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Increased vulnerability of Arctic potential ice roads under climate change

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Temporary ice roads built by the process of snow compaction, watering, and icing during cold winters are lifelines for land access in remote Arctic. In the context of the Arctic amplified warming, the vulnerability of potential ice roads under the influence of complex climate system remains unclear. Here, we construct a potential ice road assessment model that allows quantization of the climatic suitability of potential ice roads in the Arctic. Using satellite remote sensing and meteorological data, we find changes in surface air temperature and snow cover reduced the climatic suitability of potential ice roads during 1979–2017. Spatially, potential ice roads in North America face more immediate threats due to decreased snow depth compared to Eurasia. Before the end of the 21st century, we project a further decline in the climatic suitability of potential ice roads, primarily due to increasing surface air temperatures and decreasing permafrost stability. Taking precious metal/diamond exploration as an example, we conclude that mining activities associated with ice roads will face access difficulties by 2050–2100 due to the decreased potential ice roads. These results give new insights into the challenges and opportunities of Arctic overland travel.

Seasonal ice roads are built through the process of compacting snow, sprinkling water, and freezing ice during Arctic winters^{1–3}. Ice roads serve as the important means of community access, resource exploration, and supply delivery in Arctic remote land^{4–7}. The unprecedented climate change in the Arctic⁸ is affecting human systems, with transportation standing out as a striking focal point. This is because climate change has divergent effects on Arctic land and sea accessibility⁹. In addition to accelerating the melting of sea ice and opening sea routes^{10–15}, the amplified warming of the Arctic^{16–22} is melting the frozen surface to the detriment of land access^{9,23}. However, the stress on ice roads from climate change and subsequent impacts on transportation needs to be understood. Changes in ice road availability due to the unprecedented climate change in the North can impact the amount of minerals, supplies, and food shipped, which can impact not only economy but also the safety of the people^{4,7,24,25}. Therefore, further understanding of the vulnerability of potential ice roads to climate change is of great importance to enhance climate resilience and achieve sustainable development in the Arctic^{23,26,27}.

The availability of ice roads is closely associated with natural climatic conditions. Subzero surface air temperature (SAT) is a prerequisite^{9,28}, and sufficiently cold conditions are conducive to ensuring icing efficiency and ice thickness^{29,30}. Moreover, adequate snow cover provides an important role for the construction and persistence of ice roads, e.g., snow serves as natural material for paving roads and protects vegetation^{29,31,32}. The stability of Arctic permafrost affects the safety of ice road travel because the freezing and thawing effect can result in ground settlement^{7,33,34}.

Regional ice road studies primarily involve establishing weather monitoring stations near ice roads and analyzing the correlation between SAT observations or freezing degree days calculated from these observations and the operational time of ice roads^{35–37}. These studies have successfully detected the shorter operational days of regional ice roads per year and identified the dependency of ice roads on local temperature conditions. Large-scale studies across the Arctic take potential ice roads as their subject, which refers to the land surface climatically suitable for the construction of ice roads. The concept of potential ice roads originates from Stephenson et al.⁹, who utilized the specific thresholds of SAT and snow depth (SD) to

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extract Arctic potential ice roads. There were also studies that adopted different temperature conditions to analyze the temporal variability of the potential ice roads^{32,38}. However, the integration of the climatic factors considered in the current evaluations of potential ice roads^{7,9,32,38} is weak, resulting in findings that do not reflect the combined climate impacts. In this study, we improve the model of potential ice roads by combining the important factors of SAT, snow cover, and permafrost to assess potential ice road evolution. Moreover, the extractions of potential ice roads^{7,9,32,38} are all based on a binary classification, with the 0 or 1 results hiding more information about climatic suitability for ice road activities and not serving the localized climate assessment. We improve this binary classification and quantify the climatic suitability of potential ice roads. Although ice roads are products based on climatic conditions, their construction and operation also depend on management bodies and usages, which leads to differences in the suitable climate conditions adopted for ice road activities in different regions. Since the climatic conditions complying with the ice roads are flexible to some extent, the annual winter ice road plans across the Arctic land need further climatic suitability assessment.

Here, we construct a potential ice road assessment model (PIRAM) to evaluate potential ice roads by integrating key climatic factors such as SAT, snow cover, and permafrost. Unlike existing binary classification, the PIRAM allows one to quantify the degree of climatic suitability of applying ice roads on Arctic land at past and future times. We reveal how the climatic suitability of potential ice roads diminished during 1979–2100, which previous studies based on binary potential ice road classification could not tell us. The main constraints limiting the climatic suitability of potential ice roads are further analyzed under different spatiotemporal conditions, with a view to help the community determine climatic stressors from the complex climate system. Through the example of precious metal/diamond transportation, a crucial application scenario for ice roads in the Arctic, we quantify the future impact of the potential ice road evolution on land transport. The results will help to build a hierarchical understanding of climatic suitability for potential ice roads and purposefully facility the safe and efficient ice road plans under climate challenges.

Results

Differences in changes in the climatic suitability of potential ice roads in Eurasia and North America

The monthly potential ice road index outputted by the PIRAM represents the climatic suitability of potential ice roads, and a higher value represents better climate condition for the region. The maximum value of 12 indicates the excellent climatic conditions, while 9–11 and 1–8 indicate good and fair climatic conditions, respectively (see in Methods and Supplementary Table 3). The results showed that there were three stages of potential ice road index change within a year from 1979 to 2017 (Supplementary Fig. 1), they are growth (October to November), stabilization (December to February), and decline (March to May).

It is important to explore whether there are variations in the potential ice road index in the same months between years (the stability of the potential ice road index), to help people adjust their ice road activities in a timely manner to climate change to avoid direct economic and health losses. The stability of the potential ice road index decreased significantly ($p < 0.05$) from 1979 to 2017 (Fig. 1), revealing that the historical climate change across the Arctic has been detrimental to the development of ice roads. We found that the area of the decline was larger in April, December, November, May, and October than in February, January, and March. The largest area of decline occurred in April, with a decline of more than one third of the total potential ice road area for the month. Although the extent of the potential ice road index decline across the Eurasia was broader, the regions experiencing decreases in North America were predominantly concentrated in areas where ice roads are extensively utilized, such as Nunavut and the Northwest Territories in Canada. In the Canadian Arctic alone, there is a network of about 10,000 kilometers of ice roads each winter⁷. Therefore, ice road operations active in these areas need to take into account climate change in their activities.

