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Warmer winters are reducing potential ice roads and port accessibility in the Pan-Arctic

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E-mail: xiaopf@nju.edu.cn**Keywords:** potential ice roads, warmer winters, Pan-Arctic, port accessibility, terrestrial transport

Abstract

Transportation in the Pan-Arctic winter is highly dependent on ice roads, which are affected by surface air temperatures and snow cover. In the context of polar increased warming, there is an urgent need to quantify the uncertainties of ice roads and their contribution to terrestrial transport. We evaluated the spatiotemporal characteristics of potential ice road changes by calculating four indicators: potential ice road area (PIRA), potential ice road days (PIRDs), potential ice road onset date (PIROD), and potential ice road end date (PIRED) from October to May, 1979–2017. Taking port accessibility as an example, we constructed a port accessibility model to quantify the contribution of potential ice roads to terrestrial transport. All four indicators showed significant ($p < 0.05$) reductions in potential ice roads. PIRA experienced the largest share of losses in May ($\sim 25\%$) and the sharpest reductions in April ($2.77 \times 10^4 \text{ km}^2 \text{ yr}^{-1}$). PIRDs were shortened by an average of 0.41 d yr^{-1} , and delayed PIROD (0.28 d yr^{-1} on average) was more severe than advanced PIRED (0.21 d yr^{-1} on average). A stability analysis showed that potential ice roads were changing from suitable to unsuitable during November to May. Between December and April, potential ice roads can increase port accessibility by more than 24 h in Canadian Arctic and Siberia and by more than 9 h in Alaska. However, the contribution of potential ice roads has reduced over the past decades, especially in Nunavut. The results provide insights into changes in potential ice roads in the Pan-Arctic and suggest that remote land accessibility has decreased significantly with warmer winters.

1. Introduction

The Arctic is experiencing amplified warming (Overland *et al* 2019, Post *et al* 2019, Xiao *et al* 2020), and its surface air temperature (SAT) has increased more than twice as fast as the global average since 1979 (IPCC 2019). Recent studies also show that SAT is expected to increase by approximately 5°C – 12°C by the end of the century (Landrum and Holland 2020). Arctic snowpack is also changing significantly in the context of a warming climate. There is an overall trend of decreasing snow extent (Estilow *et al* 2015, Mudryk *et al* 2017), snow cover days (Shi *et al* 2013, Box *et al* 2019), and maximum snow water equivalent (SWE) in the Arctic (Mudryk *et al* 2015, AMAP

2017). The snow depth (SD) trend is relatively complex and shows spatiotemporal heterogeneity (Liston and Hiemstra 2011, Park *et al* 2012).

Arctic land is more accessible in winter as environmentally delicate ground freezes to provide a hard driving surface. As cost-effective transport facilities, ice roads (temporary roads made of snow or ice in winter) have served an important transportation role in the Arctic region (Guyer and Keating 2005). In Canada alone, there is a network of approximately 10 000 km of ice roads (Gädeke *et al* 2021). Ice roads across Canada, from Tibbitt to Contwoyto, are among the busiest ice roads in the world, with as many as 10 900 truckloads each winter (Sladen *et al* 2020). However, changes in climatic conditions, such as

ground freezing and snowfall, are reducing the availability of ice roads (Gädeke *et al* 2021). SAT and SD have been considered the main climatic factors in the vitality of seasonal ice roads (Hori *et al* 2018, Sladen *et al* 2020). Subzero ground temperatures are essential in maintaining frozen ground and ice thicknesses, which is the most important (Kiani *et al* 2018). Additionally, sufficient snow accumulation is helpful to (a) providing raw materials for paving ice roads, (b) protecting vegetation and the surface organic layer, (c) providing better traction, and (d) maintaining sufficiently high albedo to isolate frozen ground or ice roads after construction (Knowland *et al* 2010).

Understanding how ice roads change during warmer winters is critical, as local people are highly dependent on the seasonal access that ice roads provide, especially to remote aboriginal areas (Hori *et al* 2018). Shorter winters have posed serious challenges to community and mineral activities in northern Canada (Mullan *et al* 2017). The travel time across the northern Alaska permafrost zone by ice roads decreased from more than 200 d in the 1970s to approximately 100 d in the early 21st century (Hinzman *et al* 2005). The warmer Arctic surface has made the length of ice roads unstable in northern Alaska, Canada, and Russia, limiting access to Arctic terrestrial areas (Zell 2014, Mullan *et al* 2017). Predictions of future climate conditions also suggest a risk of diminished availability of ice roads. Stephenson *et al* (2011) warned that warmer winters would lead to reductions in suitable ice road areas by the mid-century, resulting in significant increases in travel time between terrestrial settlements, which is highly seasonal, with the largest delays occurring in April and November. Using a land surface model that considers the frozen state of the ground, Gädeke *et al* (2021) found that the time favourable to construct ice roads in future winters will decrease significantly, even in a low-end global warming scenario.

Arctic terrestrial resources are abundant, and the rapidly warming climate contributes to the melting of Arctic sea ice, enhancing the navigability of the Arctic Ocean, offering enormous economic potential (Kwok and Rothrock 2009). However, harsh terrestrial access conditions limit the development of socioeconomic activities (Ford *et al* 2019). Ports are the bridge between maritime and terrestrial transport (Ferrari *et al* 2011), and ease of access to them is the focus of evaluating the extension of Arctic land-based activities to the sea. Huang *et al* (2020) calculated the accessibility of Russian ports based on spatial static data such as conventional transportation networks, but the contribution of ice roads was not considered, even though it is critical to Arctic accessibility.

Previous studies have drawn attention to how the suitability of the Arctic environment for ice roads (potential ice roads) is changing with warmer

winters. Moreover, there has been a lack of quantitative assessment of the contribution of potential ice roads to Arctic terrestrial transport in different regions. Because of the specificity of Arctic terrestrial transportation and the socioeconomic importance of crossing Arctic land, it is urgent to explore further the spatiotemporal change in Arctic potential ice roads and their contribution to regional transportation.

There are two goals of this study. The first is to quantify the change in Pan-Arctic potential ice roads under the influence of key climate variables (SAT and SD) from October to May, 1979–2017. The second is to further examine the contribution of potential ice roads to land transport in a port accessibility example.

