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Changing access to ice, land, and water in Arctic communities

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Arctic climate change has the potential 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, applying these thresholds to instrumental data on weather and sea ice conditions to model daily trail accessibility from 1985-2016 for 16 communities. We find that overall trail access has been minimally affected by >2°C warming in the last three decades, increasing by 1.38-1.96 days, differing by trail type. Across models, the knowledge, equipment, and risk tolerance of trail users was substantially more influential in determining trail access than changing climatic conditions.

The Arctic is undergoing transformative climate change, with profound implications for transportation[30,31]. Studies seeking to understand these impacts have primarily focused on quantifying how transport-relevant climatic conditions are changing and modeling future climate trends, focusing on shipping and winter roads[32,33]. A smaller body of research focuses on unmaintained semi-permanent trails on the sea ice, lakes, rivers, ocean, and the frozen ground (referred to as 'trails'), which are critically important for travel between settlements, to cultural sites, and for practicing traditional hunting, fishing, and gathering activities[34,35]. This work catalogues local observations of changing climatic conditions and examines how they are affecting access[36,37], 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[33,38].

This paper develops a modeling framework to connect Indigenous knowledge (IK) 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, 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 the land, water, or sea ice, often involving traveling hundreds of kilometers in remote regions. The region is witnessing rapid warming, with Inuit one of the most sensitive populations globally to climate impacts[39].

Three decades of trail access trends

Trail access models were created using the modeling framework described in *Online Methods* based on in-depth research in 9 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)) (Figure 1), resulting in the creation of 9 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 1985-2016 (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) (*Online 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 there was an average of 194 days per year (*Land 1*) when land trails were accessible across the 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 times 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 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 2.18ºC. 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 0.45km over the 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 1985-1990 were ice free, compared to 98.9% of days for September from 2010-2015. 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 1985-2016 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*) (Figures 2, 3).

The time series models showed that access to land trails was increasing in 25.0% (*Land 1&2*) and 37.5% (*Land 3*) of the study communities, and declining in 6.0% (*Land 1&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*) to 0.32 days (*Land 3*), with improved access primarily driven by decreasing high wind speed (6 communities) and visibility improvements (2 communities). The reason for being categorized as an inaccessible day did not vary widely by trail type or user type. There were no significant changes in access correlated to precipitation or temperature changes. In the communities with reduced access, visibility was the primary driver.

Access to ice trails was modeled to be declining significantly in between 12.5% (*Ice 3*) to 56.0% (*Ice 2*) of communities from 1985-2016, driven by changing ice concentration, later freeze-up, and earlier breakup. In no communities was ice access observed to increase, although declining number of fails due to wind was observed in 7 communities, a reduction in fails due to visibility in 2 communities, with precipitation related fails decreasing for 1 community and increasing for 1 community (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 1985-2016. Modeled improvements reflect decreasing high wind speed (6 communities), improved visibility (5 communities), and changes in temperature (1 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 1985-2016, including >2°C warming, the models indicate that overall trail access has been minimally affected, increasing overall between 1.38 and 1.96 days over the study period. While changing ice conditions are reducing trail access, improvements in visibility and wind were modeled to be 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; participants describe temperatures in the critical range of -5 to 5°C as having the most influence on trail access yet the greatest change is happening in the 1st and 4th quartiles (i.e. -40°C and 15°C). These findings are supported by some studies which illustrate how Inuit are developing new trails and alternating forms of transport[37,40,41], but challenges other work which argues that trail access is rapidly declining across northern Canada[42-44]. Heretofore, our focus on modeling regional trends differs from the literature which is based on in-depth case studies in single communities[42]. It is also possible that variables not captured in our models may account for the difference (*supplementary table 1*), or that communities have been unable to take advantage of improving water access due to low levels of boat ownership[45,46]. Nevertheless, the dominance of findings across communities and models challenges researchers to: i) further investigate the role of under-studied variables in affecting trail access (e.g. wind speed, visibility); ii) focus on change in critical thresholds for trail access; and iii) 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.

Secondly, 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 8 communities, no change in ice access for 5 communities, and no change in water access for 1 community. This reflects the limited sensitivity of land trails to wind and visibility, and 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 (i.e. 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[47,48].

