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Changing access to ice, land and water in Arctic communities

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Arctic climate change has the potential to affect access to semi-permanent trails on land, water and sea ice, which are the main forms of transport for communities in many circumpolar regions. Focusing on Inuit Nunangat (the Inuit homeland in northern Canada), trail access models were developed drawing upon a participatory process that connects Indigenous knowledge and science. We identified general thresholds for weather and sea ice variables that define boundaries that determine trail access, then applied these thresholds to instrumental data on weather and sea ice conditions to model daily trail accessibility from 1985 to 2016 for 16 communities. We find that overall trail access has been minimally affected by >2 °C warming in the past three decades, increasing by 1.38–1.96 days, differing by trail type. Across models, the knowledge, equipment and risk tolerance of trail users were substantially more influential in determining trail access than changing climatic conditions.

The Arctic is undergoing transformative climate change, with profound implications for transportation[1,2]. Studies seeking to understand these impacts have primarily focused on quantifying how transport-relevant climatic conditions are changing and modelling future climate trends, focusing on shipping and winter roads[3,4]. A smaller body of research focuses on unmaintained semi-permanent trails on the sea ice, lakes, rivers, ocean and frozen ground (referred to as 'trails'), which are critically important for travel between settlements, to cultural sites and for practising traditional hunting, fishing and gathering activities[5,6]. This work catalogues local observations of changing climatic conditions and examines how these are affecting access[7,8], but does not assess regional trends or quantify how climate affects transportation. An absence of integrative approaches that cross scales and incorporate qualitative and quantitative methods has been noted to constrain understanding of how climate change affects Arctic transportation systems[4,9].

This paper develops a modelling framework to connect Indigenous knowledge and science to quantify how climate change affects trail access, focusing on the Inuit Nunangat. The 50 permanently inhabited communities of the Nunangat are primarily coastal and accessible year-round by air, with marine transportation possible in the summer. Travel outside of settlements by all-terrain vehicle (ATV), small watercraft and snowmobile is common year-round, involving the use of extensive networks of trails on land, water or sea ice and often involving travelling hundreds of kilometres in remote regions. The region is witnessing rapid warming, with Inuit among the populations most sensitive globally to climate impacts[10].

Three decades of trail access trends

Trail access models were created using the modelling framework described in Methods based on in-depth research in nine communities, and specify quantitative thresholds for weather and sea ice variables that determine trail access. Models were created for different trail types (land, water, sea ice) and categories of trail user (normal risk tolerance (Type 1), low risk tolerance (Type 2), high risk tolerance (Type 3)) (Fig. 1), resulting in the creation of nine trail access models (Land 1, 2, 3; Water 1, 2, 3; Ice 1, 2, 3). Thresholds in the model are outlined in Table 1. We examine the frequency of trail access threshold exceedance on a daily basis between 1985 and 2016 (11,504 days), applying the model to 16 communities that had sufficient and reliable data on the selected weather variables (from community meteorological stations) and sea ice conditions (from sea ice egg charts produced by the Canadian Ice Service) (Methods). Results are not disaggregated by community, as the modelling framework is designed to quantify general regional associations between climate-related conditions and trail access.

For normal-risk tolerance trail users, between 1985 and 2016 on average there were 194 days per year (Land 1) when land trails were accessible across all 16 communities; 195 days for ice trails (Ice 1) and 96 days for water trails (Water 1) (access days for different trail types are not mutually exclusive). Access varies by category of trail user, with 166 (2.26-fold greater) more access days per year estimated for land travel for high-risk tolerance (Land 3) compared to low-risk tolerance users (Land 2); 81 (+156.0%) more days per year for ice trails for high- versus low-tolerance users; and 55 (190.2%) more days per year for water trails for high- versus low-tolerance users. Trail access was most commonly constrained by ice conditions (38.9% of fails for all models), followed by temperature (30.6%), wind (24.4%), precipitation (4.6%) and visibility (1.4%), varying by trail type and community.

Mean monthly temperature of all study communities increased over the study period ($P = 0.002$) by an average of 2.18 °C. Daily total precipitation and mean wind speed changed significantly in some communities, but aggregated monthly values did not result in any significant regional changes ($P > 0.05$). Aggregated mean monthly visibility for all study communities increased ($P < 0.0001$), and mean daily minimum visibility increased by 0.45 km over the

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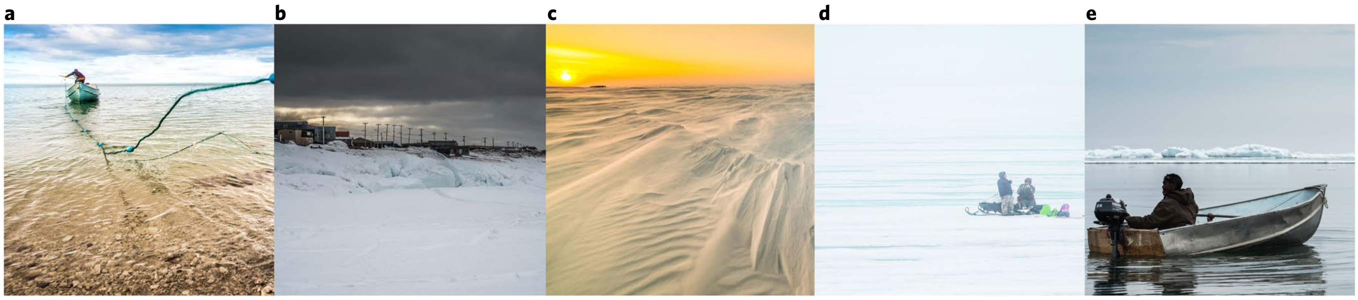