2. Study area and datasets

2.1. Study area

The study area covers the portions of Eurasia and North America within the Pan-Arctic (north of latitude 60° N, as shown in figure 1). The European Arctic has a dense conventional transportation network (railways, major roads, and minor roads). Ice roads are usually built on flat plains. In winter, ice roads connect large areas of remote communities that lack conventional transportation and are only accessible by air the rest of the time. There are 178 ports in the study area, most of which are located along the Nordic coast.

2.2. Climate variables and static datasets

This study relied on satellite observations and meteorological data to quantify the SD and SAT in the Pan-Arctic, respectively.

Time series observations of the continuous geographic extent of SD are often calculated by the Globsnow SWE product. The Globsnow v3.0 NH SWE product combines satellite-based passive microwave measurements (SMMR and SSM/I) with ground-based meteorological data in a data assimilation scheme. It is considered the most advanced scheme because it provides a more realistic representation of the spatial distribution of SWE over the Arctic than previous standalone passive microwave algorithms (Hancock *et al* 2013, Pulliainen *et al* 2020). In the Globsnow SWE production algorithm, the northern hemisphere snow density was set to a constant value of 0.24 g cm⁻³ (Takala *et al* 2011). Thus, we calculated the monthly and daily SD by dividing the monthly and daily SWE by the snow density, respectively.

The Climate Prediction Center (CPC)'s global daily SAT dataset is produced using the optimal interpolation of quality-controlled gauge records of the Global Telecommunication System network and has been applied to the analysis of meteorological trends (Nashwan *et al* 2019). GHCN_CAMS gridded 2 m

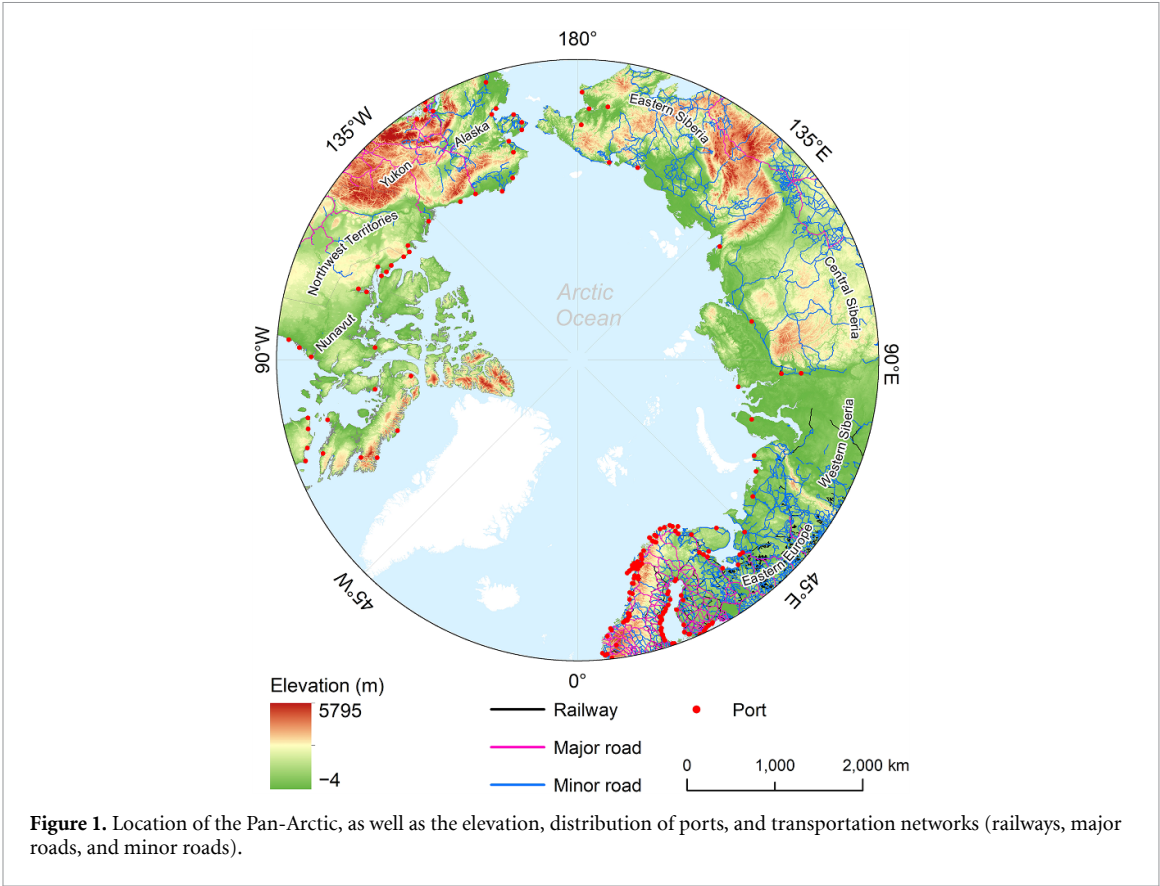


Table 1. Data sources of the study.

Type	Dataset	Period/year	Temporal resolution	Spatial resolution	Source
Climate variables	Globsnow v3.0	1979–2017	Daily/monthly	25 km	www.globsnow.info/
	NH SWE data	1979–2017	Daily	0.5° × 0.5°	https://psl.noaa.gov/data/gridded/data.cpc.globaltemp.html
	CPC global daily temperature	1979–2017	Monthly	0.5° × 0.5°	https://psl.noaa.gov/data/gridded/data.ghcncams.html
Static datasets	GHCN_CAMS global gridded 2 m temperature	1979–2017	—	1 km	https://forobs.jrc.ec.europa.eu/products/glc2000/glc2000.php
	GLC2000 global land cover dataset	2000	—	0.008° × 0.008°	http://poles.tpd.ac.cn
	Arctic digital elevation model	2010	—	1:1000 000	http://poles.tpd.ac.cn
	Arctic road dataset	2014	—	1:1000 000	https://arcticinfrastructure.org/
	Arctic maritime infrastructure	2009	—		

temperature is a land monthly mean SAT dataset that combines two large individual datasets of station observations collected from the Global Historical Climatology Network, version 2, and the Climate Anomaly Monitoring System. The quality of these datasets is reasonably good, and the data capture the most common spatiotemporal characteristics of the observed climatology and anomaly fields over both regional and global domains (Fan and van den

Dool 2008). The CPC daily data and CHCN_CAMS monthly data were input as the daily and monthly SAT in this study.