Thirdly, the knowledge, skillsets, 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 between 1.38 and 1.96 days. For changing access, the difference between the average and low tolerance user (Type 2) and a high tolerance user (Type 3) for all trail types is 0.31 days of access over the 31year 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 (IK) in affecting trail usage and adapting to climate change is well-documented[49,50], 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 users shifting to become normal tolerance users by developing competence and confidence in traveling in 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 programing (e.g. school programs, community mentorship initiatives), alongside investment in making diverse types of transport equipment locally available through harvester support programs[50]. Results also support the use of select technology (e.g. GPS, 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[50-52].

Modeling future impacts from the bottom-up

A key contribution of the paper is to advance a new approach for modeling climate impacts. Heretofore, traditional climate impacts studies begin with climate projections, modeling 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[53,54]. In this context, place-based approaches are increasingly common[55], focusing attention on complex interactions between climate change and society in specific locations, and have been described as ‘bottom up’ as they focus on locally identified and relevant conditions[54]. Such approaches develop rich detail, but have been critiqued as being too context specific, providing limited basis for scaling up, with their qualitative nature constraining the ability to link to climate models to project future trends[56,57]. The modeling framework developed here seeks to bridge this disconnect by explicitly focusing on connecting Indigenous knowledge (IK) with 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 IK holders possess detailed, place-specific, and longitudinal knowledge on how climatic and non-climatic factors affect human activities from which climatic parameters, thresholds, and interactions can be identified, measured, and tracked. Future work will compliment the focus here by developing a broader ethnoclimatology of changing trail access, with emphasis on value systems embodied within IK and how they 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 modeling 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 localised 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* IK and science is key to the approach; the aim is not to compare observations of changing conditions from both knowledge systems, nor to use IK to fill in gaps in scientific understanding as is common in the literature[58], nor to integrate IK into science, but rather to use IK 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.

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JF designed the study, helped analyze data, and wrote the paper; DC collected and analyzed data, and helped write the paper; TP, LBF, LC, JD, MN, and SLH assisted with study design, analysis, and write-up. The authors declare no competing interests.

Figures and Tables in Main Text

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	• Temperature between -5°C and 5°C

	normal risk tolerance (Land 1)	• Precipitation > 10mm/day when temperatures > 0°C • Precipitation > 5mm/day when temperatures < 0°C • Wind > 40km/hr when temperatures > 0°C • Wind > 20km/hr when temperatures < 0°C • Visibility of < 1km
	Land trail users with low risk tolerance (Land 2)	• Temperature between -8°C and 5°C • Precipitation > 5mm/day when temperatures > 0°C • Precipitation > 2mm/day when temperatures < 0°C • Wind >30m/hr when temperatures > 0°C • Wind > 15km/hr when temperatures < 0°C • Visibility of < 2km
	Land trail users with high risk tolerance (Land 3)	• Temperature between 0°C and 4°C • Precipitation > 15mm/day when temperatures > 0°C • Precipitation > 10mm/day when temperatures < 0°C • Wind > 50m/hr when temperatures > 0°C • Wind >35km/hr when temperatures < 0°C • Visibility of < 1km
Sea Ice	Ice trail users with normal risk tolerance (Ice 1)	• Temperature between -5°C and 5°C • Precipitation > 3mm/day • Wind >30km/hr • Visibility of < 1.5km • Ice concentration < 80% • Ice thickness < 15cm
	Ice trail users with low risk tolerance (Ice 2)	• Temperature between -5°C and 10°C • Precipitation > 1mm/day • Wind > 15km/hr • Visibility of < 3km • Ice concentration < 90% • Ice thickness < 30cm
	Ice trail users with high risk tolerance (Ice 3)	• Temperature between 3°C and 10°C • Precipitation > 5mm/day • Wind >40km/hr • Visibility of < 1km • Ice concentration < 70% • Ice thickness < 10cm
Water	Waterway users with normal risk tolerance (Water 1)	• Temperature < -5°C • Precipitation > 4mm/day • Wind > 20km/hr • Visibility of < 2.5km • Ice concentration > 30%
	Waterway users with low risk tolerance (Water 2)	• Temperature < 0°C • Precipitation > 1mm/day • Wind >15km/hr • Visibility of < 4km • Ice concentration > 10%
	Waterway users with	• Temperature < -10°C • Precipitation > 8mm/day

	high risk tolerance (Water 3)	- Wind > 30km/hr - Visibility of < 1km - Ice concentration > 50%