Fig. 1 | Numerous climatic conditions are important for individuals travelling over land, water and sea ice across Canada's Inuit communities. **a**, Temperature influences machine functioning, potential of getting stuck, and conditions of ice and snow. **b**, Precipitation affects ice conditions, visibility and risk of hypothermia. **c**, Wind speed and direction are influential on visibility, ice dynamics, waves and comfort. **d**, Visibility is important in wayfinding and monitoring the safety of surrounding ice conditions. **e**, Ice conditions are influential on the safety of travelling on ice and water. Credit: Photographs, D. Clark

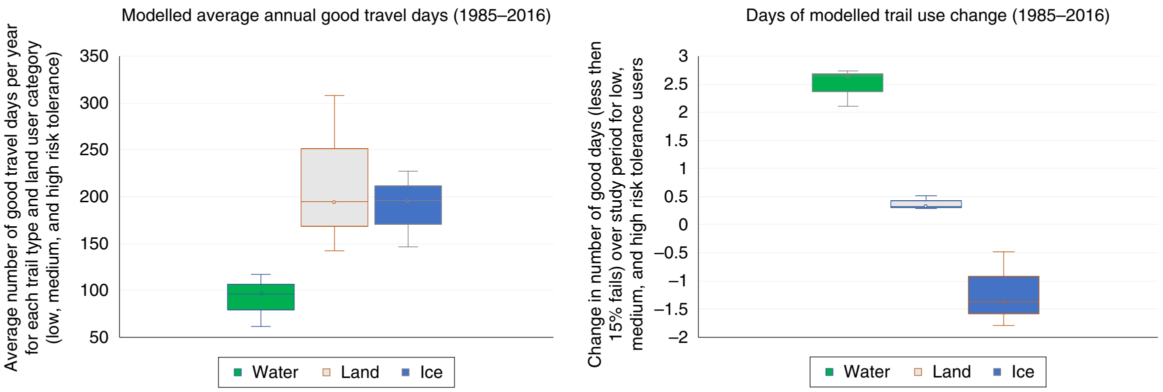

Fig. 2 | Modelled trail use has changed across the Inuit Nunangat over the past 30 years, although changes in the number of good days have been relatively small in comparison to the range in access available to travellers if they are among the most skilled and have access to high-quality equipment. We observe that access to land trails has increased by 0.52 and 0.27 days (Land 1 and Land 2, respectively), access to sea ice trails has decreased by 1.79 and 0.48 days (Ice 1 and Ice 2, respectively), and access to water trails has increased between 2.74 and 2.11 days over the study period (Water 2 and Water 3, respectively) (95% confidence). The whiskers represent Type 2 (low risk tolerance) and Type 3 (high risk tolerance) trail-users.

study period. Trends in ice conditions included later freeze-up dates and earlier break-up dates. On average, for all communities, 95.9% of days in September from 1985 to 1990 were ice free, compared to 98.9% of days for September from 2010 to 2015. An increase in ice-free days during the same time periods was noted in June (11.6 to 17.2%) and in December (3.2 to 6.3%), respectively. July, October and November experienced the greatest change during the time period, with an increase in ice-free days by 11.9, 16.7 and 16.4%, respectively. Across trail types, user categories and communities, overall modelled trail access from 1985 to 2016 increased between 1.38 days (Type 2 users) and 1.96 days (Type 3 users). For land trails, access increased by between 0.52 (Land 1) and 0.33 days (Land 3), for water trails it increased between 2.64 (Water 1) and 2.11 days (Water 3), while access to ice trails decreased between 1.78 (Ice 1) and 0.48 days (Ice 3) (Figs. 2 and 3).

The time-series models showed that access to land trails increased in 25.0% (Land 1 and 2) and 37.5% (Land 3) of the study communities, and declined in 6.0% (Land 1 and 2) of communities over the study period. In communities where a change in trail access was detected, land access increased by between 0.27 days (Land 2) and 0.32 days (Land 3), with improved access primarily driven by decreasing high wind speed (six communities) and visibility improvements (two communities). The reason for a day being categorized as inaccessible did not vary widely by trail type or user type. There were no significant changes in access correlated to precipitation or temperature changes. In those communities with reduced access, visibility was the primary driver.

Access to ice trails was modelled as declining significantly in between 12.5% (Ice 3) and 56.0% (Ice 2) of communities from 1985 to 2016, driven by changing ice concentration, later freeze-up and earlier break-up. In no communities was ice access observed to increase, although declining numbers of fails due to wind were observed in seven communities, a reduction in fails due to visibility in two communities, with precipitation-related fails decreasing for one community and increasing for another (all Ice 1). No trends were observed due to temperature.

Increased access to water trails was significant in 56.0% (Water 2) and 75.0% (Water 3) of communities from 1985 to 2016. Modelled improvements reflect decreasing high wind speed (six communities), improved visibility (five communities) and changes in temperature (one community). Water access was estimated to be declining in between 0% (Water 3) and 18.7% (Water 2) of communities, reflecting increased wind speed in these locations.

New perspectives on changing trail access

The trail access models reveal several new insights on the role of climate in affecting access. First, despite significant change in climate-related conditions from between 1985 and 2016, including warming of >2 °C, the models indicate that in general trail access has been minimally affected, increasing overall between 1.38 and

Table 1 | Fail thresholds computed for different trail types (land, sea ice, water) and users (low, normal, and high risk tolerance), as identified by Inuit.