The static datasets consist of land cover, digital elevation model, conventional transport networks (railways, major roads, and minor roads), and ports. They are assumed to remain constant during the study period. The main characteristics of the datasets are described in table 1.

Table 2. Formulas of potential ice road indicators.

Indicator	Temporal resolution	Formula
PIRA	Monthly	$\text{PIRA} = \sum_{i=1}^n (S_i),$ where S_i represents the area of a potential ice road pixel; and n represents the number of potential ice road pixels within a month.
PIRDs	Yearly	$\text{PIRDs} = \sum_{i=1}^n (D_i),$ where D_i represents a pixel 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 PIRED	Yearly Yearly	$\text{PIROD} = \min \{t\} \mid \left\{ t \in [0, m-4] \text{ and } \sum_{k=0}^4 D_{t+k} = 5 \right\},$ $\text{PIRED} = \max \{t\} + 4 \mid \left\{ t \in [0, m-4] \text{ and } \sum_{k=0}^4 D_{t+k} = 5 \right\},$ where t indicates a date; m is the number of dates from October to May within a year; and D_t represents the value of a pixel with 1 indicating potential ice road and 0 no potential ice road.

Note: The conditions for identifying a pixel as potential ice roads are SAT < 0 °C, SD > 20 cm, elevation ≤ 500 m, and slope ≤ 5%.

3. Methodology

3.1. Calculation of potential ice road indicators

To quantify the changes in potential ice roads in the Pan-Arctic, we calculated the values of four indicators: potential ice road area (PIRA), potential ice road days (PIRDs), potential ice road onset date (PIROD), and potential ice road end date (PIRED). The first two indicators refer to the area of potential ice roads in a month and the number of days suitable for building potential ice roads in a year, both of which reflect potential ice road changes from spatial and temporal perspectives. PIROD represents the first date when potential ice roads appear for the first five consecutive days, and PIREDD represents the last date when potential ice roads appear for the last five consecutive days. PIROD and PIREDD are similar to the snow cover onset date and snow cover end date, which are indicators of when snow cover steadily appear and disappear (Choi *et al* 2010, Chen *et al* 2015). The formulas for calculating the potential ice road indicators are shown in table 2.

To extract information on potential ice roads, we adopted a set of potential ice road criteria. The conditions were as follows: (a) SAT < 0 °C, (b) SD > 20 cm, and (c) non-mountainous areas (Stephenson *et al* 2011). A subzero surface temperature is critical as it provides opportunities for the frozen ground and ice road construction. Therefore, SAT falling below 0 °C directly reflects the possibility of ice road appearance (ACIA 2005). Although packed snow is not necessary for ice road construction, at least 20 cm of snow can be compacted to create stable ice roads in subzero conditions. Thus, 20 cm of snow indicates the presence of raw materials for building ice roads (Adam 1978). Finally, mountainous areas (elevation > 500 m and slope > 5%) are considered unsuitable for ice road construction (Stephenson *et al* 2011).

Since the potential ice roads are closely related to the SAT and SD, exploring the variability of suitable SAT and SD may be useful in explaining the spatiotemporal distribution of potential ice roads changes. The grids with significant changes in PIRDs, PIROD, and PIREDD from 1979 to 2017 were selected to analyse the changes in the number of days, onset date, and end date when SAT < 0 °C and SD > 20 cm. The number of days, onset date, and end date of SAT < 0 °C and SD > 20 cm were calculated in the same way as the PIRDs, PIROD, and PIREDD.

Furthermore, the stability of potential ice roads in different months was evaluated. We denoted the existence and absence of potential ice roads using 1 and 0 for each pixel after monthly potential ice roads were extracted. From 1979 to 2017, if a pixel was always marked as 1 or 0, it was defined as stably suitable or stably unsuitable, respectively. We classified those pixels as ‘suitable to unsuitable’ or ‘unsuitable to suitable’ according to the positive or negative slope of their temporal simple least squares fit ($p < 0.05$). The remaining cells were defined as fluctuant. Finally, for areas changing from suitable to unsuitable, there are three potential reasons (local SAT ≥ 0 °C, SD ≤ 20 cm, or both) for being unsuitable for potential ice roads. We tallied the most frequent reasons to determine the main reason for the change.

Sen slope estimator and Mann–Kendall (MK) tests were used to calculate the temporal trends for all the potential ice road indicators and changes in SAT and SD. All of the above calculations were performed uniformly at a 25 km resolution.

3.2. Calculation of port accessibility

Raster-based port accessibility was assessed to quantify the contribution of potential ice roads to terrestrial transportation in a port access example. Port