We also discerned a pronounced disparity in the principal months during which the potential ice road index decreased between North America and Eurasia. The potential ice road index across the North America exhibited a notable decrease ($p < 0.05$) principally during the months such as January and February, whereas in Eurasia, this predominately occurred

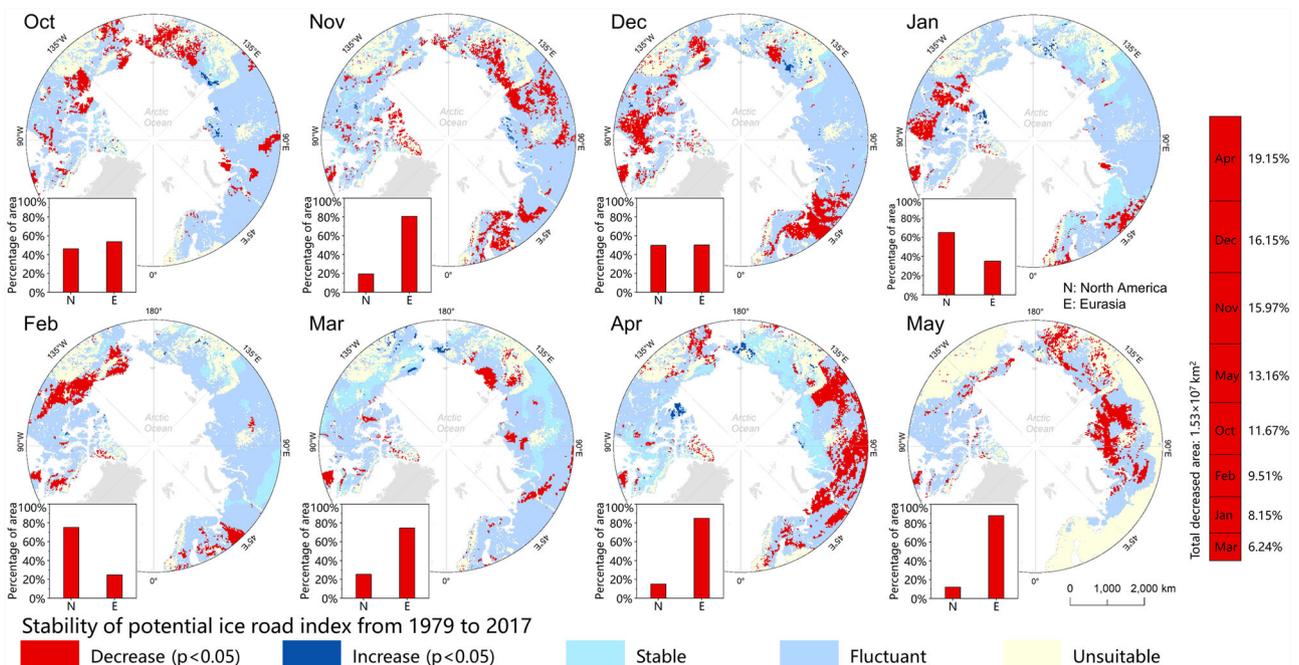


Fig. 1 | Stability of potential ice road index from 1979 to 2017. ‘Decrease’ or ‘Increase’ indicates that the temporal trend analysis has detected a significant ($p < 0.05$) decrease or increase in the potential ice road index, ‘Stable’ signifies that the potential ice road index is consistent and nonzero annually, ‘Unsuitable’ denotes

the potential ice road index remains zero every year, and ‘Fluctuant’ indicates the others. The bar chart for each subfigure indicates the percentage of area with decreased regions in Eurasia and North America. The bar on the right side indicates the area statistics for the decreased regions for each month.

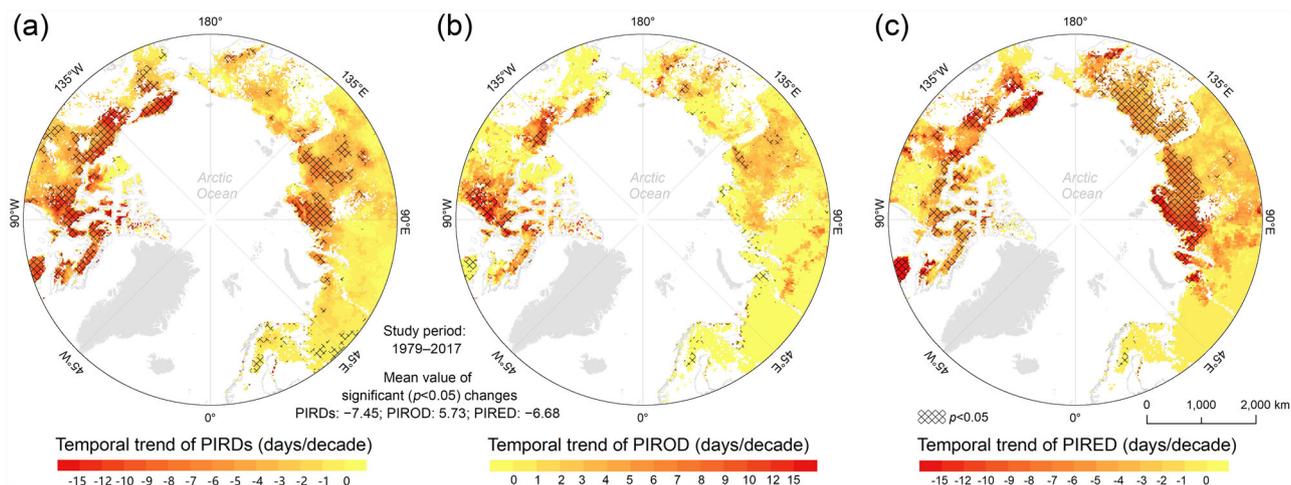


Fig. 2 | Variations of the potential ice road indicators from 1979 to 2017. Temporal trends of PIRDs **a**, PIROD **b**, and PIREd **c** with potential ice road index = 12. The crossed lines indicate the region that has passed the test of statistical significance ($p < 0.05$).

during the months such as November, March, April, and May (Fig. 1). Our attribution analysis results may elucidate the reason behind these discrepancies (Supplementary Fig. 2). During the months such as October, November, March, April, and May, the principal cause was attributed to the rise in SAT. Contrasting with this, more than half of the decreased regions in months such as December, January, and February could be attributed to the decreased SD. This also reflects a more severe decline in SD in North America than in Eurasia. The decline in potential ice road index in North America occurs during the main period of current ice road operations, suggesting that North America needs to adapt more than Eurasia, while in Eurasia there exists potential opportunities for ice road applications in the cold winter.

Temporal characteristics of potential ice roads

Three indicators, i.e., potential ice road days (PIRDs), potential ice road onset date (PIROD), and potential ice road end date (PIRED), were calculated with the highest index from 1979 to 2017 as an example, to quantify the temporal characteristics of the potential ice roads. The PIRDs, PIROD, and PIREd represent the duration, the time when steady appearance, and steady disappearance of potential ice roads within a year (see in Methods). These indicators can clarify the window of time climatically suitable for ice road plans. In general, we detected a rapid decline in the temporal window of potential ice roads during winters (Fig. 2a), manifested by decreased ($p < 0.05$) PIRDs (7.45 days/decade on average). Especially in the Canadian Arctic, the temporal trend in PIRDs shortening was above average at 10.17 days/decade. The inverse trends of PIROD (5.73 days/decade on average) and PIREd (− 6.68 days/decade on average) also suggest a later potential opening and earlier ending time of the ice roads (Fig. 2b and Fig. 2c). The results indicate that warmer winters have a wider range of effects on PIREd compared to PIROD, concentrated in northern Siberia, the North Slope of Alaska, and the Canadian Arctic. However, PIROD was more severely damaged than PIREd in Nunavut, Canada, where land transportation is highly dependent on ice roads. It is also consistent with local reports of greater stress on the opening date of ice roads than on the closing date^{1,39}.