Trail type	Model	Fail thresholds identified by Inuit
Land	Land trail users with normal risk tolerance (Land 1)	• Temperature between −5 °C and 5 °C • Precipitation >10 mm day^{-1} when temperatures > 0 °C • Precipitation >5 mm day^{-1} when temperatures <0 °C • Wind >40 km h^{-1} when temperatures >0 °C • Wind >20 km h^{-1} when temperatures <0 °C • Visibility <1 km
	Land trail users with low risk tolerance (Land 2)	• Temperature between −8 °C and 5 °C • Precipitation >5 mm day^{-1} when temperatures >0 °C • Precipitation >2 mm day^{-1} when temperatures <0 °C • Wind >30 m h^{-1} when temperatures >0 °C • Wind >15 km h^{-1} when temperatures <0 °C • Visibility <2 km
	Land trail users with high risk tolerance (Land 3)	• Temperature between 0 °C and 4 °C • Precipitation >15 mm day^{-1} when temperatures >0 °C • Precipitation >10 mm day^{-1} when temperatures <0 °C • Wind >50 m h^{-1} when temperatures >0 °C • Wind >35 km h^{-1} when temperatures <0 °C • Visibility <1 km
Sea ice	Ice trail users with normal risk tolerance (Ice 1)	• Temperature between −5 °C and 5 °C • Precipitation >3 mm day^{-1} • Wind >30 km h^{-1} • Visibility <1.5 km • Ice concentration <80% • Ice thickness <15 cm
	Ice trail users with low risk tolerance (Ice 2)	• Temperature between −5 °C and 10 °C • Precipitation >1 mm day^{-1} • Wind >15 km h^{-1} • Visibility <3 km • Ice concentration <90% • Ice thickness <30 cm
	Ice trail users with high risk tolerance (Ice 3)	• Temperature between 3 °C and 10 °C • Precipitation >5 mm day^{-1} • Wind >40 km h^{-1} • Visibility <1 km • Ice concentration <70% • Ice thickness <10 cm
Water	Waterway users with normal risk tolerance (Water 1)	• Temperature <−5 °C • Precipitation >4 mm day^{-1} • Wind >20 km h^{-1} • Visibility <2.5 km • Ice concentration >30%
	Waterway users with low risk tolerance (Water 2)	• Temperature <0 °C • Precipitation >1 mm day^{-1} • Wind >15 km h^{-1} • Visibility <4 km • Ice concentration >10%
	Waterway users with high risk tolerance (Water 3)	• Temperature <−10 °C • Precipitation >8 mm day^{-1} • Wind >30 km h^{-1} • Visibility <1 km • Ice concentration >50%

1.96 days over the study period. While changing ice conditions have reduced trail access, improvements in visibility and wind were modelled as offsetting these negative trends by enhancing access to both land and water trails. As would be expected, there is a negative correlation between ice trail use and water trail use. The models reveal that average temperature, per se, has had limited impact on trail access; although participants describe temperatures in the critical range of −5 to 5 °C as having the most influence on trail access, the greatest change is happening in the first and fourth quartiles (that is,−40 and 15 °C). These findings are supported by other studies which illustrate how Inuit are developing new trails and alternating forms of transport[8,11,12], but they challenge other work which argues that trail access is rapidly declining across northern Canada[13–15]. Our focus on modelling regional trends thus differs from the literature, which is based on in-depth case studies in single communities[13]. It is also possible that variables not captured in our models may account

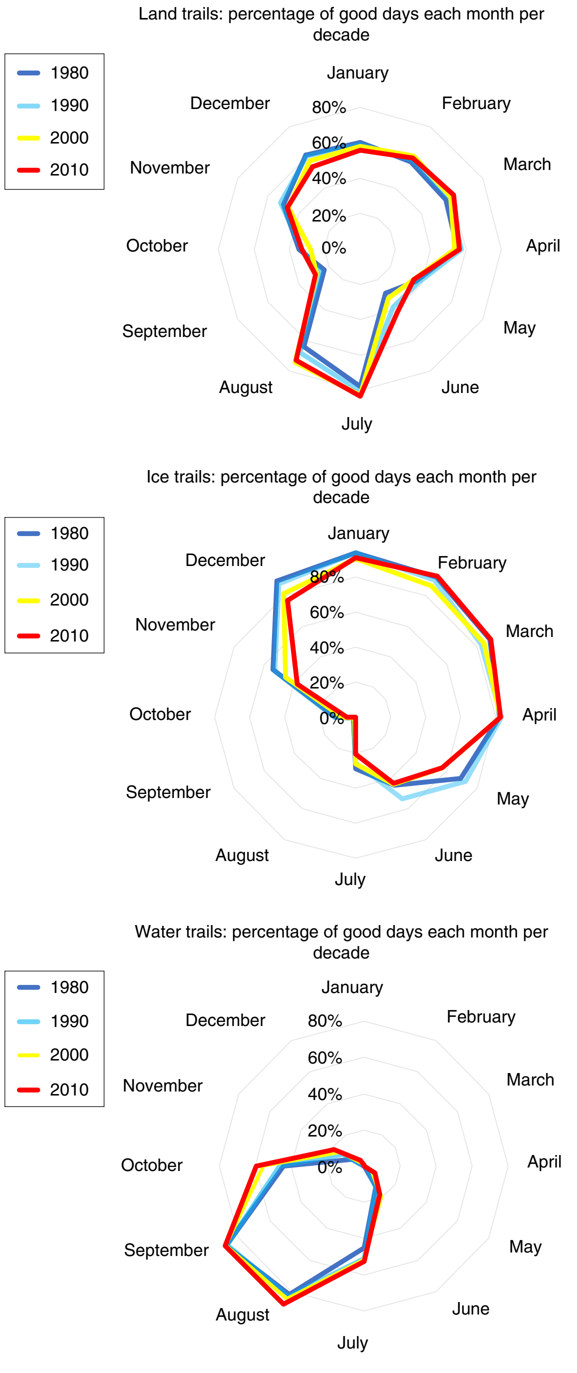

Fig. 3 | Seasonal and decadal patterns of trail access were observed across the study region. We observe that periods of trail use are both shifting and changing in length.

