the far northern coast of North America, immediately downstream of the MOSAiC oceanographic activities. Permafrost thaw, climate change, and aquatic ecosystems were central themes for many of the projects in T-MOSAiC, including the development of standardized protocols and the identification of research priorities for the future. The complex relationships among transport infrastructure, climate, and landscape change were also key subjects in T-MOSAiC, with analysis of the social as well as environmental consequences of road and railway developments in the North, and attention to adaptation strategies to mitigate the effects of climate change. Finally, and importantly, all T-MOSAiC field activities took place on northern lands where Indigenous Peoples have lived for millennia (Fig. 1), and Indigenous Knowledge and perspectives on conservation, monitoring, and research were therefore given particular respect and attention. This included the appropriate research permits and reporting, consultations with local communities, and participation of Indigenous Knowledge holders in the T-MOSAiC planning workshops and in research and writing projects. Here we provide an overview of the papers in this special collection (available via the dedicated web page at https://cdnsciencepub.com/topic/as-terrestrial) within the core themes of ocean–land connections, permafrost thaw and aquatic ecosystems, transport infrastructure, and Indigenous perspectives.

Ocean–land connections in the Last Ice Area

In the oceanographic project MOSAiC, the German icebreaker Polarstern drifted with the pack ice across the North Polar region in the Transpolar Current. Some of that central Arctic Ocean sea ice, along with ice advected across the Canada Basin by the Beaufort Gyre, pushes up against the northern coasts of Canada and Greenland, to produce a vast accumulation zone of the thickest, oldest ice in the Arctic Ocean basin (Newton et al. 2021). The Arctic Ocean is likely to lose most of its summer ice by the middle of this century, but this band of accumulating thick ice is projected to persist. It has therefore been named the LIA and is considered the ultimate refuge for ice-dependent species in the fast-warming North Polar region (WWF 2011).

The northern coastal lands act as a barrier to sea-ice advection and cause the ice to accumulate to the considerable age and thickness observed in the LIA. In reciprocal fashion, this persistent ice has a strong cooling influence on the terrestrial margin of the LIA, and the northernmost coast of Canada and Greenland is characterized by perennial cold temperatures even in summer, with polar desert landscapes containing glaciers, ice rises, permafrost soils, ice-capped lakes, and persistent snow and ice patches. Five articles in this special collection focus on environments in this terrestrial margin of the LIA.

Bégin et al. (2021) describe the limnological features of Ward Hunt Lake, and draw attention to the distinctive physical, chemical, and biological conditions that are found in the moat—the band of open water that persists in summer around the perennial ice cap. This lake has undergone major shifts over the last 15 years, from thick, stable perennial ice-cover to large-scale variations from year to year: ice-out in some years and multiyear ice in others, thereby weakening the inshore–offshore gradients associated with the moat. This shift to extreme variability in ice and associated limnological conditions has been attributed to rapid warming in the region, as registered by the Ward Hunt Island (CEN) and Alert climate stations, two of the closest land-based stations to the MOSAiC ship-based operations.

The marked shift in ice regime at Ward Hunt Lake has taken place at the same time as major changes in the coastal ice regime of the LIA. Large areas of multiyear sea ice have been lost, and most of the ice shelves have collapsed completely or have greatly contracted, including the ice shelf that up until 2011 surrounded Ward Hunt Island (previously reported by T-MOSAiC in Vincent and Mueller 2020). The loss of these coastal ice features has likely accelerated the warming and attrition of the land-based cryosphere; however, some of these features are proving resilient. Davesne et al. (2022) examined the formation and properties of a set of perennial ice patches on Ward Hunt Island that appear to have remained in place for thousands of years. The older ice in these patches was substantially reduced during recent warmer summers, but the ice volume recovered during cooler summers. Kochtitzky et al. (2023) examined the Thores Glacier and its associated proglacial Thores Lake, which are

Fig. 1. Inuit sculpture at Kuujjuarapik-Whapmagoostui, Canada. This was a source of inspiration throughout the T-MOSAiC research program and workshops, as a continuous reminder that Indigenous Peoples have lived in the North for millennia, and that research on these homelands is done with respect, consultation, and increasingly by and in partnership with northern communities. This magnificent 3.3 m high inuksuk (innunguaq) is located on the shores of eastern Hudson Bay, with one side facing the seasonally ice-covered bay and the other side looking inland, evocative of the T-MOSAiC theme of how changing Arctic seas are affecting northern terrestrial systems. Photo credit: João Canário.