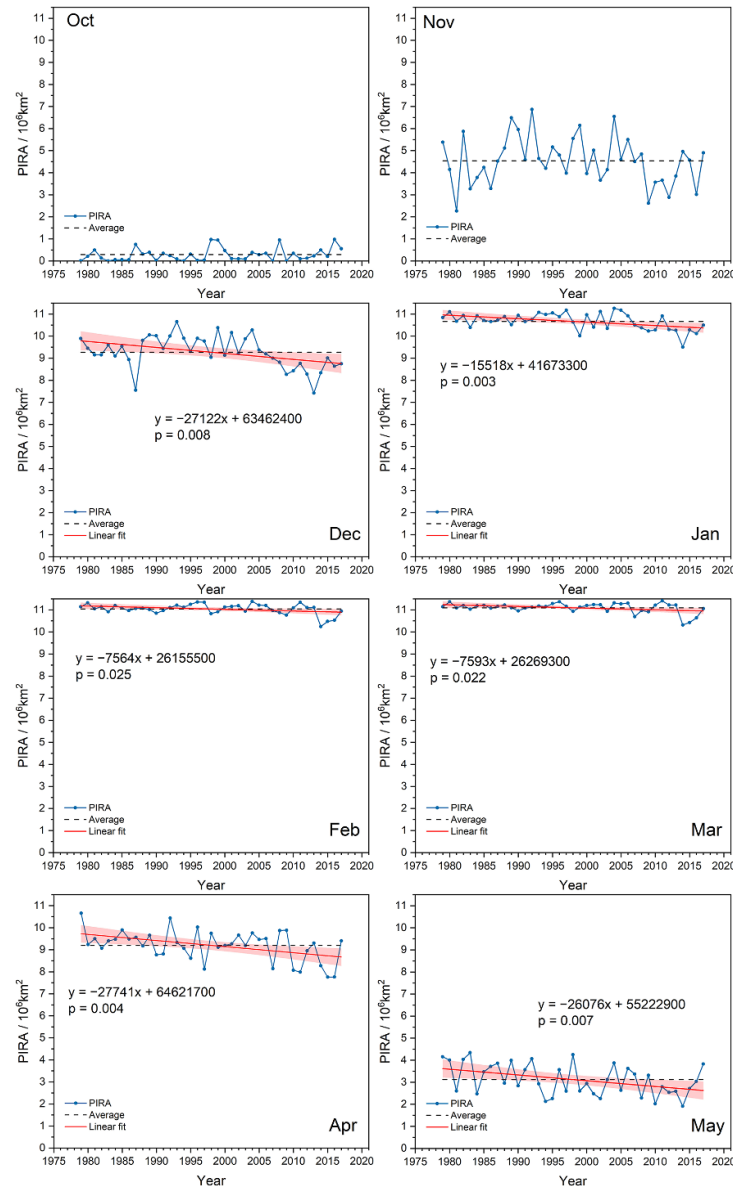


Figure 2. Monthly PIRA, 1979–2017. The dotted blue line indicates the variation from year to year, the dashed black line indicates the multiyear average, and the solid red line indicates the linear fit. The red shading indicates the 95% confidence range. No significant trends were detected for October and November, so no linear fit was determined for these months.

accessibility for each grid cell was calculated as the shortest travel time from the grid cell to the nearest port (Adriaensen *et al* 2003, Siljander *et al* 2015). Since travel time is essentially a measure of economic accessibility, it is a better indicator of the potential for human social interaction and communication than Euclidean distance and thus was adopted for use in the calculations (Weiss *et al* 2018, Nelson *et al* 2019).

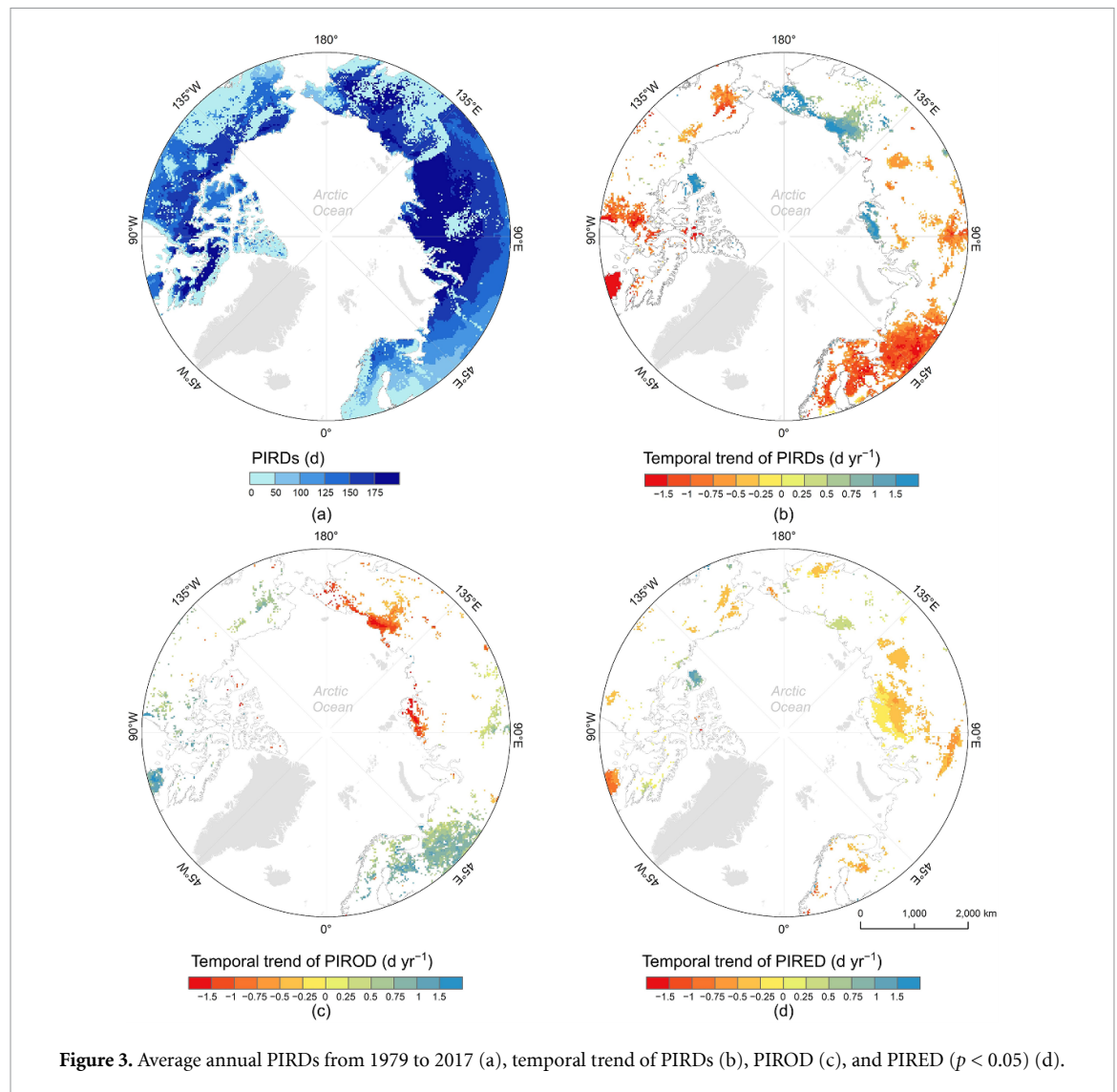
Port accessibility rasters were generated using the cost distance function in Python, following the framework described by Nelson (2008). The contribution of potential ice roads to port accessibility was determined by calculating the difference in port accessibility times with and without potential ice road grids. The travel speed on potential ice roads was set to 10 km h^{-1} (Stephenson *et al* 2011). We also employed the Sen slope estimator and MK tests in the trend

analysis. The calculations were performed for a 1 km resolution, with the potential ice road data down-scaled to 1 km by the inverse-distance-weighted interpolation method.