for the differences observed (Supplementary Table 1) or that communities have been unable to take advantage of improving water access due to low levels of boat ownership[16,17]. Nevertheless, the dominance of findings across communities and models challenges researchers to: (1) further investigate the role of under-studied variables in affecting trail access (for example, wind speed, visibility); (2) focus on change in critical thresholds for trail access; and (3) examine how changing access in one trail type is offset by change in another, and how this varies by category of trail user, trail type and community.

Second, the impact of changing climatic conditions on trail access is strongly influenced by the type of trail. Across communities, land trail access changed the least. In at least one model, for example, no change in land access was detected for eight communities, no change in ice access for five communities and no change in water access for one community. This reflects the limited sensitivity of land trails to wind and visibility and the diversity of transport options for land travel (snowmobile, ATV, foot), and indicates that communities with a greater reliance on land trails may be less sensitive to climate impacts. For some communities where ice and/or water trail access is declining, land trails may offer alternative access routes, varying by local geography and the ability to use land trails (that is, knowledge, equipment). 'Trail switching', however, may have negative implications, with the use of the ice and its associated hunting and fishing niches closely linked to food systems, cultural identity and well-being[18,19].

Third, the knowledge, skill sets and risk tolerance of trail users are substantially more important than changing climate-related conditions in determining trail access. Across trail types, a high risk tolerance (Type 3) user, on average, has 101 days per year more access than a low-risk tolerance user (Type 2); this exceeds the impact of changing climatic conditions, which increased overall access by 1.38–1.96 days. For changing access, the difference between the average and low-risk tolerance user (Type 2) and a high risk tolerance user (Type 3) for all trail types is 0.31 days of access over the 31-year study period (±35% of total good days). Most studies on Arctic transportation and climate change do not take into consideration different types of trail users, which is a major limitation.

The importance of Indigenous knowledge in affecting trail usage and adapting to climate change is well documented[20,21], although this is the first study to quantify the magnitude of the impact on trail access. If training and experience resulted in all low-tolerance risk users shifting to become normal-tolerance risk users by developing competence and confidence in travelling under a broader set of conditions, this could potentially improve access by 45 days per year across transport types. This underpins the importance of investing in skills training and cultural programming (for example, school programmes, community mentorship initiatives), alongside investment in making diverse types of transport equipment locally available through harvester support programmes[21]. Results also support the use of selected technology (for example, global positioning system, satellite phones) if the equipment helps move a land user from a Type 2 to a Type 1 or 3 user, although there is limited evidence that technology alone can produce the shift[21–23].

Modelling future impacts from the bottom up

A key contribution of the paper is to advance a new approach for modelling climate impacts. Traditional climate impacts studies have generally begun with climate projections, modelling how projected changes in temperature, precipitation and extremes will affect human systems. Such work has been described as top-down, focusing on climatic conditions captured by models, and has been critiqued as poorly representing real-world complexities[24,25]. In this context, place-based approaches are increasingly common[26], focusing attention on complex interactions between climate change and society in specific locations, and have been described as bottom-up because these focus on locally identified and relevant conditions[25]. Such approaches develop rich detail, but have been critiqued as being too context specific and providing limited basis for scaling up, with their qualitative nature constraining the ability to link to climate models to project future trends[27,28]. The modelling framework developed here seeks to bridge this disconnect by explicitly focusing on connecting Indigenous knowledge with the vocabulary necessary to incorporate instrumental climate and ice data to facilitate a quantitative examination of trends. Such an ethnoclimatology approach is built upon recognition that Indigenous knowledge holders possess detailed, place-specific and longitudinal knowledge on how climatic and non-climatic factors affect human activities and from which climatic parameters, thresholds and interactions can be identified, measured and tracked. Future work will complement the focus here by developing a broader ethnoclimatology of changing trail access, with emphasis on value systems embodied within Indigenous knowledge and the way in which these affect how change is perceived, experienced and responded to.

The interdisciplinary approach facilitates the scaling up of understanding derived from place-based research, and can guide future modelling to focus on climate-related conditions that matter. The new generations of higher-resolution global and regional climate models have the potential to provide information on how critical variables might change, and what that means for trail access. However, the ability of climate models to represent the variables of interest varies with temperature and precipitation, using appropriate downscaling and bias correction methods being most amenable (Supplementary Table 2). With these localized projections, a way forward might be to use climate model projections to develop a set of scenarios for future trail access, with estimated uncertainties, from which a portfolio of adaptation and risk reduction options could be identified and tested. The focus on connecting Indigenous knowledge and science is key to the approach; the aim is not to compare observations of changing conditions from both knowledge systems, nor to use Indigenous knowledge to fill in gaps in scientific understanding as is common in the literature[29], nor to integrate Indigenous knowledge into science, but rather to use it as the foundation from which to develop a more nuanced, locally grounded and ultimately more relevant picture of how climate affects human activities. While we develop a modelling framework in the context of Indigenous trail use in the Arctic, its key components hold broad relevance to impacts, adaptation and vulnerability research globally.