Spatially, we found some connections among the trends of three indicators. For example, the reduction of PIRDs in Nunavut, Canada was likely due to the delayed PIROD, while in North Slope of Alaska and Russian Siberia, it was more likely due to the advanced PIREd. Upon conducting an attribution analysis, it has been determined that the decrease in the time window for ideal SAT was the main reason for the adverse changes in the three indicators (Supplementary Fig. 3), and this reason accounted for an

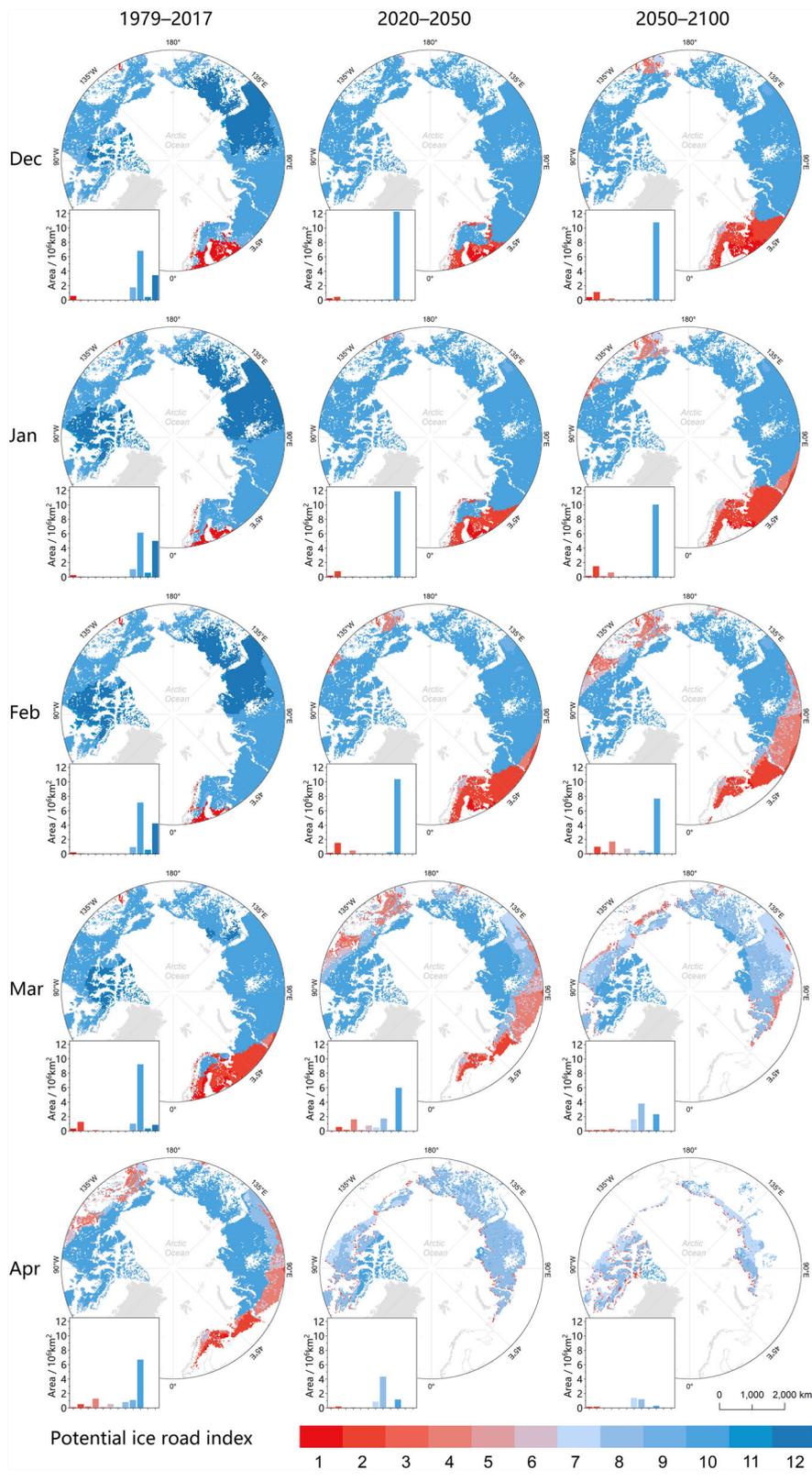
average of 58% of the attribution results. In addition, we found that time window for ideal conditions did not show a strong change. It is important to understand the climatic drivers that cause potential ice road reductions, as this will help government policymakers, businesses, and communities to target the risks of ice road activities arising from climate impacts.

Spatiotemporal patterns of the climatic suitability of potential ice roads in the future

According to the PIRAM, we produced maps of potential ice road index from 1979 – 2017 (past), 2020 – 2050 (near future), and 2050 – 2100 (far future), as shown in Fig. 3. Since the potential ice road index indicates specific climatic conditions, it is possible to reveal not only spatiotemporal patterns of the climatic suitability of potential ice roads, but also variations in climatic stress on potential ice roads from the results of time-series calculations. We found the potential ice road index will be markedly lower in the future. Our results showed that there would be no region with the optimal surface air temperature condition for potential ice roads (potential ice road index = 11 and 12) by 2020 – 2050, suggesting the future ice road development will face serious temperature challenge across the Arctic. As a result, ice road builders may need to respond to the threat of rising temperatures to ensure safe ice activities.

By 2050 – 2100, the potential ice road index will decline further and permafrost thawing will be a strong stressor. In December, January, February, and March, the potential ice road index symbolizing the risk of permafrost thawing (potential ice road index < 9) will be widely distributed in both North America and Eurasia, whereas it was mainly present in the European Arctic during 1979 – 2017 (Fig. 3). The shift in March is dramatic, and we found over 78% of high index areas without permafrost thaw risk were exposed to permafrost thaw stress compared to 1979 – 2017. Moreover, the month in which the potential ice road index starts to decline within a year is coming earlier (Fig. 3 and Supplementary Fig. 1). During 1979 – 2017, climatic conditions were great in February and the vast majority of the potential ice roads were not at risk of permafrost thaw. However, the permafrost thaw risk area will be widely presented in February during 2050 – 2100, two months earlier compared to April during 1979 – 2017 (Supplementary Fig. 1). Spatially, these areas were primarily located in southwestern Russia, southcentral Alaska, and southwestern Canada. The climatic suitability of future ice road construction has received widespread attention, and our results directly project key shifts in the potential ice road index, which has important implications for the planning of future ice road operations.

Fig. 3 | Potential ice road index from December to April during 1979 – 2017, 2020 – 2050, and 2050 – 2100. For 1979 – 2017, it is obtained by calculating the mode based on annual results. For 2020 – 2050 and 2050 – 2100, we firstly calculated the mean values of the climate variables for different SSPs, and then obtained the mode for the annual potential ice road index extracted from these data. Higher index indicates more suitable natural conditions for paving ice roads.