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located some 40 km inland from the coast and 300 m (the glacier terminus and lake) to 1600 m (the peaks in the glacier catchment) above sea level. They conclude that at this location and altitude, the glacier and its lake have remained relatively buffered from the large temperature rises at the coast, and that the glacier and its lake have remained relatively stable over timescales of hundreds of years.

In the associated study by Culley et al. (2023), perennially ice-covered Thores Lake was shown to have many distinct features, including a deep, cold, well-mixed water column, a diverse phytoplankton assemblage, and a limited zooplankton community composed exclusively of rotifers. Both Kochtitzky et al. (2023) and Culley et al. (2023) note that although Thores Lake is currently stable, it is vulnerable to ongoing warming since its existence depends on the ice dam formed by Thores Glacier, and the loss of that glacier would result in complete drainage and loss of this ecosystem. Similarly, Davesne et al. (2022) concluded that ongoing warming in the Ward Hunt Island region would likely result in the extinction of ice patches that may have been present on the island for millennia.

Klanten et al. (2021) undertook a related study of a set of four lakes in Stuckberry Valley, at the LIA coastal margin, 100 km to the east of Ward Hunt Island. The four lakes contrasted greatly in their limnological conditions, with morphometry and dissolved oxygen as the main determinants of their pronounced biogeochemical differences. The authors draw attention to the need for paleolimnological studies of the lakes combined with paleoceanographic studies of the adjacent marine environment, to better understand the linkages in the LIA between coastal terrestrial environments and the Arctic Ocean.

Permafrost, climate change, and aquatic ecosystems

Permafrost is a defining feature of the terrestrial Arctic environment, and large changes are now being observed

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throughout the region in permafrost temperatures and active layer thickness as a consequence of climate warming (Biskaborn et al. 2019). The changes have implications for landscape integrity, northern ecosystems, biogeochemical processes including greenhouse gas emissions, water quality, and the maintenance and safety of engineered infrastructure (Vincent et al. 2017). However, there are large regional differences that, to date, are only poorly quantified, and there is a pressing need to improve spatial and temporal monitoring. Boike et al. (2022) address this need by presenting a set of user-friendly protocols to obtain standardized metadata and data on permafrost thaw. The protocols provide detailed information, via associated video capsules (https://permafrostthaw.org/), for transect measurements of key properties and drivers of permafrost thaw, including snow depth, thaw depth, vegetation height, soil texture, and water level. The methods have the advantage of not requiring sophisticated equipment, so they can be widely adopted. They come with an app (myThaw) to guide the user through the process, and the data can be readily incorporated into a database using standardized formats, including the associated metadata.

Paquette et al. (2023) considered the effects of permafrost thaw on the release of solutes into downstream receiving waters. They compared two sites in the High Arctic, one with dry polar desert soils that have a low ground ice content and the other with a well-vegetated wetland site that is rich in ground ice. There were large quantitative as well as qualitative differences in the solute content of the ground ice, with greater orders of magnitude of major ion concentrations in the polar soil ice, reflecting a period of postglacial marine inundation. These marine-influenced soils have the potential to release high concentrations of sodium and chloride ions during thaw, and the results draw attention to the importance of considering the spatial distribution of both ground ice and solutes in warming permafrost landscapes.

Manseau et al. (2022) examined the effects of thawing permafrost on the export of sediment by a subarctic river. They found a significant correlation between air temperatures and river turbidity, which was related to changes in discharge. Warmer air temperatures were associated with greater discharge, and an increase in river bank erosion. Precipitation events, notably their duration and intensity, played a role in affecting discharge and sediment mobilization. The authors also suggest that thermokarst ponds in the catchment contribute to these dynamics by acting as sediment traps.

Most polar lakes and ponds are oligotrophic, and many are ultraoligotrophic (Vincent et al. 2008). However, this may change in the Arctic as permafrost catchments thaw, active layers deepen, and soil weathering and microbial processes accelerate with increased warmth, precipitation, and vegetation development, in turn resulting in increased mobilization of nutrients from land to water. Ayala-Borda et al. (2021) report an interesting exception to "polar oligotrophy" in the drainage basin of Greiner Lake on Victoria Island in the Canadian Arctic Archipelago. In this one shallow lake, they measured total phosphorus levels in excess of 30 μg/L and an abundant phytoplankton community with 43% cyanobacteria by biovolume. The authors attributed this eutrophication to increased delivery of nutrients from soils in the local catchment and sensitivity to ongoing climate change, but note that nutrient supply from migrating birds may also play a role.