Online content

Any methods, additional references, Nature Research reporting summaries, source data, statements of data availability and associated accession codes are available at https://doi.org/10.1038/s41558-019-0435-7.

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Author contributions

J.F. designed the study, helped analyse data and wrote the paper. D.C. collected and analysed data and helped write the paper. T.P., L.B.F., L.C., J.D., M.N. and S.L.H. assisted with study design, analysis and write-up.

Competing interests

The authors declare no competing interests.

Additional information

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Methods

Modelling framework. We developed a modelling framework to quantify how climate change is affecting access to trails, connecting Indigenous knowledge and science. The modelling framework has four steps (Supplementary Fig. 1), with key definitions provided in Supplementary Table 3.

In the first step, we identified and characterized climate-related conditions affecting trail access, working closely with nine communities. Semi-structured interviews ($n=273$) were conducted with regular trail users, focusing on documenting: (1) highly localized and detailed descriptions of climate-related conditions that affect the ability to safely use trails and which determine whether a trail is usable; (2) knowledge about past and current use of trails which Inuit use to identify how the nature of climate-related conditions poses risk and varies by type of transport (for example, boat, ATV, snowmobile), and by the location and timing of travel; and (3) knowledge on how travel risks are perceived and managed (Supplementary Table 4). Interviewees were selected based on referral by community hunters and trappers associations, land search and rescue groups or elders, then snowballing. Interviews were recorded where permission was given. Taken together, this information allowed us to assess how trail access differs by individual depending on environmental knowledge and skill sets, access to resources and risk tolerance. To validate and contextualize our qualitative findings, we employed methods of triangulation, member-checking, ground-truthing and spending considerable time travelling with trail users across seasons from 2015 to 2017, asking questions while using trails. The communities were selected to capture a sample reflective of diverse settlements and the varied geographies in which trails are used, with the aim of developing a generalizable understanding of climate-relevant conditions affecting trail access across Inuit Nunangat. Team members had well-established working relationships with the selected communities before this project commenced.

In the second step, we quantified thresholds of climate-related conditions that affect trail access, as identified in step 1 (Supplementary Table 5). This involved developing a list of variables specific to each climate-related condition that could be measured, and was narrowed to those that were recorded on at least a daily basis by Environment and Climate Change Canada community weather stations (that is, daily average temperature, total precipitation, average wind speed and average visibility) or weekly sea ice egg charts produced by the Canadian Ice Service (weekly average ice concentration and thickness). Then, informed by the components of Indigenous knowledge identified above, we created thresholds specific to each variable that define boundaries of whether a trail is accessible (pass) or not (fail). Thresholds were identified by analysing interview transcripts, disaggregated by trail type and user category, with interviewees explicitly asked about specific thresholds that limit trail access; thresholds were also imputed from interviewee descriptions of 'good' and 'bad' conditions.

Interview data were analysed using thematic content analysis. In all cases, interview data were triangulated with participant observation and published literature, and reviewed with communities. For example, if a particular wind threshold was identified as being dangerous for travel, this was cross-referenced by observing the behaviour of different trail users on windy days, asking questions while travelling when windy and reviewing relevant publications on how wind affects trail usage. Identified thresholds are generalized across communities (see Table 1). These thresholds were identified for three types of trail: land (ATV, snowmobile), water (boat) and sea ice (snowmobile). To account for variation in how individual skill level, knowledge, risk tolerance and equipment affect trail access, thresholds were set differently for different categories of trail user: Type 1 (normal risk tolerance); Type 2 (low risk tolerance); and Type 3 (high risk tolerance) (Supplementary Tables 6, 7). This stratification by trail type and trail user type resulted in the creation of nine trail access models (Land 1, 2, 3; Water 1, 2, 3; Ice 1, 2, 3).

In the third step we developed a procedure for characterizing trail access on a particular day, whereby each variable was classed as either pass or fail on a specific day using the thresholds for each trail type and user category. Passes and fails were then aggregated and, if >15% of variables were classed as a fail, the trail was defined as not accessible on the particular day in question. This step was validated by Inuit community members, and reviewed by university-based researchers ($n=10$) with a combined 135 years of experience working with Inuit communities.

In the fourth step, the trail access variables were used to model and examine long-term trends in trail access for the period 1985–2016 at a regional scale, focusing on 16 communities (32% of communities in the Inuit Nunangat). The communities were selected based on the availability of sufficient and reliable weather and ice data for the study period.

Trail access models. Here we characterized the components of the models, supported and illustrated with quotes from interviews and cross-referenced with relevant literature. Table 1 provides specific thresholds. Results are not disaggregated by community, reflecting the fact that trail access models were created to capture climate-related conditions that affect trail access regionally, not just specific to a particular location.

