ENVIRONMENTAL RESEARCH LETTERS

LETTER • OPEN ACCESS

Simulating future climate change impacts on snow- and ice-related driving hazards in Arctic-boreal regions

To cite this article: Heather E Greaves *et al* 2023 *Environ. Res. Lett.* **18** 025006

ENVIRONMENTAL RESEARCH
LETTERS

CrossMark

OPEN ACCESS

RECEIVED
26 October 2022

REVISED
19 January 2023

ACCEPTED FOR PUBLICATION
24 January 2023

PUBLISHED
6 February 2023

LETTER

Simulating future climate change impacts on snow- and ice-related driving hazards in Arctic-boreal regions

Heather E Greaves[1,*], **Natalie T Boelman**[2], **Todd J Brinkman**[1], **Glen E Liston**[3], **Laura R Prugh**[4] **and Adele K Reinking**[3]

[1] Institute of Arctic Biology, University of Alaska Fairbanks, Fairbanks, AK, United States of America
[2] Lamont-Doherty Earth Observatory, Columbia University, Palisades, NY, United States of America
[3] Cooperative Institute for Research in the Atmosphere, Colorado State University, Fort Collins, CO, United States of America
[4] School of Environmental and Forest Sciences, University of Washington, Seattle, WA, United States of America
[*] Author to whom any correspondence should be addressed.

E-mail: hegreaves@alaska.edu

Keywords: road conditions, travel safety, MERRA-2, GFDL-CM3, NCAR-CCSM4, SnowModel

Supplementary material for this article is available online

Abstract

As Arctic and boreal regions rapidly warm, the frequency and seasonal timing of hazardous driving conditions on all-season Arctic-boreal roads are likely to change. Because these roads link remote Arctic areas to the rest of the North American road system, climate change may substantially affect safety and quality of life for northern residents and commercial enterprises. To gain insight into future hazardous driving conditions, we built Random Forest models that predict the occurrence of hazardous driving conditions by linking snow, ice, and weather simulated by a spatially explicit modeling system (SnowModel) to archived road condition reports from two highly trafficked all-season northern roads: the Dalton Highway (Alaska, USA) and Dempster Highway (Yukon, Canada). We applied these models to downscaled future climate trajectories for the study period of 2006–2100. We estimated future trends in the frequency and timing of icy, wet-icy, and snowy road surfaces, blowing and drifting snow, and high winds. We found that as the climate warms, and the portion of the year when snow and ice occur becomes shorter, overall frequency of snow storms and ice- and snow-related driving hazards decreased. For example, the mean number of days per year when roads are covered in snow or ice decreased by 51 d (−21%) on the Dalton Highway between the 2006–2020 and 2081–2100 time periods. However, the intensity of storms was predicted to increase, resulting in higher mean annual storm wind speeds (Dalton +0.56 m s^{-1} [+17%]) and snowfall totals (Dalton +0.3 cm [+36%]). Our models also predicted increasing frequency of wet-icy driving conditions during November, December, January, and February, when daylength is short and hazardous conditions may be more difficult to perceive. Our findings may help road managers and drivers adapt their expectations and behaviors to minimize accident risk on Arctic-boreal roads in the future.

1. Introduction

Snow and ice are defining features of Arctic-boreal regions (ABRs) and play an important role in local socio-ecological systems, including transportation networks (Datla *et al* 2013, Bokhorst *et al* 2016). As the climate warms rapidly in northern latitudes, seasonal patterns of snow and ice are shifting and affecting travel and transportation in several ways. For example, the winter ice road season is contracting (Hinzman *et al* 2005, Prowse *et al* 2011), dangerous river ice and open waterways are arising unexpectedly and obstructing winter trail networks, and unseasonable weather and precipitation events are making all modes of travel less predictable, particularly during fall, winter, and spring (Herman-Mercer *et al* 2011, Wilson *et al* 2015, Brown *et al* 2018, Cold *et al* 2020). Partly in response to these changes, the network of all-season high-latitude roads continues to expand, often to support reliable access for resource extraction. Examples of this expansion include the Inuvik-Tuktoyaktuk Highway, which was built in 2017 in the

Northwest Territories (Bird 2017) and the planned road to Ambler in Alaska (Partlow 2022). However, because the ABR cold season is long and extreme relative to lower latitudes, and because road maintenance stations are sparsely distributed, safety and ease of travel on all-season roads remain strongly influenced by snow, ice, and weather conditions. Consequently, understanding how future climate changes may impact driving conditions on these all-season roads would provide important insight into their future safety, trafficability, and maintenance needs.