Figure 1. Numerous climatic conditions are important for individuals traveling on the land, water, and sea ice across Canada's Inuit communities. *Temperature* (a) influences machine function, potential of getting stuck, and conditions of ice and snow. *Precipitation* (b) affects ice conditions, visibility, and risk of hypothermia. *Wind speed and direction* (c) is influential in visibility, ice dynamics, waves, and comfort. *Visibility* (d) is important in wayfinding and monitoring the safety of surrounding ice conditions. *Ice conditions* (e) are influential in safety of traveling on ice and water (Photos: Dylan Clark).

Figure 2. Modeled trail use has changed across the Inuit Nunangat over the past 30 years, although changes in the number of good days has been relatively small in comparison to the range in access that travelers have 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*), access to sea ice trails has decreased by 1.79 and 0.48 days (*Ice 1* and *Ice 2*), and access to water trails has increased between 2.74 and 2.11days over the study period (*Water 2* and *Water 3* respectively) (95% confidence). The whiskers in this figure reflect the different user types.

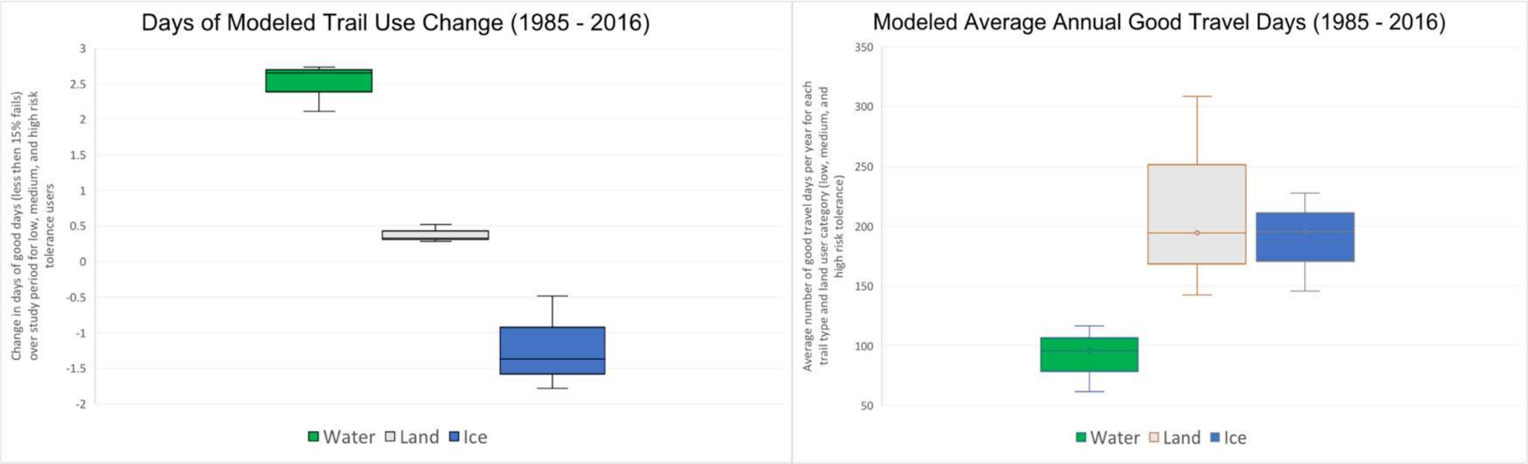
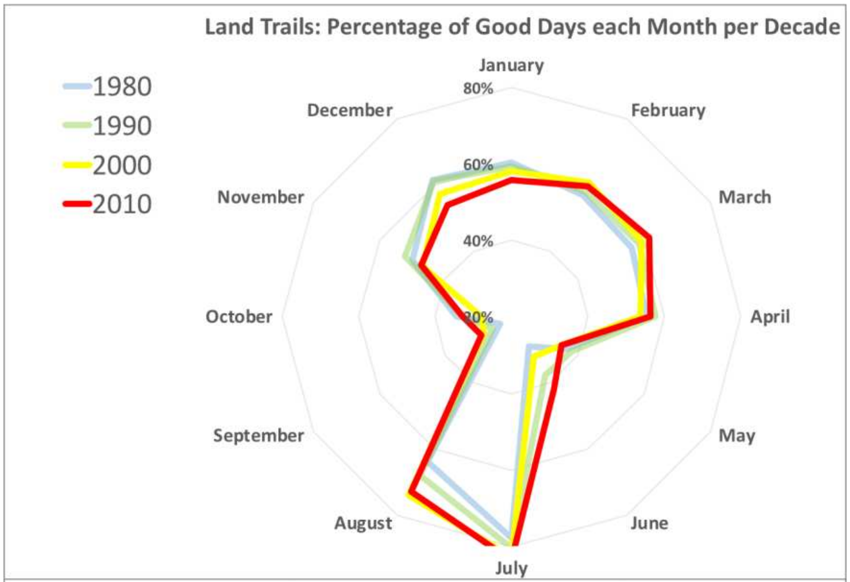
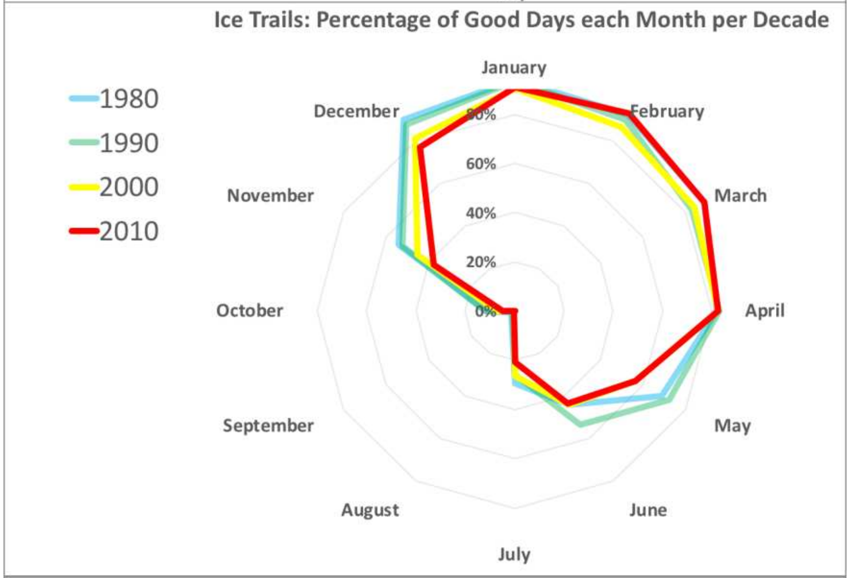
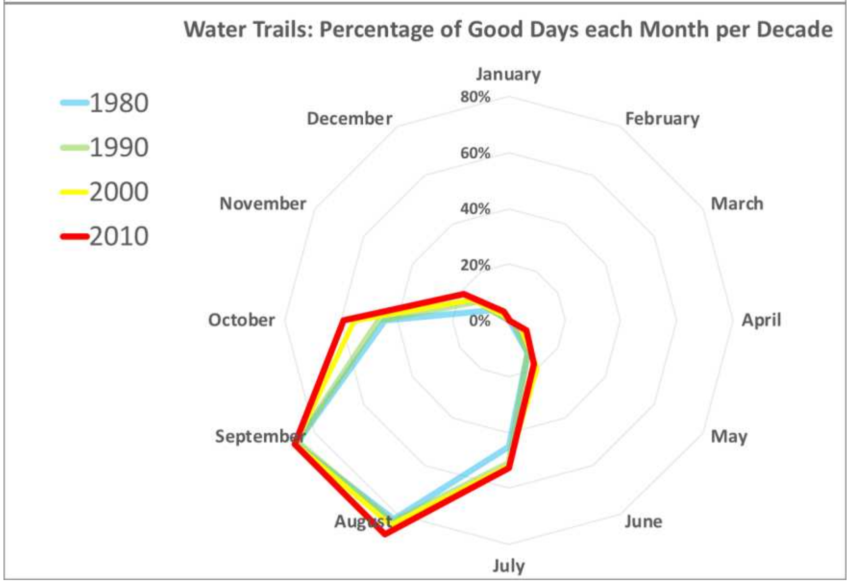


Figure 3. Seasonal and decadal patterns of trail access were observed across the study region. We observe that periods of trail use are both shifting and changing in length. Whiskers represent the type 2 (low risk tolerance) and type 3 (high risk tolerance) trail users.