Temperature. There are critical temperature windows in which different risks occur. Temperature affects the functioning of snowmobiles and traveller comfort, and can be dangerous if travellers become wet or experience an emergency. Community members explained that cold temperatures (that is, below −20 °C) alone are not problematic, with temperature identified as a significant risk factor when it was within the margins of 0 °C for travel on land and ice due to snowmelt, which leads to muddy/slushy conditions on trails and higher river levels, making it challenging to drive a snowmobile or ATV; the exposure of rocks in spring and autumn, which can damage snowmobiles; more dynamic ice conditions resulting in unpredictable hazards; and temperatures above 0 °C increasing overheating in snowmobiles[8,30]. As one interviewee explained,

> In the spring, the weather is warm so people don't bring warm clothes … You are kind of in between the seasons where it can be either really cold or warm and you … [have rain and open water with potential to get] wet and cold. You have got to prepare both ways: you need to have your winter gear and your rain gear. And most people don't. [Type 3 individual]

High-risk tolerance individuals are also more prepared for a change in conditions or risks that come with the spring and fall seasons, and thus have a narrow band of temperatures between <0 and <4 °C defining the failure threshold, compared to <−8 to <5 °C for Type 2 individuals (low risk tolerance) (Supplementary Table 4). Across seasons, temperatures between −5 and 5 °C have been associated with increased risk based on analysis of search and rescue data (Land 1, Ice 1)[31]. For travel by boat, temperatures below 0 °C are not generally desired as it is uncomfortable, and those below −10 °C can create hazards if ice forms, which makes it difficult to return to shore. Type 3 individuals have an in-depth understanding of how trail conditions are affected by climate-related conditions, knowledge of alternative routes and well-developed skill sets, which underpin greater ability and confidence in using trails despite temperature-induced challenges.

Precipitation. Precipitation falls most often as snow on the Arctic coast, with rainfall most common from June to September. Separate thresholds are created for rain and snow, reflecting the different risks posed. For land travel, rain is generally not desired and can pose a risk if temperatures are near freezing, due to high risk of hypothermia, while white-out conditions associated with snow are not favourable. Five millimetres of precipitation can equal 10 cm of snow in the winter, and was identified as resulting in dangerous travel conditions for a Type 1 user (normal risk tolerance), with a total daily rainfall of >10 mm of rain considered uncomfortable for travelling. Snow is associated with poor visibility: for travel on the ice, this limits the ability to observe ice colour and judge ice thickness, and can cause a rapid reduction in both ice quality and safety, particularly in spring, creating challenges for those without an in-depth understanding of trail conditions and ice dynamics[12,17,32–35]. Based on interviews and the participatory methods, 3 mm day^{-1} of rain or 9 cm day^{-1} of snow would probably create unsafe conditions for ice trail access for a Type 1 user (normal risk tolerance). For travel on water, although neither light rain nor snow are desired, if this does not decrease visibility and is <5 mm of precipitation in a 24 h period it generally does not impact safety. Fail thresholds reflect how precipitation, especially rainfall, can be problematic for low-risk tolerance trail users (Type 2 users) given the risk of hypothermia if unprepared. As one interviewee explained,

> I have had relatives pass away on a trip a few years ago on a [rainy day] like this. Springtime, warm weather. Bad weather came, and they got so wet they passed away. [Type 1 individual]

Wind. Wind is the weather variable that impacts all types of travel and can have substantial safety effects when thresholds are reached, although for land trails it was reported by Inuit as important more in terms of personal comfort than safety. Wind conditions were frequently described as being hazardous for travel on ice and water, with separate thresholds calculated to capture the different risks posed by wind if temperatures are above (rain) or below (snow) 0 °C. For travel on the ice, wind during the winter can create blizzards and limit visibility, affect ice leads and ice surface roughness, making travelling more difficult, and create unfavourably cold conditions through wind chill. Based on studies in Clyde River and Iqaluit, Nunavut, wind thresholds of 30 and 20 km h^{-1} were identified (refs. [7] and [8], respectively) as being indicative of dangerous conditions for ice use. We established fail thresholds ranging 15–50 km h^{-1}, with the breadth of range reflecting our differentiation by category of trail user. As two Inuit interviewees explained, "I wouldn't want to be on the ice when the wind picks up from the North, the ice chunk ice comes off" [Type 1 individual]; and "Once you could see ten miles and a few minutes later you could see less than a mile. Rain and snow are dangerous. Wind is dangerous on the water, not on the land" [Type 3 individual]. Rough water is particularly dangerous for the small watercraft (<5 m) commonly used by Inuit, with wind speeds >30 km h^{-1} having the potential to create waves near 1 m that are beyond the limits of most small boats. During periods of ice break-up and in the summer, wind can blow ice into the shore and limit the ability of Inuit to return from trips by boat[36,37].

Visibility. Visibility was discussed mostly in relation to blizzards or foggy conditions, which reduce the ability to observe trail conditions. This variable is important for travel on land where trails traverse steep and rocky terrain and involve crossing potentially unstable ice on frozen rivers and lakes, or on ice where trails may cross areas of thin ice, requiring unencumbered awareness of conditions. Poor visibility can also challenge navigation, and while experienced land users described being able to navigate using snow drifts, topographic features or global positioning systems[38–40], limited visibility was also described as being disorienting and requiring people to make shelter and wait for better conditions to travel to safety. For those without the required skill sets, such situations can be life threatening[16,32,40]. Poor visibility impacts the safety of all travellers because it is needed for navigation and helps in detecting potential ice hazards, although it was reported as generally less of a challenge for boating except for when fog is very thick. Varying by user category and trail type, the failure thresholds were set between 1 and 4 km minimum visibility.

Ice conditions. Sea ice conditions are critically important for trail use and are continuously changing, affected by tides, wind, temperature, precipitation and cloud-free days[37,41]. Ice concentration is important for water and ice trails[8,32,42,43]. Low or no ice concentrations are preferred by Inuit for boating, with a number of accidents involving loss of life occurring where boats have been sunk by ice strikes[8] or occupants have been thrown overboard, with the presence of ice also increasing the risk of routes being closed off if blown together by wind[12]. Less than 30% ice coverage is generally preferred for boating, with a 50% upper limit for high-risk tolerance individuals (Type 3) and 10% for a Type 2 user (low risk tolerance). For travel on ice, low ice concentrations can make travel difficult and for those less knowledgeable it can be dangerous; indeed, each year individuals lose snowmobiles in incidents involving open water leads. Over 80% ice concentration was identified as optimal for a Type 1 user (normal risk tolerance).