Reduced potential ice roads leads to declined Arctic land accessibility

We quantified the past and future contribution of potential ice roads to the transportation example of precious metal/diamond accessibility (see in Methods). The contribution of potential ice roads to precious metal/diamond accessibility indicates the time difference in fastest accessible time

from one place to precious metals/diamonds with and without potential ice roads. Since there will be few excellent potential ice roads in the future, we included good potential ice roads (potential ice road index > 8) for this section. From 1979 to 2017, the regions with strong contribution were primarily located in the Canadian Arctic region, eastern and western Siberia (Supplementary Fig. 4), this is because of the large area of potential ice roads.

Among these regions, the contribution effect is highest in the Canadian Arctic. The average regional contribution effect amounted to 86 h from December to March in the Canadian Arctic, which indicates the fastest precious metal/diamond accessible time when potential ice roads exist will be 86 h less than if there are no potential ice roads. Therefore, the utilization of potential ice roads would greatly facilitate regional resource activities. In the near future, this contribution effect of potential ice roads would remain high. We found the regions with a strong contribution would be relatively less affected in January and February, from 2020 to 2050. The results indicate that the potential transport time for resource activities utilizing ice roads during January to February remains stable compared to the past.

However, the contributions will rapidly decrease by 2050–2100. Especially in the Canadian Arctic, the contribution effect in February will reduce to an average of 28 h (–67% compared to 1979–2017), which poses a perilous signal for the resource activities that sustain the local economy at present. The most severe decline will occur in March, as the weak contribution during that month suggests that the climate conditions for resource activities using ice roads may no longer be available. As a result, there is reason to believe that the cost of transportation activities will increase after mid-century. Projections of future land accessibility not only shed light on the unique challenges faced by transportation in remote Arctic regions but also play a critical role in guiding economic and social system responses to climate change. By understanding and adapting to the changing land accessibility, we can strive towards sustainable development and resilience in the Arctic region.

Discussion

We present an interdisciplinary method to monitor the potential ice road evolution under climate change. It comprehensively considers key factors such as snow cover, SAT, and permafrost that affect the construction of ice roads, thus achieves a breakthrough in the critical problem of integrating multiple climatic elements to assess potential ice roads in the Arctic. Researchers in different disciplinary fields can also use PIRAM to monitor potential ice road changes from a factorial perspective in which they specialize. In contrast to the previous binary classification approach for potential ice roads^{7,9,32}, the PIRAM enables us to quantify the climatic suitability of potential ice roads in the Arctic. The magnitude of the potential ice road index represents climatic conditions with different levels of suitability, which can be used as a reference for academia, business, and communities in relation to ice road decisions. Furthermore, our attribution results suggest that simply attributing the reduction of potential ice roads to increased SAT will lead to a one-sided understanding of the climatic factors constraining the development of ice roads. For example, in eastern Nunavut, where land travel heavily relies on temporary roads in winter, we found the decline in local PIRs was due to fewer days of ideal snow conditions (Supplementary Fig. 3a). This is because winter SATs there are already low and do not rise enough to cross the SAT thresholds, but changes in SD exceed the limiting conditions for snow suitability. Therefore, snow cover may be the foremost material condition that restricts the availability for local ice roads. Future work emphasizing the effect of snow cover would be helpful to address the hazards of climate change on ice roads. Although PIRAM improves understanding of the impacts of climate change on potential ice roads, in the future it would be good to include additional climatic elements such as wind. Meanwhile, extreme weather events can suddenly threaten operating ice roads, and enhancing dynamic monitoring would help improve the future adjustment capacity. We need to note that PIRAM does not include socioeconomic or technological elements, which is beyond the scope of this study.

Taking precious metal/diamond accessibility as an example, this study demonstrates the challenges and opportunities of potential ice road changes for terrestrial human activities in the Arctic. Ice roads are both environmentally friendly and economically beneficial⁵, as such they remain of great value to society. The Arctic land holds abundant mineral resources, with five of the six operational mines in the Canadian Arctic being gold/diamond mines and substantial untapped resources in Siberia⁴⁰. In the past

few decades, ice roads have been lifelines for precious metal and diamond mining activities in the Arctic⁴¹. Given the number and economic value of ice roads in Canadian Arctic, there is an urgent need for action to respond to shorter time window for potential ice road activities. Adaptation suggestions include paving bridges and culverts at river and stream crossings of key ice roads and building all-weather permanent roads on frequently used routes. Our results indicate that the contribution of potential ice roads to precious metal/diamond accessibility will not diminish before 2050, thus it is possible to explore the Arctic land resources within this time window by expanding the use of ice roads. Especially in Siberia, the cold climate there offers great potential for utilizing ice roads, opening up opportunities for resource exploration.

It is worth noting that plans are in place to construct permanent roads in the Arctic to alleviate the transportation difficulties caused by the decreasing availability of ice roads⁴². However, permanent roads can also be unstable if they are built on thawing permafrost³³. There will be additional local impacts on the local ecosystem if permanent roads are constructed which need to be fully assessed. Considering the divergent changes in sea⁴³ and land transportation⁴⁴, the estimation of future passage conditions in the Arctic will have an important impact on the economic and social development, making it worthy of further in-depth study combined effects of changes in sea and land transport conditions.

In conclusion, by constructing a coupled evaluation model that integrates the key factors of snow cover, SAT, and permafrost, this study quantifies the climatic suitability of potential ice roads across the Arctic from 1979 to 2100. The assessment process achieves a hierarchical understanding of the climate suitability of potential ice roads, rather than the binary-based potential ice road analyses of the past, thus we discover temporal differences in the evolution of North American and Eurasian potential ice roads. During 1979–2017, there are divergent main months of the declining trend of potential ice road index in North America (in January and February) and Eurasia (in November, March, April, and May). Moreover, in January and February, which are critical months for ice road applications, the area of decreased potential ice road index in North America is greater than in Eurasia. We conclude that ice road activities in North America face more direct climate pressures, while there is potential for utilizing ice roads in the colder winter in Eurasia, especially in Russian Siberia. Future climate change will continually be detrimental to potential ice roads, and the risk of permafrost thawing on potential ice roads will become higher by 2050–2100. In the precious metal/diamond accessibility case we find the contributing effect of potential ice roads to be reduced by 2050–2100, especially in February. Spatially, future utilization of ice roads for precious metal and diamond exploration in Russian Siberia is more environmentally advantageous and resilient than in North America. The results will provide new perspectives on the future potential ice road evolution and contribute to the action of Arctic resilience under climate change.