4. Results

4.1. PIRA, PIRDs, PIROD, and PIRED

The PIRA for the Pan-Arctic in different months from 1979 to 2017 is presented in figure 2. Larger PIRA values occurred from January to March, with the average values for these months all exceeding $1.06 \times 10^7 \text{ km}^2$. The maximum PIRA of $1.14 \times 10^7 \text{ km}^2$ occurred in March 2011, which is approximately equal to the total area of Canada and Alaska. However, PIRA decreased significantly ($p < 0.05$) from December to May, with the fastest in April ($2.77 \times 10^4 \text{ km}^2 \text{ yr}^{-1}$). For May,



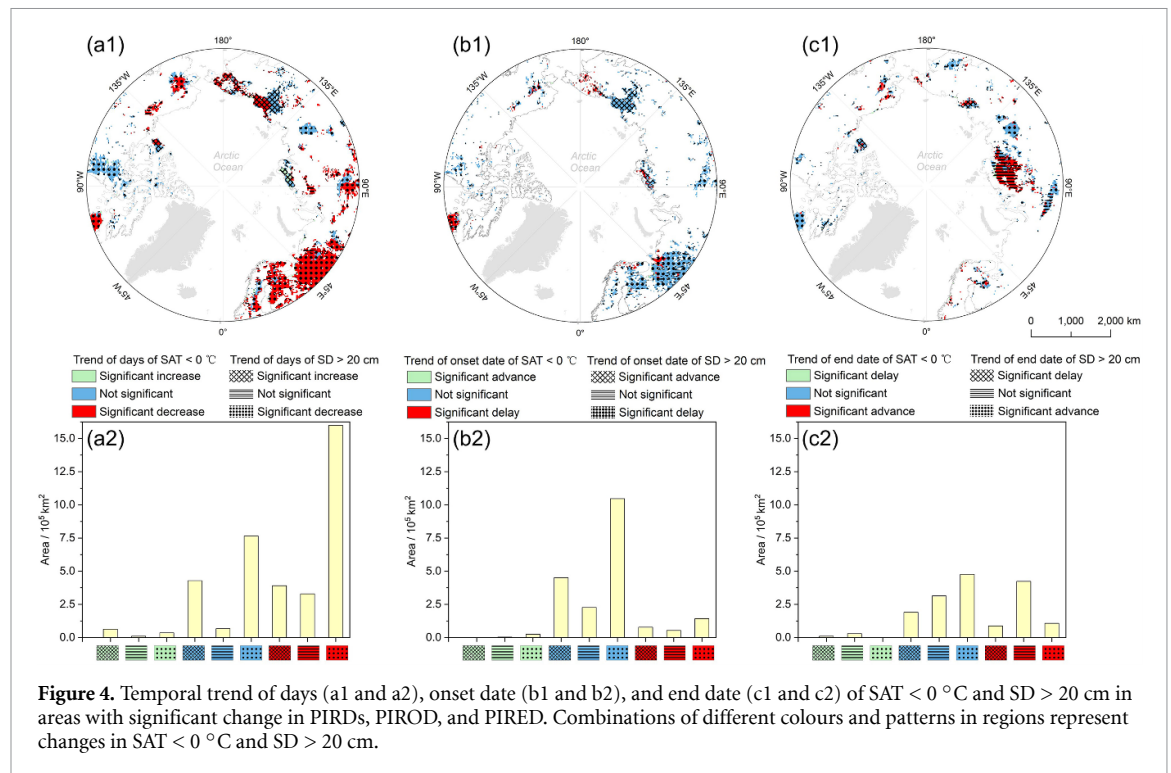
the smaller PIRA experienced the largest share of loss ($\sim 25\%$), declining by $2.61 \times 10^4 \text{ km}^2 \text{ yr}^{-1}$. If the current trend continues in the future, the month could see the disappearance of PIRA. There were no significant trends observed for October and November, which indicates that climate change has not had a strong impact on PIRA in these two months.

The construction time of potential ice roads was evaluated by analysing the average annual PIRDs and the changes in PIRDs, PIROD, and PIRED, as shown in figure 3.

According to the average annual values from 1979 to 2017, the PIRDs of the entire Pan-Arctic region decreased with decreasing latitude (figure 3(a)). PIRDs were above 150 d in Northwest Territories, Nunavut, the North Slope of Alaska, and Siberia because of the cold weather. Figure 3(b) shows that PIRDs are decreasing significantly ($p < 0.05$) in the Pan-Arctic (0.41 d yr^{-1} on average). The largest area of decrease ($1.26 \times 10^6 \text{ km}^2$) was observed in the European Arctic, where PIRDs were already lower, with an average decrease of 1.03 d yr^{-1} . PIRDs in

central Alaska, the northern Yukon, Nunavut, and Siberia also showed a significant decreasing trends of $0.25\text{--}1.5 \text{ d yr}^{-1}$. The shortening of PIRDs indicates that the time window of potential ice roads for remote areas is becoming shorter.

The changes in PIROD (0.28 d yr^{-1} on average) and PIRED (-0.21 d yr^{-1} on average) provide evidence of the shortening time window for potential ice road construction from another perspective. As shown in figure 3(c), rapidly delayed PIROD mainly occurred in the European Arctic and eastern Nunavut ($0.5\text{--}1.5 \text{ d yr}^{-1}$). PIRED in Western Siberia significantly advanced ($0.1\text{--}0.5 \text{ d yr}^{-1}$, as shown in figure 3(d)), which indicates that the local community may be facing the risk of early closure of ice roads. We can conclude some associations of the changes by combining the maps of the temporal trends. For example, by comparing figures 3(b)–(d), we can find that the decrease in PIRDs in the European Arctic is more likely to be due to the delayed PIROD rather than the advanced PIRED. Advanced PIRED is relatively mild compared to the delayed



PIROD. A possible reason for the difference is the changes in SAT. Thus, our results confirm that warm winters put more pressure on the PIROD than on the PIREd.

4.2. Influence of changes in SAT and SD on potential ice roads

We calculated and analysed the changes in the number of days, onset date, and end date when SAT < 0 °C and SD > 20 cm (figure 4) to explain the reasons for the changes in PIRDs, PIROD, and PIREd.

