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Divergent long-term trajectories of human access to the Arctic

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Understanding climate change impacts on transportation systems is particularly critical in northern latitudes, where subzero temperatures restrict shipping, but enable passage of ground vehicles over frozen soil and water surfaces. Although the major transport challenges related to climate warming are understood, so far there have been no quantitative projections of Arctic transport system change. Here we present a new modelling framework to quantify changing access to oceans and landscapes northward of 40° N by mid-century. The analysis integrates climate and sea-ice model scenarios[1,2] with topography, hydrography, land cover, transportation infrastructure and human settlements. Declining sea-ice concentration and thickness suggest faster travel and improved access to existing (+5 to +28%) and theoretical (+11 to +37%) offshore exclusive economic zones of Canada, Greenland, Russia and the US. The Northern Sea Route, Arctic Bridge and North Pole routes are projected to become fully accessible from July–September, averaging ∼11, 15 and 16 days to traverse, respectively, whereas the Northwest Passage will not. All eight Arctic states are projected to suffer steep declines (−11 to −82%) in accessibility inland, driven by lost potential for winter road construction caused by milder winters and deeper snow accumulation.

Projected ∼2–4 °C increases in global mean temperature by the end of the century will be strongly amplified in the Arctic (2–9 °C), especially in winter (∼4–11 °C; refs 3–5). Early signals of this are already apparent from observations of decreased summer sea-ice extent together with increased glacier and ice-sheet mass losses, coastal erosion, and duration of seasonal soil thaw[4,6]. Of these, reduced sea ice and thawing ground have the greatest potential to affect human access to the region, owing to their strong influence on two critical transportation systems: (1) maritime shipping, and (2) temporary winter roads and ice pavements constructed across frozen landscapes[7].

As sea ice is the single greatest obstruction to ship navigation, reductions in its concentration and thickness encourage maritime activities owing to increased navigable area, vessel safety and shipping season length[6,8]. In the Arctic Ocean, reduced multi-year ice (MYI) is also important because it is harder and thicker than first-year ice (FYI; refs 9–12). Trans-Arctic routes have the potential for significant distance savings: 40% via the Northern Sea Route (Rotterdam–Yokohama, compared with the Suez Canal)[13]; 33% via the Northwest Passage (St Johns–Yokohama, compared with the Panama Canal)[14]. Thus, four consecutive record lows in the September sea-ice minimum from 2007–2010 (ref. 15) have spurred renewed interest in the Northwest Passage and Northern Sea Route, with the latter successfully traversed by two escorted voyages in 2010 and ten more pending for 2011 (refs 16–18).

Unlike the Arctic Ocean, which is most accessible in summer, Arctic landscapes are most accessible in winter, when wet and/or environmentally delicate surfaces freeze sufficiently hard to provide a viable driving surface. ‘Winter roads’ are temporary roads and ice pavements constructed across frozen ground, lakes and rivers using compacted snow, applied ice caps, ice aggregates, or groomed bare ground. As they have a low cost to build, they enable the transport of equipment and cargo for resource development, construction projects, and community resupply in remote areas that would otherwise be uneconomic using permanent roads or aircraft. Winter roads provide critical transportation infrastructure in Alaska, Finland, Norway, Russia and Sweden, with over ∼5,400 km active in Canada alone[19]. However, subzero ground temperatures are essential to maintaining adequate ground strength and ice thickness[6,20], so milder winter temperatures and/or increased snow depth (which insulates the ground) shorten their seasonal life. On Alaska’s North Slope, winter road seasons have dwindled in some areas from over 200 days to just over 100 days since the 1970s (ref. 21). The Tibbitt–Contwoyto winter road, the Northwest Territories’ longest, is projected to lose ∼17% of its operating season between 2008 and 2020 (ref. 22) (Supplementary Discussion).