Ice thickness is also important for travel over ice, and was observed to be dependent on the weight of the machinery and load, as well as on the knowledge and risk tolerance of the individual. It is generally recommended that for an average situation, most ice in the area should be >15 cm thick. Furthermore, in some communities, trail users pull their boat to the ice floe edge on a sledge and then harvest seal, whale, narwhal or walrus from there[36,41]. It was determined that if ice concentration decreased at distant points and remained high at near points, this would still allow travellers to access the ice edge. Low sea ice thickness and concentration have been associated with a higher probability of a search-and-rescue incident[31]. While river and lake ice are important for land travel, instrumental data were not available. As one interviewee explained,

> It's mostly dangerous [for travelling on] on the sea ice when it starts building up. Some ice [is] very dangerous. Last spring, or last year, my brother went down with his Skidoo [snowmobile] and the ice was very thin all the way, all the same. [Type 1 individual]

Analysing trends in trail access. A time-series of weather variables was developed using an Environment and Climate Change Canada historic almanac of daily and hourly observations. All available weather data for the 16 communities (1985–2016) were downloaded. Mean daily temperature and total daily precipitation data were downloaded; wind speed and visibility data were downloaded from hourly observations and were transformed into daily mean, minimum and maximum values. As a quality control measure for weather data we examined outlier observations, comparing observed daily variable mean values to minimum and maximum observations[44]. Weather data were assessed for homogeneity using penalized maximal *t*- and *F*-tests[45,46]. To homogenize observations, we began by capping the maximal observed visibility at 14 km (9 nm). Visibility was then aggregated to mean monthly observations and homogenized using the penalized maximal *F*-test that accounts for autoregressive and non-zero trend change[46]. Resulting monthly data shifts were applied to daily observations[46]. Daily wind speed was also homogenized by applying non-zero trend change.

Ice data were collected from weekly egg charts published by the Canadian Ice Service[47]. Ice charts were converted from coverage files to 4,721 shapefiles using python scripts in ESRI ArcGIS 10.2. We then extracted the egg code variables from three observation points around each of the 16 communities for all weeks during the study period, staggered at near (<35 km), medium (75–200 km) and far (175–300 km) distances from shore. These observation sites were selected based on interviews, literature review and trail maps from land-use monitoring programmes to identify key areas where trails cross. We developed and ran a script in R CRAN to extract data at the observation sites from overlaid egg code polygons. The average distance from observation points to communities was 25.2 km for all near points, 125.0 km for medium points and 275.0 km for far points.

To best represent user-experienced conditions, ice data were transformed for application as an index of both ice thickness and ice concentration. Total ice concentration is generally represented as $(0\text{–}10)\,10^{-1}$, or the sum of each partial concentration for every type of ice present. We focused on the total ice concentration, as this has been correlated with increased numbers of search-and-rescue incidents[31]. We also transformed the data categorization label for land-fast ice from 0 to 10 because, while land-fast ice can be difficult to travel on (at times very rough), there is a low risk of falling through the ice. Similarly, because 'bergy' water was consistently considered unsafe for ice travel, we considered this to be a concentration of 0. Ice thickness for each observation point was assumed to be the value for the ice type with the highest concentration in the area. This assumption has also been validated in previous search-and-rescue research[31]. Similar to the ice concentration variable, we transformed ice thickness values from categorical to discrete values. Land-fast ice which is usually not assigned a thickness was assumed to have an ice thickness of 10 (thicker than any minimum limit set in the various trail models), and all ice thicker than 70 cm was recoded as 10, 11, 12, etc. Finally, ice observations were transformed to daily observations by creating linear splines using each weekly observation as a knot to interpolate ice thickness and ice concentration. Missing weekly observations were also estimated using linear splines with a maximum gap between observations of 21 days. During weeks with missing observations, splines allowed for the estimation of ice thickness and concentration.

Weather and ice data were collapsed and/or organized into daily observations for the time frame for the communities using R CRAN computational environment in RStudio. We ran the 'if–then' statements on the ice and weather time-series data for each trail and trail user type, computing whether each weather and ice variable on each day represented a pass or fail. The number of variables that failed per day was tabulated, and a new dichotomous variable was created with one observation per day generated for each day for each trail and user type (for example, the trail was inaccessible on a given day if >15% of variables failed; the trail was accessible if <15% of variables failed on a given day). The 15% threshold was selected based on distribution of fails and participant observations. Furthermore, time-series analysis were also conducted for counts of fails per day, providing a confirmation test of modelled day access trends. Additionally passes/fails for each parameter for each model were recorded, allowing us to assess how individual parameters were affecting access over time.