Suitable SAT conditions (SAT < 0 °C) for potential ice roads reduced significantly (figures 4(a1), (b1) and (c1)). This trend was mainly presented as a reduction in the days with SAT < 0 °C in Eurasia (figure 4(a1)). Only very few areas had significant increased days, advanced onset date, and delayed end date when SAT is below zero degrees (figures 4(a2), (b2) and (c2)), which suggests that changes in SAT are almost unfavourable to the potential ice roads.

Suitable SD conditions (SD > 20 cm) are also reducing as a whole. The decrease in suitable SD days happened in European Arctic, Alaska, and eastern Nunavut. Specially, these areas experienced a reduction in both suitable SD and SAT except for Nunavut, a region that highly depends on ice roads for land access. Therefore, SD is a more imminent factor that needs to be focused on for construction of ice roads in Nunavut.

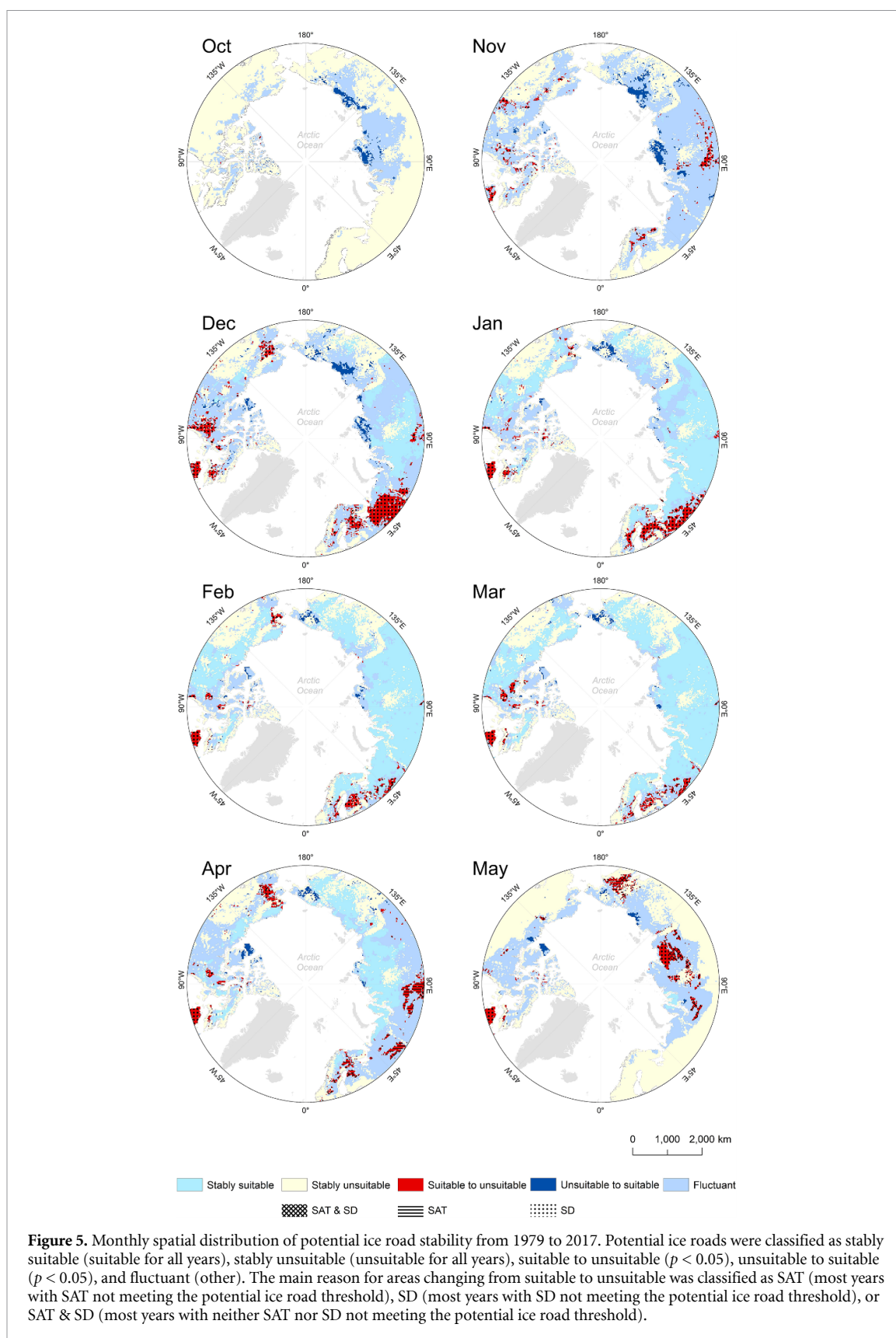
Nevertheless, there are opposite trends in suitable SD changes in Siberia. A significant decrease in suitable SD was observed in the inland areas of Siberia.

By contrast, we found the days of suitable SD significantly increased and the onset date of suitable SD advanced in the northeast coastal regions. A possible reason for the increasing trend of suitable SD is that reduced Arctic sea ice enhances water vapour sources in winter, which leads to earlier and deeper snow cover (Park *et al* 2013, Wegmann *et al* 2015).

4.3. Stability of potential ice roads

The result of the potential ice road stability assessment is shown in figure 5. During the study period, the distribution of stable potential ice roads is strongly seasonal and spatial. In Arctic winter, stable areas were first detected in Siberia, December. Large areas of stable potential ice roads were mainly observed in Siberia, Alaska and Canada from January to March. By April, there was a huge reduction in the extent of stable areas, occurring mainly in southern Siberia, central Alaska, and Nunavut.

Areas suitable for potential ice roads change to unsuitable in some months. The largest area of the change was found in December ($1.52 \times 10^6 \text{ km}^2$), approximately equal to one-sixth of the multi-year average of PIRA in this month (figure 2). In addition, we note differences in the time of the change in North America and Eurasia. For example, Siberia showed the change mainly in April and May, while Alaska was concentrated in December and April. This change from suitable to unsuitable even happened in cold months like January, February, and March. During these months, there were many areas of the change in Canada and Alaska. The primary reason for the areas changing from suitable to unsuitable was always



that SD did not meet the threshold for potential ice roads, except for Siberia in April and May. The SAT was well below 0°C during polar winters, and the rise in SAT was insufficient to alter the potential ice roads.