This study offers a numerical basis to discussions of future human activity in northern latitudes by modelling the projected impacts of climate change on maritime and inland transportation systems. To achieve this, we present a novel modelling framework, the Arctic Transport Accessibility Model (ATAM), which adapts a long legacy of transportation modelling[23–26] to integrate climate model projections of air temperature, snow depth, and sea ice with static datasets on land cover, topography, hydrography, built infrastructure, and locations of human settlements. To isolate the effects of climate change, these latter natural and anthropogenic features are here assumed to remain geographically fixed into the future, but ATAM may also be used to model impacts to human access caused by changed infrastructure or hydrography (Supplementary Methods).

By 2045–2059, a broad pattern of declining winter road accessibility potential on land and rising ship accessibility potential in the Arctic Ocean is observed in all ATAM simulations (Fig. 1). Most of the Arctic Ocean basin becomes newly accessible to Type A class (below Polar Class icebreakers, but capable of limited icebreaking) vessels for eight months of the year (July–February, in green). Losses in winter road potential occur from October to May (in red). Little change is projected between July and September as these months are already too warm to support winter roads today.

Condensed to country-level, annual averages, all eight Arctic states experience significant reductions in total land area climatically suitable for winter road construction (Table 1) (note: Table 1 numbers are conservative, as July–September are still included in the annual average). These declines range from −11 to −82% relative to baseline, but in absolute terms, Canada and Russia account for the vast majority of declining winter road potential (∼1 M km^2 out of ∼1.2 M km^2 total land area lost).

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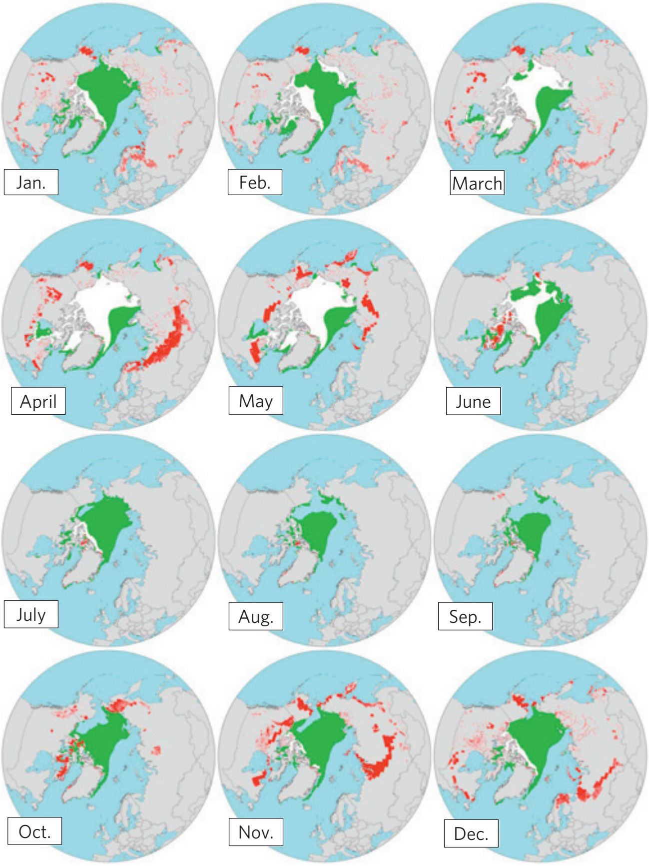

Figure 1 | Change in maritime and land-based transportation accessibility by mid-century, baseline (2000–2014) minus mid-century (2045–2059). Green indicates newly formed maritime access to Type A (light icebreaker) vessels. Red indicates lost winter road potential for 2,000 kg ground vehicles. White indicates areas still inaccessible to Type A vessels by mid-century.

In contrast, all five Arctic littoral states are projected to gain increased maritime access to their current exclusive economic zones (EEZs) (Table 1), especially Greenland (+28% relative to baseline), Canada (+19%), Russia (+16%), and the United States (+5%). An even larger increase is projected for the Arctic Ocean high seas ($\sim$1.8 M km^2 newly accessible, or +406% relative to baseline). If maximum plausible EEZ extensions are awarded in the future under Article 76 of the United Nations Convention on the Law of the Sea (UNCLOS; ref. 27), the national figures rise to +37%, +32%, +29%, and +11%, respectively. Iceland, Norway, Sweden and Finland display little to no increase in maritime accessibility, as sea ice rarely impedes Type A shipping in these countries today.