We applied Mann–Kendall tests for all trend analyses of indices and variables. These tests allow for analysis of non-parametric data with missing observations, and are commonly used to examine environmental and climatic trends[48–50]; using a Shapiro–Wilk test, we confirmed that the data were not normally distributed. We removed seasonality from time-series before analysis, first by aggregating data from daily observations into monthly mean values then applying a seasonal-trend decomposition based on loess[50,51]. There is strong evidence that serial correlation exists for most of the environmental variables, thus making likely a Type I statistical error[52]. Using the *mkTest* function in R, we applied both a Mann–Kendall test and a modified Mann–Kendall test[42]. These tests correct for Type 1 statistical error by assessing the strength of serial correlation in a time-series and then adjusting results accordingly (variance of S is multiplied by a factor of $n \times n s^{-1}$). Results from these latter tests were used to determine statistical significance and slope of trends. Pre-whitening was not used due to the large sample size and often high slope trends[52]. In the development of the model and trend analysis process, we examined residual trends to observe model fit. For analysis, missing data were approximated using linear splines. All results presented were considered statistically significant using an alpha <0.05. Sen slope of significant variables was multiplied by 377 months to determine the change in y over the study period. To determine change in good days, Sen slope was multiplied by 377 months and (365 ÷ 12) to convert from percentage of good days per month to good days over the study period. Trends for base variables, such as temperature and precipitation, were also assessed by calculating monthly averages, de-seasonalizing the values and calling a Mann–Kendal test to correct for autocorrelation.

Reporting Summary. Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability

The full data that support the findings of this study are available from the corresponding author upon request.

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Reporting Summary

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☒	☐	Clearly defined error bars *State explicitly what error bars represent (e.g. SD, SE, CI)*

Our web collection on statistics for biologists may be useful.

Software and code

Policy information about availability of computer code

Data collection	A script was developed in Python to pull historic weather data from the Environment Canada repository. Scripts used in this study will be made upon request to the authors.
Data analysis	Scripts were developed in R in order to iteratively condense datasets and run Mann Kendal and timeseries analyses. Open source RStudio was used in this study. The following open source packages were used: chron, forecast, lubridate, timeSeries, timeDate, tseries, trend, dplyr, snht, xts, and mkTrend, fume. The copyrighted R package RHtestsV4 was used with author's permission.

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The datasets analyzed during the current study are available in the Environment Canada Historic Data repository, http://climate.weather.gc.ca/historical_data/search_historic_data_e.html and in the Environment Canada Ice Archive, http://iceweb1.cis.ec.gc.ca/Archive/page1.xhtml;jsessionid=9EE00D84446B26639CF8597412582AE5?lang=en

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Study description

We develop a modeling framework to quantify how climate change is affecting access to unmaintained semi-permanent trails on the land, water, and sea ice. We identified general thresholds for weather and sea ice variables that define boundaries that for trail access, applying these thresholds to instrumental data on weather and sea ice conditions to model daily trail accessibility from 1985-2016 for 16 communities. To analyze trends we use modified Mann Kendall tests on 11,504 days of weather and ice observations.

To assist with model parameterization, data from participant observation and semi-structured interviews (n=273) were used.

Research sample

This study focuses on weather and ice trends across Inuit Nunangat region of the Canadian Arctic. Data from 16 communities are used in this study. Weather and ice characteristics and model parameters were based on a review of regional case studies, and qualitative work with communities across the region.

To assist with developing goal posts for the model parameters, data from participant observations and semi-structured interviews came from multiple field seasons in 9 communities across Inuit Nunangat (18% of all communities). Interviews and observations were conducted (n=273) were conducted with Elders and active trail users. Samples in each community were determined based on community size and saturation - a method that is standard when working with Indigenous communities across the Canadian Arctic.

Sampling strategy

All communities across Inuit Nunangat where consistent weather and ice data were available between 1985 and 2016 were selected for this study. The 16 selected communities were spatially representative of the diverse geography and latitudes across the Canadian Arctic

Study participants for the participant observations and semi-structured interviews were selected based on recommendations from Elder councils and hunting and trapping organizations, and snowballing - this the standard approach used across the region and is reflexive to community desires and values.

Data collection

Data was obtained from the Environment Canada historic weather database and ice chart archives.

Timing and spatial scale

This study analyzed daily weather and ice conditions between January 1985 and June 2016. The spatial extents of Inuit Nunangat region in the Canadian Arctic were used,

Data exclusions

Linear splines were used to estimate values where observations were missing. No data were excluded from the study.

Qualitative data used to inform the model perimeters was analyzed using thematic content analysis.

Reproducibility

Procedures and methods applied in this study are well documented. Models run to analyze data are written as scripts in R and will be made upon request. There was no attempt to repeat the study.

Randomization

This study uses timeseries analysis through Mann Kendall tests. Covariates were not tested. Data were grouped by location of weather and ice observations.

Blinding

Blinding was not relevant for this retrospective analysis.

Did the study involve field work? ☐ Yes ☒ No

Reporting for specific materials, systems and methods

Materials & experimental systems

n/a	Involved in the study	
☒	☐	Unique biological materials
☒	☐	Antibodies
☒	☐	Eukaryotic cell lines
☒	☐	Palaeontology
☒	☐	Animals and other organisms
☐	☒	Human research participants

Methods

n/a	Involved in the study	
☒	☐	ChIP-seq
☒	☐	Flow cytometry
☒	☐	MRI-based neuroimaging

Human research participants

Policy information about studies involving human research participants

Population characteristics	Parameters to define what conditions individuals do not travel on the ice, water, and land across Inuit Nunangat were defined, in part using data from participant observations and semi-structured interviews (n=279). Interviews were with Elders and regular trail users from 9 communities across Inuit Nunangat, 18% of all communities. The sample communities provided rich spatial and geographic representation across the region, including interviews from the Kivalliq, Inuviauit, Baffin, and Kitikmeot regions.
Recruitment	In-line with standard practice across the region, participants were selected based on recommendations from Elder Councils, hunters and trappers organizations, and through snowballing. Research licenses were obtained through Research Ethics Boards at McGill University and University Guelph, as well as from regional ethics boards (Nunavut Research Institute and Aurora College). Oral permission was also requested and granted from community leadership. Written consent was obtained from all study participants.