Methods

Study area and datasets

The Arctic in this study refers to land north of 60°N and excludes Greenland and some archipelagos (Supplementary Fig. 5) because of missing snow water equivalent (SWE) data in these areas. The study period contains 1979–2017 (past), 2020–2050 (near future), 2050–2100 (far future), from October to May. The past period is in keeping with our previous work³². The summary of main characteristics of the datasets in this study are showed in Supplementary Table 1 and Table 2. We used GLOBsnow v3.0 NH SWE⁴⁵ to calculate the SD for the past period with snow density values fixed at 0.24 g cm⁻³. The SWE product combines satellite-based passive microwave measurements (SMR and SSM/I) with ground-based observations in a data assimilation approach⁴⁶. This data has been demonstrated to have a more realistic spatial distribution of Arctic SWE than previous passive microwave algorithms⁴⁷. The CPC daily mean SAT dataset and the GHCN_CAMS land monthly mean SAT dataset were employed as inputs for daily and monthly mean SAT for the past period, respectively. Both types of the meteorological data have the capability to monitor global and regional

land SAT changes^{48,49}. We obtained the daily mean SAT by averaging the CPC maximum and minimum SAT according to the official description. For climatic variables in the future, the SSP1-2.6, SSP2-4.5, and SSP5-8.5 scenario data from the Coupled Model Intercomparison Project Phase 6 (CMIP6) model were selected to project changes in SAT and SD for the period 2020–2100. The criteria for model selection were a nominal resolution of 100 km, time coverage of 2020–2100, with the r11p1f1 variant, and the SSP1-2.6, SSP2-4.5, and SSP5-8.5 scenario projections that included SAT ('tas' in the CMIP6 variable) and SD ('srd' in the CMIP6 variable). We selected the models shown in Supplementary Table 2. In this study, the future climatic variables were calculated by ensemble averaging of the data from three SSPs. We also provided the results for each SSP in the supplementary information (see Supplementary Fig. 7 and Supplementary Fig. 8).

There are two types of auxiliary data for this study, one for potential ice road calculations and the other for accessibility calculations. All auxiliary data are assumed to remain static during the study period. The auxiliary data utilized in the potential ice road calculation comprise permafrost type, ground ice content, soil thickness, soil texture, and digital elevation model. The permafrost type categorizes the land surface as continuous (90–100%), discontinuous (50–90%), sporadic (10–50%), and isolated (0–10%) based on the percentage of spatial extent of permafrost. The ground ice content is classified into three categories based on the volume share of ice within 20 m of permafrost: high (>20%), medium (10–20%), and low (0–10%). In this study, the discontinuous, sporadic, and isolated permafrost were combined as discontinuous permafrost, and the medium and low ice contents were combined as low ice content. The soil thickness data provides high-resolution estimates of the thickness of the permeable layers above bedrock within a global 30-arcsecond (~1 km). We extracted grids with a permeable layer thickness of zero as exposed bedrock. Soil texture is derived from the Harmonized World Soil Database and originally categorized as coarse textured (clay<18% and sand>65%), medium textured (18%<clay<35% and sand<65%), and fine textured (clay>35%). We dichotomized the soil texture by combining medium and fine textured as fine textured. The auxiliary data for accessibility calculations include land cover, world mineral deposits, and Arctic permanent roads. We filtered the precious metal/diamond sites in the study area based on the mineral type field in world mineral deposits database published by the U.S. Geological Survey. It is noted that we produced potential ice road maps at a spatial resolution of 25 km and accessibility maps at a spatial resolution of 1 km, and the relevant data were resampled to that resolution accordingly by inverse-distance-weighted interpolation.

Potential ice road assessment model

We designed the PIRAM to quantify potential ice road index using a seven-indicator control flow that takes topography, SAT, SD, and permafrost into account (Supplementary Fig. 6). Firstly, ice roads are usually built on flat terrain⁹, and mountainous areas were therefore filtered out by a topographic indicator. PIRAM assigned the value of potential ice road index as 0 for surfaces with elevations greater than 500 m and slopes greater than 5°. Secondly, flat areas were categorized according to local SAT. SAT in PIRAM is the dominant controlling factor as it directly impacts the formation of ice roads^{9,28,32}. The potential ice road index for areas with SAT greater than 0 °C was assigned the value of 0 as ice roads can only occur when the SAT drops below freezing point. We further subdivided the SAT below 0 °C thus distinguishing the suitability of building ice roads. The transportation on ice roads necessitates an adequate thickness of ice layer, as the lower the SAT, the faster the growth pace of the ice layer, thereby enhancing the stability of the ice structure. SAT below –28 °C is represented by ideal temperature conditions⁷, and PIRAM assigned a higher potential ice road index to areas below –28 °C compared to areas between –28 °C and 0 °C. This is because under these conditions, the rate at which the sprayed water freezes is well balanced with the amount of time required for water storage and transportation on the sprinklers, which is when ice roads are most efficiently built⁷.

We also contemplated the stability and safety of ice road application in the Arctic permafrost region. The stability of permafrost is strongly related

to SAT^{50–52} and –7 °C is the critical point⁵³. In general, when the SAT is lower than –7 °C, the state of permafrost is relatively stable and less prone to thawing. However, once the SAT rises above this critical value, there is a risk of permafrost thaws⁵⁴. Therefore, the potential ice road index in regions where the SAT ranges from –7 °C and –28 °C is higher than in regions where the SAT ranges from –7 °C and 0 °C. The PIRAM used a decision-making approach to differentiate the magnitude of the risk of permafrost thaw for ice road applications when the SAT ranges from –7 °C and 0 °C. The decision-making method is currently widely employed as a rapid and efficient assessment approach for evaluating the risk of permafrost thaw^{33,54,55}. Our decision-making approach considered four factors that affect the risk of permafrost thaw: surface properties, frozen ground type, soil texture, and ground ice content. Firstly, the surface with permeable layer thickness equal to zero was classified as bedrock, without considering the risk of permafrost thaw in these areas⁵⁵. Secondly, we assigned lower potential ice road index for the discontinuous permafrost zones compared to the continuous permafrost zones because they have higher risk of thawing and may experience more abrupt thawing^{54,56}. Then, soil texture and ground ice content were used as measures of permafrost thaw risk in discontinuous permafrost zones³³. Fine textured soils exhibit a higher risk of permafrost thaw regardless of ground ice content due to their high water-storage capacity. Coarse textured soils have higher permafrost thaw risk only when ground ice content is high. In PIRAM, we specified that the potential ice road index of high permafrost thaw risk areas is lower than that of low permafrost thaw risk areas. Finally, the seasonally frozen ground was set to have the least potential ice road index as it is highly susceptible to ground settlement due to freeze-thaw processes⁵⁷.

Furthermore, we considered deep snow cover as an important contributing factor in the PIRAM. There is currently no uniform SD standard in the Arctic that is suitable for paving ice roads, with SD thresholds varying between 15–23 cm in different regions⁵. We used a SD of 20 cm as the threshold for ideal snow conditions in this study. Surfaces were categorized by the presence or absence of ideal snow conditions, with areas of ideal snow conditions having higher potential ice road index.

The above PIRAM design outputted 13 potential ice road indexes, with higher values indicating better potential ice roads (Supplementary Table 3). We categorized potential ice roads into three classes: excellent, good, and fair. Excellent areas with a potential ice road index of 12 have both ideal SAT and SD. Areas with potential ice road index between 9 and 11 were categorized as good because their efficiency of ice road application may be lower than that of excellent potential ice roads. There are different degrees of permafrost thawing risk for areas with the potential ice road index of one to eight, so these areas were categorized as fair. The potential ice road index of 0 in this study indicates that the region is not suitable for ice road construction.