The accessibility of a land or sea area dictates the transportation modes eligible to be used there. Projected changes in air temperature, snow accumulation, and sea ice directly alter travel times by restricting or enabling transportation modes inland (for example, lost winter roads, or vessel mobility in rivers) and ship speeds at sea (for example, $\sim$7 km h^{-1} in FYI versus $\sim$20 km h^{-1} in open water). To illustrate this, ATAM simulations of travel time to nearest settlement (TTNS) are presented for baseline and mid-century for the month of November (Fig. 2). Darker tones indicate longer travel times owing to the combined effects of remote distance, sparse transportation infrastructure, rugged topographic relief, low winter road potential and river ice in continental interiors; and thick and/or concentrated sea ice in the Arctic Ocean. Solid black indicates areas completely inaccessible to Type A ships (that is, sea ice $\sim$120 cm or thicker) or on foot (that is, permanent glaciers on land). By mid-century, higher TTNS (longer travel time) is seen for many inland areas, including Russia's West Siberian Lowland and Far East, northern Canada, and Alaska. In contrast, declining TTNS (faster travel time) is seen throughout the circumpolar ocean, especially near previously impassible ice margins in the central Arctic Ocean basin. The effect of declining winter road potential on inland TTNS is especially powerful in areas lacking permanent roads or rail. For example, the time required for November overland travel from Bathurst Inlet to Yellowknife increases from 3.8 days at baseline to 6.5 days by mid-century.

The aforementioned changes are strongly seasonal, especially over land, where maximum travel delays are projected in November and April across vast northern continental interiors ($\sim$2.5 M km^2 total, Fig. 3). These months capture typical annual opening and closing dates for current operations for many winter roads, suggesting truncated cargo transport seasons from delayed openings and earlier closures in the future. In contrast, this seasonal effect is less pronounced in the Arctic Ocean, with sizeable marine areas

Table 1 | Annually averaged changes in inland and maritime transportation accessibility by mid-century (2045–2059) versus baseline (2000–2014).

	Change in winter road-accessible land area (km^2) (2,000-kg GVWR vehicle)	Change in maritime-accessible ocean area (km^2) (Type A vessel)—current EEZ	Change in maritime-accessible ocean area (km^2) (Type A vessel)—extended EEZ claims[24]
Canada	−399,810 (−13%)	+714,088 (19%)	+1,201,226 (32%)*
Finland	−15,235 (−41%)	0 (0%)	Not applicable
Greenland	−23,400 (−11%)	+432,713 (28%)	+579,117 (37%)*
Iceland	−2,038 (−82%)	+1,550 (<1%)	Not applicable
Norway	−10,173 (−51%)	+40,688 (2%)	+48,471 (2%)†
Russia	−617,956 (−13%)	+989,255 (16%)	+1,819,239 (29%)‡
Sweden	−14,490 (−46%)	0 (0%)	Not applicable
USA (Alaska)	−128,185 (−29%)	+184,779 (5%)	+374,892 (11%)*
High seas	Not applicable	+1,830,980 (406%)	+188,010 (173%)§
Total	−1,211,287 (−14%)	+4,194,053 (23%)	+4,210,955 (24%)

GVWR, gross vehicle weight rating. *Theoretical claim. †Includes area awarded by UNCLOS in 2009 in addition to a theoretical claim north of the 'Banana Hole'[27]. ‡Pending claim. §Unclaimed. Additional details in Supplementary Table S1.