Northern aquatic ecosystems are particularly sensitive to climate change. In a comprehensive review, Saros et al. (2023) synthesize the diverse physical, chemical, and biological responses of northern aquatic ecosystems as sentinels of climate change. These include shifts in ice cover, thermal structure, river flow, lake water levels, nutrient status, carbon cycling, oxygen concentrations, and aquatic communities, including the arrival and establishment of invasive species. Remaining knowledge gaps are summarized and the authors conclude with three principal recommendations for future work: (i) adopt common protocols for comparisons across sites, as in Boike et al. (2022) for permafrost; (ii) give greater attention to Indigenous Knowledge for understanding the nature and responses of Arctic freshwater sentinels; and (iii) integrate multiple sentinel responses by way of a systems approach that includes attention to T-MOSAiC system-level themes such as linkages, feedbacks, thresholds, and scale.

Transport infrastructure in the changing Arctic

Roads and railways play a major and expanding role in the socio-economic development of the Arctic. Several articles in this T-MOSAiC special collection describe the vulnerability of northern linear infrastructure to climate change, and they illustrate many of the T-MOSAiC system-level themes, including threshold effects; sensitivity to extreme events such as floods and fires; feedback effects such as thermo-erosion; connectivity, including disruption of hydrological connectivity across the landscape, and the social consequences of increased mobility for Indigenous communities; and emergent properties, whereby the transport infrastructure transforms the landscape and the human activities across it, producing a new system with markedly different environmental and social characteristics to those before the development.

Wildfires are increasing in frequency throughout the world as a consequence of climate change, and northern lands are also experiencing these effects (McCarty et al. 2021). Roads and railways can increase the probability of fires. For example, in their study of the causes and effects of northern fires, Kuklina et al. (2023) combined community observations with satellite imagery in the Irkutsk region of Siberia, where around 20% of the study region was consumed by fire during the 2016 season. They found that there was a strong relationship between fires and land use, with the highest fire frequencies near forestry roads and the lowest frequencies near subsistence roads. This study also underscored the importance of local and Indigenous observations for monitoring and understanding northern wildfires.

Roads and railways over ice-rich ground are especially prone to the effects of climate warming on permafrost degradation. Kanevskiy et al. (2022) examined ice wedges adjacent to road infrastructure in the Prudhoe Bay Oilfield, Alaska, USA, and found that their vulnerability to thawing and collapse depended on the structure and thickness of soil layers. The authors identified processes that stabilize the thawing and prevent further deepening of the active layer, specifically

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the formation of an ice-rich intermediate layer that protects the ice wedges from additional melting. This was observed in deep water-filled troughs, where increased vegetation, litter, and mineral material, including dust, contributed to the development of the intermediate layer.

Walker et al. (2022) present a detailed analysis of the effects of roads and climate change on the network of ice-wedge polygons in the Prudhoe Bay area. They found little change over the 20 years prior to development, but over the subsequent 50 years, there was a mixture of climate- and road-related effects, including an increased abundance of thermokarst ponds, and changes in geomorphology, snow distribution, thaw depth, and vegetation. Road dust had a strong effect on the plant-community structure, and flooding increased permafrost degradation but also vegetation productivity. They conclude their analysis with a set of recommendations to assess the cumulative impacts of new roads and other types of infrastructure over ice-rich permafrost, and to address the consequences of climate change. These include the need to produce landscape sensitivity maps for thermokarst risk assessment, as in Kanevskiy et al. (2022), and as used for municipal planning in subarctic Québec (Vincent et al. 2017). Road dust and the damming effect of roads on natural waterways were identified as two issues requiring particular attention.

In a third study of the Prudhoe Bay Oilfield, Bergstedt et al. (2023) focused on the influence of infrastructure and road dust. Using a combination of in situ and remote sensing observations, they found significant effects on snowmelt, near-surface ground temperatures, surface water area, and vegetation. The authors also present compelling images showing how pipelines, in combination with their access roads, create large snow drifts that persist into early summer and extend over large areas of the tundra.

In the review article by Povoroznyuk et al. (2023), the authors consider the social as well as environmental consequences of northern transport infrastructure. Their analysis illustrates many of the system-level themes of T-MOSAiC, first by way of general features of relevance to Arctic railways and roads, and second by seven case studies in northern high-latitude areas of North America and Russia. The authors draw attention to commonalities across these northern regions, including vulnerability to ongoing climate change (including through floods and fires) and the need for adaptive engineering strategies, but also regional differences, such as the degree of attention given to Indigenous issues. They conclude their review by advocating for a comprehensive approach to assessing new transport projects that includes attention to local voices, integrates social as well as environmental aspects, and considers short-term consequences as well as long-term (multi-decadal) cumulative impacts.