Potential ice road indicators and attribution analysis

In this study, the regions with an index of 12 was extracted as the potential ice roads as an example to analyze their temporal characteristics. We took the potential ice road index of 12 as an example because it indicates the best climatic conditions and may be preferred for ice road construction when only climatic conditions are considered. Therefore, the index of 12 was converted to 1 and all other values were converted to 0.

We proposed PIRDs, PIROD, and PIREO to quantify temporal characteristics of potential ice roads from 1979 to 2017, inspired by the studies of snow phenology^{58,59}. The three indicators are conceptually like snow cover duration, snow cover onset date, and snow cover end date, which are considered valid proxies for characterizing snowpack phenology^{60,61}.

The formula are as follows:

$$\text{PIRDs} = \sum_{i=1}^n (D_i) \quad (1)$$

where D_i represents a grid value with 1 indicating potential ice road and 0 no potential ice road; and n represents the number of days from October to

May within a year.

$$PIROD = \min\{t\} \left\{ t \in [0, m - 4] \text{ and } \sum_{k=0}^4 D_{t+k} = 5 \right\} \quad (2)$$

$$PIRED = \max\{t\} + 4 \left\{ t \in [0, m - 4] \text{ and } \sum_{k=0}^4 D_{t+k} = 5 \right\} \quad (3)$$

where t indicates a Julian date from October to May; m is the number of dates from October to May within a year; k indicates the number of days after the base date; and D_t represents the value of a pixel with 1 indicating potential ice road and 0 no potential ice road.

Furthermore, we explored the reasons for changes in the potential ice road index and the potential ice road indicators from 1979 to 2017.

$$R_Index = \begin{cases} SAT \text{ and } SD & \text{both } T_{SAT} \text{ and } T_{SD} < 0 \\ SAT & T_{SAT} < 0 \\ SD & T_{SD} < 0 \end{cases} \quad (4)$$

where R_Index means the reason for the decreases in potential ice road index, SAT and SD indicates the decreases in potential ice road index are attributed to the decreases in both SAT and SD, SAT or SD indicates the changes are only attribution to the decrease in SAT or SD, T_{SAT} or T_{SD} represents the interannual trend of SAT or SD, which passes the significance test of $p < 0.05$.

For potential ice road indicators, we selected grids with significant changes ($p < 0.05$) in PIRDs PIROD, and PIREd, and calculated changes in the number of days, onset date, and end date for $SAT \leq -28^\circ\text{C}$ and $SD \geq 20\text{ cm}$. The number of days, onset date, and end date were calculated in the same way as the corresponding potential ice road indicators.

$$R_PIRDs = \begin{cases} SAT \text{ and } SD & t_{days} \text{ of } SAT \leq -28^\circ\text{C} \text{ and } SD \geq 20\text{cm} < 0 \\ SAT & t_{days} \text{ of } SAT \leq -28^\circ\text{C} < 0 \\ SD & t_{days} \text{ of } SD \geq 20\text{cm} < 0 \end{cases} \quad (5)$$

$$R_PIROD = \begin{cases} SAT \text{ and } SD & t_{onset \text{ date}} \text{ of } SAT \leq -28^\circ\text{C} \text{ and } SD \geq 20\text{cm} > 0 \\ SAT & t_{onset \text{ date}} \text{ of } SAT \leq -28^\circ\text{C} > 0 \\ SD & t_{onset \text{ date}} \text{ of } SD \geq 20\text{cm} > 0 \end{cases} \quad (6)$$

$$R_PIRED = \begin{cases} SAT \text{ and } SD & t_{end \text{ date}} \text{ of } SAT \leq -28^\circ\text{C} \text{ and } SD \geq 20\text{cm} < 0 \\ SAT & t_{end \text{ date}} \text{ of } SAT \leq -28^\circ\text{C} < 0 \\ SD & t_{end \text{ date}} \text{ of } SD \geq 20\text{cm} < 0 \end{cases} \quad (7)$$

where R_PIRDs , R_PIROD , and R_PIRED mean the reason for the changes in PIRDs, PIROD, and PIREd, respectively. SAT and SD indicates that the variations in potential ice road indicators are attributed to decreasing ideal SAT and SD conditions, SAT or SD indicates the potential ice road changes are only attributed to decreasing ideal SAT or SD conditions, and t_{days} , $t_{onset \text{ date}}$, and $t_{end \text{ date}}$ represent the temporal trend of days, onset date, and end date, respectively, which passes the significance test of $p < 0.05$. The Theil-Sen method⁶² and Mann-Kendall⁶³ test were used to calculate the temporal trends in this study.

Contribution of potential ice roads to land accessibility

Ice roads are an important means of transportation for the exploration of remote Arctic terrestrial resources. Therefore, taking the case of precious metal/diamond accessibility, we employed the cost distance accessibility method⁶⁴⁻⁶⁶ to quantify the contribution of potential ice roads to land

accessibility. The metal/diamond accessibility means the travel time required to reach the nearest precious metal/diamond site from any position on land. Since travel time is a better indicator of the potential for human social interaction and communication than Euclidean distance, it has been widely used as a measure of accessibility in a variety of fields⁶⁷⁻⁶⁹. The accessibility calculations require a movement cost grid within the study area, and we generated it by following a framework designed for the global land^{67,70}. We included potential ice roads (potential ice road index>8) as a landscape type and set movement cost for them to model the situation when potential ice roads are present. The travel speed on potential ice roads in our study was set to 10 km/h⁹. We got the contribution of the potential ice roads to precious metal/diamond accessibility by calculating the difference in the accessibility with and without potential ice road grids.

Data availability

All datasets used in this study are freely available online. CPC global daily temperature data are available at <https://psl.noaa.gov/data/gridded/data.cpc.globaltemp.html>. GHCN_CAMS global gridded 2-m temperature data are available at <https://psl.noaa.gov/data/gridded/data.ghcncams.html>. Globsnow v3.0 NH SWE data are available at <https://www.globsnow.info/>. Global 1-km Gridded Thickness of Soil, Regolith, and Sedimentary Deposit Layers data are available at https://daac.ornl.gov/SOILS/guides/Global_Soil_Regolith_Sediment.html. Harmonized World Soil Database are available at <https://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/harmonized-world-soil-database-v12/en/>. Circum-Arctic Map of Permafrost and Ground Ice Conditions data are available at <https://nsidc.org/data/ggd318/versions/2#anchor-data-access-tools>. GLC2000 global land cover data are available at <https://forobs.jrc.ec.europa.eu/glc2000>. Arctic DEM and road data are available at <http://poles.tpd.ac.cn>. Arctic maritime infrastructure are available at <https://arcticinfrastructure.org/>. Arctic precious metal/diamond data are available at <https://mrdata.usgs.gov/major-deposits/>. CMIP6 model data are available at <https://esgf-node.ipsl.upmc.fr/search/cmip6-ipsl/>.