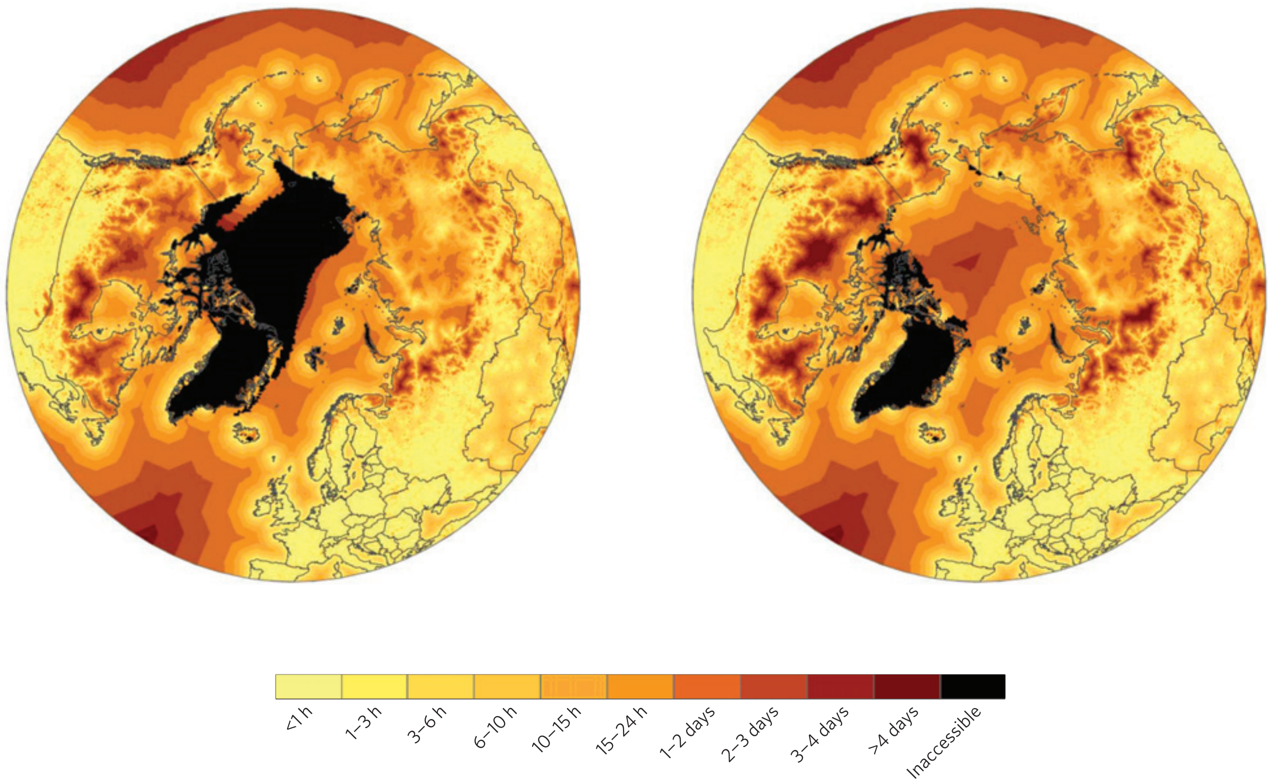

Figure 2 | November travel time to nearest settlement using multi-mode transportation (Type A shipping, winter road, permanent road, rail, walking) for baseline (2000–2014, left) and mid-century (2045–2059, right). To isolate climate change impacts, all human settlements and permanent transportation infrastructure are assumed unchanging between the two time periods. By mid-century, dark tones in continental interiors reflect longer TTNS owing to reduced winter road potential. In oceans, lighter tones reflect shorter shipping TTNS owing to reduced sea ice. Areas still inaccessible by mid-century are shown in black. For corresponding map pairs for all other 11 months see Supplementary Fig. S1.

experiencing faster travel year-round with only muted maxima in August and September (Fig. 3).

Projected maritime accessibility changes along four international shipping routes are shown in Table 2. During the July–September Arctic shipping season, increased maritime transportation accessibility is projected for the Northwest Passage (NWP), Northern Sea Route (NSR), and North Pole (NP) routes. The NP experiences the largest gains relative to baseline (+56%), becoming 100% accessible to Type A vessels with an average projected transit time of ~16 days by mid-century. The NSR, only 86% accessible from July to September today, is projected to become 100% accessible, with an average projected transit time of ~11 days. The NWP, despite a +30% accessibility increase, is projected to still obstruct Type A shipping by mid-century (82% accessible, slightly less than the NSR at baseline). The Arctic Bridge (AB) route (Churchill to Murmansk) is 100% accessible in both time scenarios with an average projected transit time of ~15 days (Supplementary Discussion).