Indigenous perspectives

Several of the articles in this T-MOSAiC special collection have northern Indigenous co-authors, and there is a growing awareness of the value of closer partnerships with northern communities in Arctic research and monitoring. This value ranges from expert support and leadership in field operations and safety, to long-term, all-season community observations of environmental change, and new opportunities for knowledge exchange and application. IASC has increasingly given attention to Indigenous participation in all facets of Arctic research, from priority setting to planning and operations, and in 2017 created the Action Group on Indigenous Involvement. This resulted in a set of recommendations for more involvement of Indigenous Peoples in northern studies and greater consideration of Indigenous/Traditional Knowledge (IASC 2020). Similarly, science funding agencies, northern institutions, and professional journals are paying increased attention to community-led initiatives, and to knowledge co-production by southern researchers in partnership with northern communities. For example, Canadian Science Publishing (CSP, the publisher of *Arctic Science*) has produced a set of guidelines for publishing community-engaged research, including methods and materials, authorship and attribution, data availability options, and ethical considerations (CSP 2022).

The T-MOSAiC theme of connectivity is nowhere more evident than in Indigenous worldviews that treat humans, wildlife, and the environment as connected parts of an integrated whole. Marine and terrestrial research in the Arctic is typically undertaken by different communities of scientists, with little communication or collaboration between them, yet the Arctic Ocean is the most terrestrially influenced part of the world ocean (e.g., Terhaar et al. 2021), and as seen in the LIA, there is a strong reciprocal influence of the Arctic Ocean on the coastal terrestrial environment. Many of the Indigenous coastal communities around the Arctic live on land, but see themselves as part of the land–ice–water ecosystem, as stated, for example, by the Inuit in the development of a Canadian marine conservation zone, Tallurutiup Imanga: "Our understanding of how we fit into the world is based on our close relationship with the land, sea, ice and environment. We are a part of the land and sea" (Parks Canada 2020). Conservation zones, such as Tuvaijuittuq and Quttinirpaaq (Vincent and Mueller 2020), currently divide across marine, land, and political jurisdictions, and there are opportunities for a more integrated Indigenous approach in the future as protected areas are connected nationally and across the Arctic.

In this Special Collection, two Indigenous scholars draw attention to the way in which sustainability and conservation are an intrinsic part of Indigenous culture and how Indigenous communities are helping to guide and lead global conservation efforts (Buschman and Sudlovenick 2023). The authors note that there is growing attention throughout the world to Indigenous protected and conserved areas and recognition of the importance of decolonization, self-determination, and Indigenous worldviews for the Arctic as well as global sustainability. They stress the enormous value of Indigenous Knowledge and local community actions for Arctic conservation and the need to support and facilitate Indigenous leadership in this area, both at the local scale of Indigenous homelands and at the global scale of protecting the biosphere.

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Final comments

The articles presented in this collection illustrate the range of important topics covered within T-MOSAiC but represent only a fraction of the total output from the project. Apart from numerous stand-alone articles in other journals, several other special issues were co-edited by Action Group members (T-MOSAiC 2018), including on the themes of environmental pollution (Canário et al. 2022), polar microbiomes (Jungblut et al. 2022), the application of drone remote sensing systems in Arctic research and monitoring (Kerby et al. 2022), and transdisciplinary research and communication to address Arctic change (Schweitzer et al. 2022).

The Covid-19 pandemic disrupted most field operations in the Arctic during 2020 and 2021, and environmental data collected from climate stations, boreholes, automated cameras, and lake moorings became available from many sites only in 2022 (e.g., Ward Hunt Island and Bylot Island in the Canadian Arctic; CEN 2022*a*, 2022*b*). Publishing of articles from this project and development of specific studies will therefore continue well into the future. In the spirit of IASC, T-MOSAiC has underscored the value of connecting across disciplines, laboratories, nations, cultures, and sites in the circumpolar Arctic, and it provides a foundation for ongoing collaborations in research and monitoring of the fast-changing northern terrestrial environment.

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Data availability

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Warwick Vincent, Julia Boike, Victoria Buschman, Frédéric Bouchard, Scott Zolkos, Greg Henry, and Brent Wolfe served as Guest Editors at the time of manuscript review and acceptance. João Canário was Chair and Warwick Vincent was Co-chair of the T-MOSAiC project. Peer review and editorial decisions regarding this manuscript were handled by the Editor in Chief of *Arctic Science*, Lisa Loseto.

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