Code availability

The processing codes for the analyses are available in a Zenodo repository at <https://doi.org/10.5281/zenodo.14557142>.

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References

- Barrette, P., Hori, Y. & Kim, A. The Canadian winter road infrastructure in a warming climate: toward resiliency assessment and resource prioritization. *Sustain. Resilient Infrastruct.* **7**, 1–19 (2022).
- Adam, K. M. *Building and operating winter roads in Canada and Alaska*. Minister of Indian and Northern Affairs (1978).
- Loneragan, S., Difrancesco, R. & Woo, M. K. Climate-change and transportation in northern Canada - an integrated impact assessment. *Climatic Change* **24**, 331–351 (1993).
- Hori, Y., Cheng, V. Y. S., Gough, W. A., Jien, J. Y. & Tsuji, L. J. S. Implications of projected climate change on winter road systems in Ontario's Far North, Canada. *Climatic Change* **148**, 109–122 (2018).
- Raynolds, M. K. et al. Landscape impacts of 3D-seismic surveys in the Arctic National Wildlife Refuge, Alaska. *Ecol. Appl.: a Publ. Ecol. Soc. Am.* **30**, e02143 (2020).
- Sladen, W. E., Wolfe, S. A. & Morse, P. D. Evaluation of threshold freezing conditions for winter road construction over discontinuous permafrost peatlands, subarctic Canada. *Cold Reg. Sci. Technol.* **170**, 102930 (2020).
- Gädeke, A. et al. Climate change reduces winter overland travel across the Pan-Arctic even under low-end global warming scenarios. *Environ. Res. Lett.* **16**, 024049 (2021).

8. AMAP. Snow, Water, Ice and Permafrost in the Arctic (SWIPA) 2017 (Arctic Monitoring and Assessment Programme (AMAP)). *Oslo, Norway* **xiv 269**, (2017).
9. Stephenson, S. R., Smith, L. C. & Agnew, J. A. Divergent long-term trajectories of human access to the Arctic. *Nat. Clim. Change* **1**, 156–160 (2011).
10. Melvin, A. M. et al. Climate change damages to Alaska public infrastructure and the economics of proactive adaptation. *Proc. Natl Acad. Sci. USA* **114**, E122–E131 (2017).
11. Mudryk, L. R. et al. Impact of 1, 2 and 4 °C of global warming on ship navigation in the Canadian Arctic. *Nat. Clim. Change* **11**, 673–679 (2021).
12. Min, C. et al. The Emerging Arctic Shipping Corridors. *Geophys. Res. Lett.* **49**, e2022GL099157 (2022).
13. Cao, Y. F. et al. Trans-Arctic shipping routes expanding faster than the model projections. *Glob. Environ. Change-Hum. Policy Dimens.* **73**, 102488 (2022).
14. Liu, M. J. & Kronbak, J. The potential economic viability of using the Northern Sea Route (NSR) as an alternative route between Asia and Europe. *J. Transp. Geogr.* **18**, 434–444 (2010).
15. Fosheim, M. et al. Recent warming leads to a rapid borealization of fish communities in the Arctic. *Nat. Clim. Change* **5**, 673–677 (2015).
16. Cohen, J. et al. Recent Arctic amplification and extreme mid-latitude weather. *Nat. Geosci.* **7**, 627–637 (2014).
17. Screen, J. A. & Simmonds, I. The central role of diminishing sea ice in recent Arctic temperature amplification. *Nature* **464**, 1334–1337 (2010).
18. Overland, J. et al. The urgency of Arctic change. *Polar Sci.* **21**, 6–13 (2019).
19. Post, E. et al. The polar regions in a 2 °C warmer world. *Sci. Adv.* **5**, eaaw9883 (2019).
20. Xiao, H. et al. Long-term trends in Arctic surface temperature and potential causality over the last 100 years. *Clim. Dyn.* **55**, 1443–1456 (2020).
21. Pithan, F. & Mauritsen, T. Arctic amplification dominated by temperature feedbacks in contemporary climate models. *Nat. Geosci.* **7**, 181–184 (2014).
22. Graverson, R. G., Mauritsen, T., Tjernström, M., Källén, E. & Svensson, G. Vertical structure of recent Arctic warming. *Nature* **451**, 53–56 (2008).
23. Ford, J. D. et al. Changing access to ice, land and water in Arctic communities. *Nat. Clim. Change* **9**, 335–339 (2019).
24. Hinzman, L. D. et al. Evidence and implications of recent climate change in northern Alaska and other Arctic regions. *Climatic Change* **72**, 251–298 (2005).
25. Sturm, M., Goldstein, M. A., Huntington, H. & Douglas, T. A. Using an option pricing approach to evaluate strategic decisions in a rapidly changing climate: Black-Scholes and climate change. *Climatic Change* **140**, 437–449 (2017).
26. Ford, J., Pearce, T., Canosa, I. & Harper, S. The rapidly changing Arctic and its societal implications. *Wiley Interdiscip. Rev.: Clim. Change* **12**, e735 (2021).
27. Ford, J. D. et al. Projected decrease in trail access in the Arctic. *Commun. Earth Environ.* **4**, 23 (2023).
28. Mullan, D. et al. Climate change and the long-term viability of the World's busiest heavy haul ice road. *Theor. Appl. Climatol.* **129**, 1089–1108 (2017).
29. Hori, Y., Gough, W., Tam, B. & Tsuji, L. Community vulnerability to changes in the winter road viability and longevity in the western James Bay region of Ontario's Far North. *Regional Environ. Change* **18**, 1–11 (2018).
30. Sharma, S. et al. Widespread loss of lake ice around the Northern Hemisphere in a warming world. *Nat. Clim. Change* **9**, 227–231 (2019).
31. Knowland, K. E., Gyakum, J. & Lin, C. A study of the meteorological conditions associated with anomalously early and late openings of a Northwest Territories winter road. *ARCTIC* **63**, (2010).
32. Dong, Y. et al. Warmer winters are reducing potential ice roads and port accessibility in the Pan-Arctic. *Environ. Res. Lett.* **17**, 104051 (2022).
33. Hjort, J. et al. Degrading permafrost puts Arctic infrastructure at risk by mid-century. *Nat. Commun.* **9**, 5147 (2018).
34. Biskaborn, B. K. et al. Permafrost is warming at a global scale. *Nat. Commun.* **10**, 264 (2019).
35. Hori, Y., Gough, W. A., Butler, K. & Tsuji, L. J. S. Trends in the seasonal length and opening dates of a winter road in the western James Bay region, Ontario, Canada. *Theor. Appl. Climatol.* **129**, 1309–1320 (2017).
36. Kiani, S., Irannezhad, M., Ronkanen, A.-K., Moradkhani, H. & Kløve, B. Effects of recent temperature variability and warming on the Oulu-Hailuoto ice road season in the northern Baltic Sea. *Cold Reg. Sci. Technol.* **151**, 1–8 (2018).
37. Mullan, D. J. et al. Examining the viability of the World's busiest winter road to climate change using a process-based lake model. *Bull. Am. Meteorological Soc.* **102**, E1464–E1480 (2021).
38. Streletskiy, D., Shiklomanov, N. & Hatleberg, E. Infrastructure and a changing climate in the Russian Arctic: a geographic impact assessment. In: *Proceedings of the 10th International Conference on Permafrost*. The Northern Publisher, Salekhard, Russia (2012).
39. Ford, J. D., Bell, T. & St-Hilaire-Gravel, D. Vulnerability of Community Infrastructure to Climate Change in Nunavut: A Case Study From Arctic Bay. In: *Community Adaptation and Vulnerability in Arctic Regions* (eds Hovelsrud G. K., Smit B.). 107–130 (Springer Netherlands, 2010).
40. Bortnikov, N. S. et al. Strategic metal deposits of the Arctic Zone. *Geol. Ore Depos.* **57**, 433–453 (2015).
41. Prowse, T. D. et al. Implications of climate change for economic development in Northern Canada: energy, resource, and transportation sectors. *Ambio* **38**, 272–281 (2009).
42. Kim, A. M. & Li, H. N. Incorporating the impacts of climate change in transportation infrastructure decision models. *Transport. Res. Part A-Policy Pract.* **134**, 271–287 (2020).
43. Melia, N., Haines, K. & Hawkins, E. Sea ice decline and 21st century trans-Arctic shipping routes. *Geophys. Res. Lett.* **43**, 9720–9728 (2016).
44. Waite, T., Evans, M., Kholod, N., Blahut, N. & Rowland, J. Review of quantitative methods to assess impacts of changing climate and socioeconomic conditions on Arctic transportation systems. *Ambio* **52**, 1155–1169 (2023).
45. Luoju, K. et al. GlobSnow v3.0 Northern Hemisphere snow water equivalent dataset. *Sci. Data* **8**, 163 (2021).
46. Takala, M. et al. Estimating northern hemisphere snow water equivalent for climate research through assimilation of space-borne radiometer data and ground-based measurements. *Remote Sens. Environ.* **115**, 3517–3529 (2011).
47. Hancock, S., Baxter, R., Evans, J. & Huntley, B. Evaluating global snow water equivalent products for testing land surface models. *Remote Sens. Environ.* **128**, 107–117 (2013).
48. He, K. J., Liu, G., Zhao, J. F. & Li, J. X. Co-variability of the summer NDVIs on the eastern Tibetan Plateau and in the Lake Baikal region: Associated climate factors and atmospheric circulation. *PLoS ONE* **15**, e0239465 (2020).
49. Fan, Y. & van den Dool, H. A global monthly land surface air temperature analysis for 1948–present. *J. Geophys. Res. Atmosph.* **113**, (2008).
50. Aalto, J., Karjalainen, O., Hjort, J. & Luoto, M. Statistical forecasting of current and future circum-arctic ground temperatures and active layer thickness. *Geophys. Res. Lett.* **45**, 4889–4898 (2018).