Land Trails: Percentage of Good Days each Month per Decade


Ice Trails: Percentage of Good Days each Month per Decade


Water Trails: Percentage of Good Days each Month per Decade

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Online Methods

Modelling framework

We develop a modeling framework to quantify how climate change is affecting access to trails, connecting Indigenous knowledge (IK) and science. The modeling framework has 4 steps (Supplementary Figure 1), with key definitions provided in Supplementary Table 3.

In the first step, we identify and characterize climate-related conditions affecting trail access, working closely with 9 communities. Semi-structured interviews (n=273) were conducted with regular trail users, focusing on documenting: i) highly localized and detailed descriptions of the climate-related conditions that affect the ability to safely use trails and which determine if a trail is usable; ii) 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 (e.g. boat, all-terrain vehicles (ATV), snowmobile) and by the location and timing of travel; and iii) knowledge on how travel risks are perceived and managed (Supplementary Table 4). Interviewees were selected based on referral by community Hunters and Trapper 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 individuals depending on environmental knowledge and skillsets, 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 traveling with trail users across seasons from 2015-2017, 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 prior to this project commencing.

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 (i.e. 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 IK 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 analyzing 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 analyzed 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 behavior of different trail users on windy days, asking questions while traveling when windy, and reviewing relevant publications on how wind affects trail usage. Identified thresholds are generalized across communities (see Table 1 in main text). These thresholds were identified for 3 types of trails: land (ATV, snowmobile), water (boat), and sea ice trails (snowmobile). To account for variation in individual skill level, knowledge, risk tolerance, and equipment in affecting 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 Table 6 and 7). This stratification by trail type and trail user type resulted in the creation of 9 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 a “pass” or a “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, as well as 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 1985-2016 at 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 characterize the components of the models, supported and illustrated with quotes from interviews, and cross referenced with relevant literature. Table 1 in the main text provides specific thresholds. Results are not disaggregated by community, reflecting the fact that trail access models are 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 traveler comfort, and can be dangerous if travelers get wet or experience an emergency. Community members explained that cold temperatures (i.e. below -20ºC) alone are not problematic, with temperature identified to be a significant risk factor when it was within the margins of 0ºC for travel on the land and ice due to snowmelt which leads to muddy/slushy conditions on trails and higher river levels which make 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[37,59]. 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°C and <4°C defining the failure threshold, compared to <-8°C to <5°C for type 2 individuals (low risk tolerance) (Supplementary Table 4). Across seasons, temperatures between -5°C and 5°C have been associated with increased risk, based on analysis of search and rescue data (Land 1, Ice 1)[60]. For travel by boat, temperatures below 0°C are not generally desired as it is uncomfortable, and 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 skillsets, which underpins greater ability and confidence to use 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 whiteout conditions associated with snow are not favorable. 5mm of precipitation can equal 10cm of snow in the winter and was identified to result in dangerous travel conditions for a type 1 user (normal risk tolerance), with a total daily rainfall of more than 10mm of rain uncomfortable for travelling. Snow is associated with poor visibility: for travel on the ice, this limits the ability to observe ice color and judge ice thickness, and can cause ice quality and safety to diminish rapidly, particularly in spring, creating challenges for those without an in-depth understanding of trail conditions and ice dynamics[41,46,61-64]. Based on interviews and the participatory methods, 3mm/day of rain or 9cm/day of snow would likely create unsafe conditions for ice trail access for a type 1 user (normal risk tolerance). For travel on the water, light rain and snow is not desired, however, if it does not decrease visibility and is less than 5mm of precipitation in a 24-hour 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 the 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 traveling more difficult, and create unfavorably cold conditions through wind chill. Based on studies in Clyde River and Iqaluit, Nunavut, Gearheard et al[36] and Ford et al[37] identify wind thresholds of 30km/h and 20km/h, respectively as indicative of dangerous conditions for ice use. We establish fail thresholds ranging from 15-50km/h, with the broader 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 (less than 5m) commonly used by Inuit, with wind >30km/hr having the potential to create waves near 1m 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[65,66].