4.4. Contribution of potential ice roads to port accessibility

The extent of potential ice roads varies in different months (figures 2 and 5). Thus, their contribution to port accessibility differs in different months of

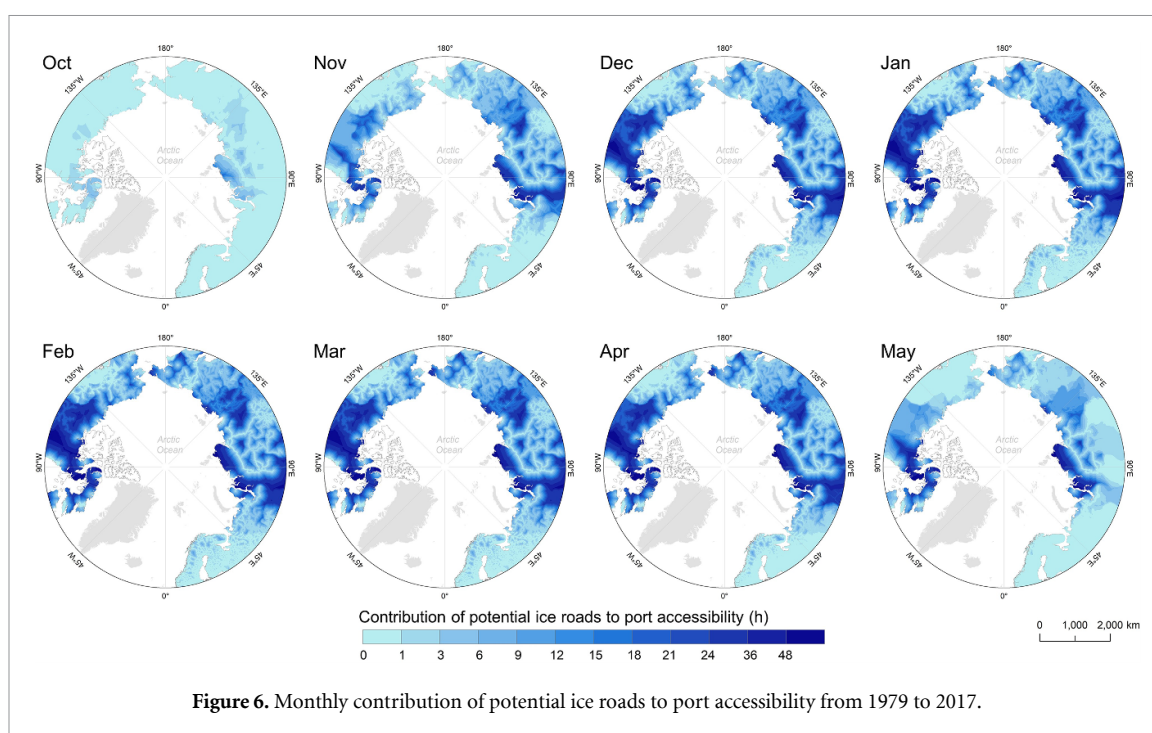


Figure 6. Monthly contribution of potential ice roads to port accessibility from 1979 to 2017.

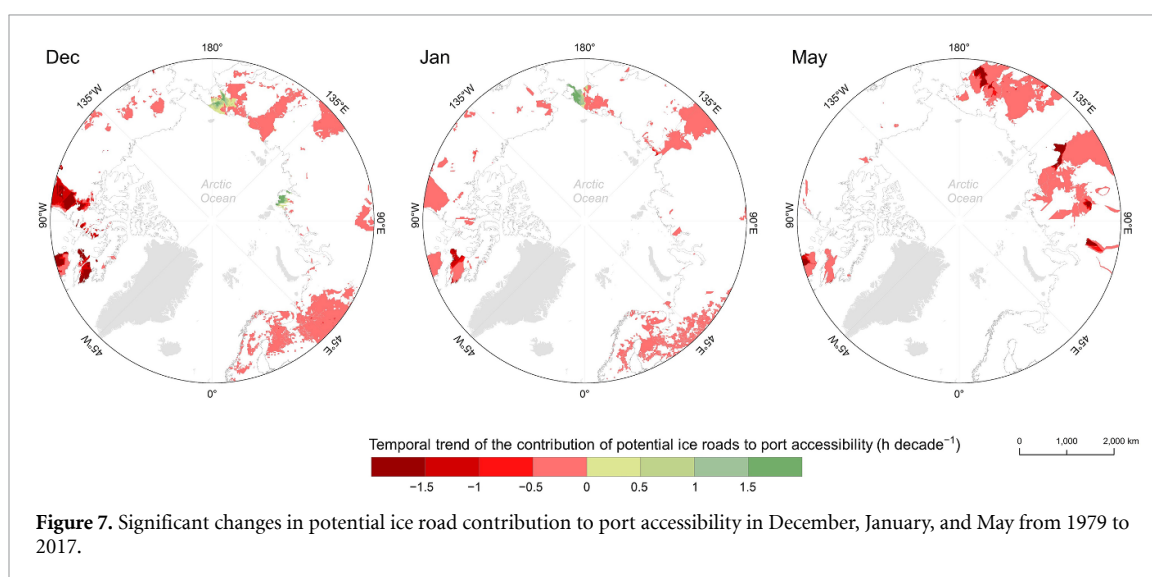


Figure 7. Significant changes in potential ice road contribution to port accessibility in December, January, and May from 1979 to 2017.

the year. The monthly contributions of potential ice roads to port accessibility are shown in figure 6.

There is strong spatiotemporal variation in the contribution of potential ice roads to port accessibility. The potential ice roads make the highest contribution to port accessibility from December to April, with the larger area of PIRA providing excellent potential access to the Pan-Arctic land area (figure 2). During these months, more than 24 h of reduction in the use of potential ice roads occurs in the Canadian Arctic and Siberia, which results in significant time savings for potential socioeconomic activities. In addition, the existence of potential ice roads also improves the accessibility by 9–21 h in Alaska. The contribution in Alaska is less than 6 h in November and May, when the areas contributing more

than 24 h in Russia and Canada also shrink significantly compared to the period of December to April. Finally, potential ice roads in October contribute less to port accessibility than in other months because of the extremely small PIRA in that month. The contribution of potential ice roads in Europe is low in every month as a result of the combined effects of the sparse PIRA and the very dense conventional transport network.