Climate change has spurred global perceptions of the Arctic as an arena of new potential for resource exploration and intercontinental shipping[8,28,29]. A core conclusion of this analysis is that reduced sea-ice concentration and thickness will cause Canada, Greenland, Russia, and the United States to experience sizable increases in maritime access to their offshore EEZs, nearly year-round, using ships with light icebreaking capability. Furthermore, in addition to this expansion of technically accessible ocean, the ATAM simulations project faster travel speeds within regions already accessible today. To the extent that sea ice alone limits Arctic shipping (as opposed to economics, existence of port infrastructure, tariffs, daylight, and other critical factors) the surprising discovery of a nearly year-round increase in accessible area and decreases in maritime TTNS (at least to Type A vessels) suggests that some level of maritime activity will become plausible even in winter, when Arctic shipping is currently limited to year-round ports such as Murmansk and Hammerfest[8] (Supplementary Discussion).

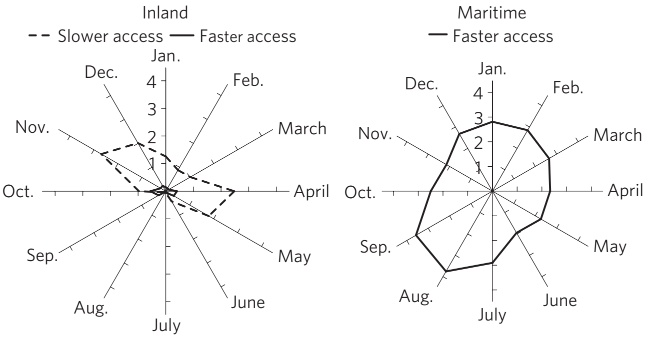

Figure 3 | Total geographic areas (million km^2) where travel time to nearest settlement increases (slower access, dashed line) or decreases (faster access, solid line) by mid-century. Large geographic areas within inland holdings of the eight Arctic states (left) will be slower to access, whereas all maritime EEZs plus high seas of the central Arctic Ocean (right) will be faster to access.

In contrast, all Arctic states face declining possibilities for constructing inland winter road networks and drivable ice pavements owing to milder air temperatures and/or deeper snowfall. Increases in inland TTNS are sharply seasonal, driven mainly by truncations in winter road potential in November and April (Fig. 3). This presents profoundly negative implications for

Table 2 | Maritime accessibility for four shipping routes at baseline (2000–2014) and mid-century (2045–2059) (Type A vessels, July—September).

Route	Length (km)	% accessible, 2000–2014	% accessible, 2045–2059	Accessibility change (%) relative to baseline	Transit time (days), 2045–2059
Northwest Passage	9,324	63%	82%	30%	-
Northern Sea Route	5,169	86%	100%	16%	11
'North Pole' Route	6,960	64%	100%	56%	16
'Arctic Bridge'	7,135	100%	100%	0%	15

numerous stakeholders located far from navigable inland waterways or coasts. Remote communities reliant on winter roads for resupply face costly increases in air cargo services. Mining, energy, and timber industries face shorter time windows for ground transport of equipment and product, and risk becoming uneconomic in some areas. Costly mitigations include building permanent roads, as has occurred north of Baker Lake, Nunavut, or a redirect towards coastal port facilities, as is proposed for Bathurst Inlet[19] (Supplementary Discussion).

The ATAM simulations suggest that by mid-century, the Northern Sea Route and North Pole route will be fully accessible to Type A vessels from July to September, whereas the Northwest Passage will not. Although new international trade routes are an oft-cited impact of this, the projected changes will also enable increased destinational shipping, for example tourism, community resupply, fishing, mining, and hydrocarbon exploration[8,30,31]. Recent geological assessments suggest that ∼30% and ∼13% of the world's undiscovered natural gas and oil, respectively, may exist in the Arctic, mostly offshore in less than 500 m of water[28,29]. Alongside growing prospects for energy development, this elevates the risk of environmental damage from spills and discharge, should maritime development of these resources advance[8].