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 the land where trails traverse steep and rocky terrain and involve crossing potentially unstable ice on frozen rivers and lakes, or on the 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 GPS[67-69], 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 required skillsets, such situations can be life threatening[45,61,69]. Poor visibility impacts safety of all travels as it is needed for navigation and helps in detecting potential ice hazards, although 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 4km 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[66,70]. Ice concentration is important for water and ice trails[37,61,71,72]. 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[37] or occupants have been thrown overboard, with the presence of ice also risking routes being 'closed off' if blown together by wind[41]. 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 the 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 on the ice and was observed to be dependent on the weight of the machinery and load, as well as the knowledge and risk tolerance of the individual. It is generally recommended that for an average situation, most ice in the area should be over 15cm thick. Further, 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[65,70]. It was determined that if ice concentration decreased at far away points and remained high at near points, this would still allow travelers to access the ice edge. Low sea ice thickness and concentration has been associated with a higher probability of a search and rescue incident[73]. While river and lake ice are important for land travel, instrumental data were not available. As one interviewee explained,

> It's mostly dangerous [for traveling 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 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 in 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 with minimum and maximum observations[74]. Weather data were assessed for homogeneity using penalized maximal t and F tests[74,75]. To homogenize observations, we began by capping the maximal observed visibility at 14km (9nm). Visibility was then aggregated to mean monthly observations and homogenized using the penalized maximal F test that accounts for autoregressive (AR-1) and nonzero trend change (PMFred)[75]. Resulting monthly data shifts were applied to daily observations[75]. Daily wind speed was also homogenized by applying PMFred.

Ice data were collected from weekly egg charts published by the Canadian Ice Service[76]. Ice charts were converted from coverage files to 4721 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 (<35km), medium (75km - 200km), and far (175km - 300km) distances from shore. These observation sites were selected based on interviews, literature review, and trail maps from land-use monitoring programs 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 25.2km for all near points, 125.0km for medium points, and 275.0km 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 (0-10)/10, or the sum of each partial concentration for every type of ice present. We focused on the total ice concentration, as it has been correlated with increased search and rescue incidents[60]. 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 it 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[9]. 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 be an ice thickness of "10" (thicker than any minimum limit set in the various trail models), and all ice thicker than 70cm 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 timeframe 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 (e.g. the trail was inaccessible on a given day if more than 15% of variables failed; the trail was accessible if less than 15% of variables failed on a given day). The 15% threshold was selected based on distribution of fails and participant observations. Further, timeseries analysis were also conducted for counts of fails per day, providing a confirmation test of modeled day access trends. Additionally pass/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 (MK) tests for all trend analyses of indexes and variables. MK tests allow for analysis of non-parametric data with missing observations and are commonly used to examine environmental and climatic trends[77-79]; using a Shapiro-Wilk test, we confirmed the data were not normally distributed. We removed seasonality from timeseries prior to analysis, by first aggregating data from daily observations into monthly mean values, then applying a seasonal-trend decomposition based on Loess (STL)[79,80]. There is strong evidence that serial correlation exists for most of the environmental variables, thus making a type I statistical error likely[81]. Using the *mkTest* function in R, we applied both a Mann-Kendall (MK) test and a modified Mann-Kendall (MMK) test[82]. The MMK test corrects for type 1 statistical error by assessing strength of serial correlation in a timeseries and then adjusting results accordingly (variance of S is multiplied by a factor of n/n^*s). Results from the MMK test were used to determine statistical significance and slope of trends. Prewhitening was not used due to the large sample size and often high slope trends[81]. 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 in order 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 percent 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, deseasonalizing the values, and calling a MMK test to correct for autocorrelation.

Data availability statement

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

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