We detected significant decreases in port accessibility in December, January, and May (figure 7) with reductions in potential ice roads. These months are also the months when the stability of potential ice roads changes (figure 5). Our results show that the contribution of potential ice roads is weakening (by $1.5 \text{ h decade}^{-1}$ in December on average) in Nunavut,

Canada, where ice roads are critical for land access in winter.

5. Discussion

5.1. On-going reduction of potential ice roads

Our results show the PIRA has reduced significantly in December and April (figure 2), and Stephenson *et al* (2011) had predicted a substantial loss of ice road in these two months by 2059. This suggests that the extent of ice road environment may be decreasing toward this anticipation. Rapid decreases in PIRDs occur in Nunavut and the Northwest Territories, where ice roads are used for transportation. In these regions, the time window for using ice roads for mineral resource exploration, community access, and product delivery has become shorter (Cochran *et al* 2013). Although potential ice roads are mainly decreasing at the Pan-Arctic scale, we also observed the opposite trend. For example, PIRDs are increasing (by 0.73 d yr^{-1} on average) in the northern coastal regions of Siberia (figure 3(b)). It is mainly due to the increase in suitable snow conditions according to our results. This also highlights the non-simplified characterizations of environmental response.

In addition, the change in potential ice roads has a huge impact on economic risk. According to an economic analysis, between 1943 and 2012, the Northwest Territories of Canada projected a \$74 million increase in the cost of air cargo due to the climatically shortened construction time of the ice road system (Sturm *et al* 2017). Our results provide information on climate-affected changes in potential ice roads in the Pan-Arctic, which can not only help operators and policymakers make decisions about climate change, but also serve as input for financial risk calculations. Some regions have begun planning permanent roads to reduce reliance on ice roads during the winter, such as Northwest Territories in Canada (Kim and Li 2020). However, as ice roads with less environmental impact become fewer, the construction of more permanent roads may further exacerbate environmental change in Arctic. This effect needs further study in the future.

Since the PIRA and the stability of potential ice roads were calculated based on monthly data, the freeze-thaw variability of ground within a month may be ignored. This may limit the reliability of our results at some times, especially in months such as November and April, as these are the months when ground freezes and thaws. There are studies that evaluate the thermal state of the regional frozen ground using a specific threshold of accumulation of freezing degree day (Mullan *et al* 2017). All these studies emphasize the importance of SAT on the vitality of ice roads. We used SAT below 0°C to consider the frozen state of ground, and extracted the potential ice roads. There are limitations on this basis, such as the water content

of frozen soil and the rapid freeze-thaw processes can affect the safety of ice road travel. The life of ice roads depends on more climatic factors, such as wind speed and direction (Hori *et al* 2018). Therefore, regional ice road plans must be established on sufficient meteorological observations. We cannot assume that interpreting trend information for key climate features implies a grasp of complex climate change trends on ice roads.

Despite these limitations, monitoring the ice road evolution under climate change requires new integrative approaches that bridge different methodologies between disciplines. This study is an effort to analyse the spatiotemporal evolution of potential ice roads. Our results provide new insights not only into the consequences of warm winters on potential ice roads, but also information on the key changes in important factors of SAT and SD. At the same time, it also provides an opportunity for future integrated studies of ice roads in a more multidisciplinary way.

5.2. Decreasing port accessibility

Ice roads allow people to cross many remote areas that are only accessible by air for most of the year (Oliver 2018). However, warmer winters are increasingly hampering ice road transportation in Arctic land areas (Ford *et al* 2019). The contribution of potential ice roads to other land traffic may also change significantly. The results of port accessibility have clearly confirmed that warmer winters will hinder local travel, as remarked in previous research on ice roads (Sladen *et al* 2020).

The speed on ice roads was set to 10 km h^{-1} , although speed limits on ice roads can vary from 10 to 60 km h^{-1} depending on load and location (Tibbitt to Contwoyto Winter Road Joint Venture 2021). Thus, we may underestimate the contribution of the potential ice roads to travel time and the value of the attenuation of potential ice road contribution. Local policies and human factors also influence the contribution of potential ice roads. Factories will use tools and technology to cope with the effects of shorter winters, even though they may pay higher economic operating costs. However, it is difficult for local communities to make quick changes, and the diminishing availability of reliable ice roads will cut off the resources they rely on for survival (Oliver 2018). As a result, the decrease of potential ice roads can have more serious consequences for the lives of people living in remote areas.

In the accessibility calculations, we did not consider the effect of climate change on conventional roads and cross-border obstruction as factors because of the lack of a unified quantitative standard. Nevertheless, we were able to quantify the change in port accessibility resulting from decreasing potential ice roads by integrating environmental science knowledge and spatial analysis method.

6. Conclusion

In this study, we evaluated changes in potential ice roads under the influence of key climatic factors (SAT and SD) and quantified the contribution of potential ice roads to port accessibility in the Pan-Arctic region from 1979 to 2017. We demonstrated that potential ice roads have shrunk significantly over the past few decades. PIRA has the largest share of loss in May ($\sim 25\%$) and the sharpest reduction in April ($2.77 \times 10^4 \text{ km}^2 \text{ yr}^{-1}$). Shortened PIRDs (0.41 d yr^{-1} on average), delayed PIROD (0.28 d yr^{-1} on average), and advanced PIRED (0.21 d yr^{-1} on average) all prove that the potential ice road construction time window in the Pan-Arctic is decreasing. In addition, potential ice roads are changing from suitable to unsuitable during November to May according to the stability analysis.

Potential ice roads contribute significantly to Pan-Arctic port accessibility, and there are spatial and temporal variations, with travel time to the nearest port from December to April shortened by more than 24 h in the Canadian Arctic and Siberia and by more than 9 h in Alaska. Nevertheless, the contribution of potential ice roads to port accessibility decreases significantly in December, January, and May. The contribution in Nunavut, Canada, is strongly decreased in December ($1.5 \text{ h decade}^{-1}$ on average), and effective measures are needed in the future to cope with the difficulties of land access due to the warmer winter.

Data availability statement

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

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