Numerous factors constrain the results of these ATAM simulations and provide opportunities for future research. Further improvements in modelling sea-ice processes, especially ice ridging and decay, will enable more sophisticated treatment of ship accessibility. As future sea-ice declines will probably be variable in space and time, shipping season lengths remain unpredictable at interannual timescales, necessitating assimilation of satellite data and improved ice forecasting models before accessibility can be simulated for practical navigation. The coarse spatial resolution of the CCSM3 climate model (∼1.4°) limits the value of ATAM for finer scales, especially in the Canadian Archipelago, where the complex geography makes its projections less robust than elsewhere in the Arctic. The effect of climate change on extant permanent infrastructure (for example, deeper snow accumulation on permanent roads) was not addressed in this study; neither were long-term phenomena of soil destabilization from thawing permafrost[32], nor climate-induced changes in terrestrial surface water extent[33]. Finally, the assumption that the optimal (fastest) eligible vehicle is omnipresent to the terrain encountered could be made more realistic by specifying port facilities, fueling stations, and the availability of emergency services.

Regardless of these limitations, modelling the societal implications of climate change requires new integrative approaches that bridge highly different methodologies between disciplines. This study provides a first effort to adapt classic transportation accessibility modelling to address questions of physical, climate-induced changes to landscapes and oceans. Our discovery of a strongly bimodal transportation outcome—improving access by sea but declining access by land—underscores not only the acute biophysical sensitivity of the Arctic to climate change, but also the inherent dangers of simplified characterizations of social response.

Methods

ATAM was developed for all land and maritime territories lying northward of 40° N and also controlled by the eight Arctic states (USA, Canada, Greenland, Iceland, Norway, Sweden, Finland and Russia). 'Maritime' analyses include both within present-day EEZs (0–200 nm offshore) and awarded, pending, or plausible EEZ extension claims under Article 76 of UNCLOS (ref. 27). Oceans lying outside these zones are designated 'high seas.' Four potential shipping lanes, the Northwest Passage (Iqaluit to Nome), Northern Sea Route (Amderma to Provideniya), North Pole (Bering Strait to Rotterdam), and Arctic Bridge (Churchill to Murmansk) were also analysed. Climate inputs to ATAM are ensemble-mean simulations of surface air temperature, snow depth, and sea-ice properties (concentration, thickness) from the Community Climate System Model 3.0 (CCSM3)[1] averaged over two 15-year windows (2000–2014 and 2045–2059) under the A1B SRES scenario[2]. Landscape inputs are land cover, hydrography (lakes, rivers), topography (elevation, slope), currently existing transportation networks (permanent roads, rail), and human settlements. To determine winter road suitability, a 2,000 kg passenger vehicle was assumed; for inland waterways, an ordinary vessel (non ice-strengthened hull); for the Arctic Ocean, a Type A vessel. Winter road suitability was defined for land with (1) elevation below 500 m and/or slope below 5%, (2) surface temperature at or below 0 °C, and (3) 20 cm or more of snow; for lakes with (1) surface temperature at or below 0 °C, and (2) ice thickness at least 22.4 cm (minimum thickness to support a 2,000 kg vehicle); for rivers, where 75% of the equivalent lake ice thickness was at least 22.4 cm thick. The full description of ATAM is available in Supplementary Methods.

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Author contributions

S.R.S. designed the methodology, performed analyses, and led the writing. L.C.S. designed the methodology, assisted with data interpretation and contributed to writing. J.A.A. assisted with background research on accessibility theory and conducted a critical review of the manuscript.

Additional information

The authors declare no competing financial interests. Supplementary information accompanies this paper on www.nature.com/natureclimatechange. Reprints and permissions information is available online at http://www.nature.com/reprints. Correspondence and requests for materials should be addressed to S.R.S.