51. Gruber, S. Derivation and analysis of a high-resolution estimate of global permafrost zonation. *Cryosphere* **6**, 221–233 (2012).
52. Callaghan, T. V. et al. A new climate era in the sub-Arctic: accelerating climate changes and multiple impacts. *Geophys. Res. Lett.* **37**, 14 (2010).
53. Chadburn, S. E. et al. An observation-based constraint on permafrost loss as a function of global warming. *Nat. Clim. Change* **7**, 340–344 (2017).
54. Kåresdotter, E., Destouni, G., Ghajarnia, N., Hugelius, G. & Kalantari, Z. Mapping the vulnerability of Arctic wetlands to global warming. *Earths Future* **9**, e2020EF001858 (2021).
55. Ran, Y. et al. Permafrost degradation increases risk and large future costs of infrastructure on the Third Pole. *Commun. Earth Environ.* **3**, 238 (2022).
56. Chen, X. et al. Different responses of surface freeze and thaw phenology changes to warming among Arctic permafrost types. *Remote Sens. Environ.* **272**, 112956 (2022).
57. Peng, X. Q. et al. Response of changes in seasonal soil freeze/thaw state to climate change from 1950 to 2010 across china. *J. Geophys. Res.-Earth Surf.* **121**, 1984–2000 (2016).
58. Liston, G. E. & Hiemstra, C. A. The Changing Cryosphere: Pan-Arctic Snow Trends (1979–2009). *J. Clim.* **24**, 5691–5712 (2011).
59. Peng, S. S. et al. Change in snow phenology and its potential feedback to temperature in the Northern Hemisphere over the last three decades. *Environ. Res. Lett.* **8**, 014008 (2013).
60. Choi, G., Robinson, D. A. & Kang, S. Changing Northern Hemisphere Snow Seasons. *J. Clim.* **23**, 5305–5310 (2010).
61. Chen, X. N., Liang, S. L., Cao, Y. F., He, T. & Wang, D. D. Observed contrast changes in snow cover phenology in northern middle and high latitudes from 2001–2014. *Sci. Rep.* **5**, 16820 (2015).
62. Sen, P. K. Estimates of the Regression Coefficient Based on Kendall's Tau. *J. Am. Stat. Assoc.* **63**, 1379–1389 (1968).
63. Hamed, K. H. & Rao, A. R. A modified Mann-Kendall trend test for autocorrelated data. *J. Hydrol.* **204**, 182–196 (1998).
64. Páez, A. et al. Comparing distance, time, and metabolic energy cost functions for walking accessibility in infrastructure-poor regions. *J. Transp. Geogr.* **82**, 102564 (2020).
65. Weiss, D. J. et al. Global maps of travel time to healthcare facilities. *Nat. Med.* **26**, 1835–1838 (2020).
66. Adriaensen, F. et al. The application of 'least-cost' modelling as a functional landscape model. *Landsc. Urban Plan.* **64**, 233–247 (2003).
67. Weiss, D. J. et al. A global map of travel time to cities to assess inequalities in accessibility in 2015. *Nature* **553**, 333–336 (2018).
68. Walther, O. J., Dambo, L., Koné, M. & van Eupen, M. Mapping travel time to assess accessibility in West Africa: The role of borders, checkpoints and road conditions. *J. Transp. Geogr.* **82**, 102590 (2020).
69. Siljander, M., Venäläinen, E., Goerlandt, F. & Pellikka, P. GIS-based cost distance modelling to support strategic maritime search and rescue planning: a feasibility study. *Appl. Geogr.* **57**, 54–70 (2015).
70. Nelson, A. et al. A suite of global accessibility indicators. *Sci. Data* **6**, 266 (2019).

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Author contributions

Y.D., P.X., and X.Z. designed the PIRAM. Y.D., J.Y., Y.C., W.L., and H.L. developed the code used to implement the PIRAM. Y.D., Q.W., and Y.M. developed the code used to download and process the data. Y.D., J.Y., and R.L. performed the trend and attribution calculations. Y.D., J.Y., Y.C., and J.B. performed the calculations related to accessibility. Y.D. wrote the original manuscript, which was reviewed and modified by P.X., X.Z., and D.G.

Competing interests

The authors declare no competing interests.

Additional information

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