Although not a direct proxy for accident risk, driving conditions reported by governmental agencies can indicate the occurrence of hazardous conditions that increase accident risk. We are unaware of studies that relate reported driving conditions to accident risk on remote, mainly gravel-surfaced roads like all-season roads common in ABRs; however, research on mainly paved roads throughout Finland (∼60–70° N latitude) found that snowy and icy conditions increased accident risk by four to five times, depending on specific conditions and road type (Malin *et al* 2019 and Finnish-language research summarized therein). Malin *et al* (2019) also found that accident risk was generally highest when the road surface temperature was at or just below −1 °C, likely because wet-icy road surfaces, which can occur due to freezing rain or freeze-thaw events, produce the most dangerous driving conditions (Norrman *et al* 2000, Andrey *et al* 2003, Malin *et al* 2019). In addition, in a study of Canadian cities (∼43–50° N latitude), precipitation was associated with a 75% increase in vehicle accidents between 1995 and 1998, with snowfall having a greater impact on accident rates than rain (Andrey *et al* 2003). Given the link between hazardous snow- and ice-related driving conditions and increased accident risk, estimating future changes in these conditions will provide insight into future accident risk on ABR all-season roads.

With climate warming, the seasonal timing, frequency, and severity of adverse cold-weather driving conditions is shifting. Hanesiak and Wang (2005) found that the frequency of freezing precipitation has increased in fall, winter, and spring in most parts of the Canadian Arctic since the mid-1900s, and a modeling study by Bieniek *et al* (2018) found that the frequency of freezing rain and rain-on-snow events increased in some areas of northern Alaska between 1979 and 2013, and was projected to increase more dramatically between 2006 and 2100. However, climate warming is likely to reduce the overall frequency of hazardous snow- and ice-related driving conditions as the snow season becomes significantly shorter in the future (Liston and Hiemstra 2011, Lader *et al* 2020). For example, Hanesiak and Wang (2005) also found that blowing snow events decreased in frequency in most areas studied, especially in spring. And in Sweden, Andersson and Chapman (2011) anticipate fewer snow- and ice-related adverse weather events overall in a warmer future, as cold conditions that produce snowy and icy road surfaces become less frequent. The impact of these potential future changes on the frequency, magnitude, and seasonality of hazardous driving conditions along all-season roads remain largely unknown.

All-season roads are the backbone of transportation infrastructure in ABRs, providing social and economic connectivity across large, sparsely populated areas and linking networks of winter roads and trails. Acquiring insight into potential future trends in snow- and ice-mediated driving conditions on these roads would support planning for future travel, road maintenance, and budgeting within governmental transportation departments. The goal of our study was to establish quantitative associations between hazardous driving conditions and snow, ice, and weather dynamics in ABRs, and use them to improve understanding of possible future trends in hazardous driving conditions on all-season roads. To this end, using archived driving conditions and simulated snow and weather products, we built models linking past snow and weather conditions to the occurrence of hazardous driving conditions. We then applied the models to two future global climate simulations to predict possible future trends in the timing, severity, and frequency of hazardous driving conditions.

2. Methods

2.1. 511 reports

We used records of driving conditions ('511 reports') archived by regional 511 traveler information systems for two all-season roads: the Dalton Highway (Alaska Route 11) and the portion of the Dempster Highway within the Yukon Territory (YT) (Yukon Highway 5; figure 1). The Dalton Highway begins northwest of Fairbanks, Alaska, USA, and runs north for 666 km to Deadhorse, on Alaska's northern coast. The Dempster Highway begins east of Dawson City, YT, Canada, and runs 736 km north to Inuvik, Northwest Territories (NWT), Canada (see supplemental §S1 for additional information about these roads). Driving conditions were not archived for the portion of the Dempster within the NWT, so our analysis only includes the southern 465 km of the Dempster within the YT. For the Dalton Highway, the 511 reports included roughly 49 000 records from March 2010 through December 2019. Each record described driving conditions (for example, 'blowing snow', 'high winds') that were occurring at a specific location (i.e. in a road section, delineated by mileposts), over a specified time duration (minutes to days). For the Dempster, the 511 reports included roughly 41 500 records in a similar format covering March 2008 through October 2020. To prepare the 511 reports for analysis, we tabulated hazardous driving conditions that occurred in each road section on each day.

Figure 1. In (A), the Dalton Highway (left) and the Yukon portion of the Dempster Highway (right) are shown within the rectangular modeling extents for each study area. In (B) and (C), the modeling extents for (B) the Dalton Highway and (C) the Yukon portion of the Dempster Highway are shown in more detail within their topographic distributions. Alternating red and black road segments illustrate the road sections that were used as spatial sample units in this modeling study.

For more information on the background and preparation of the 511 reports, see §2.3.1 and supplemental §S2. Hazardous driving conditions (or 'hazardous conditions') selected for modeling are shown in table 1.

2.2. Weather and snow modeling

2.2.1. SnowModel and recent climate data

We used SnowModel to estimate spatially and temporally explicit weather, snow, and ice variables along our two study highways (table 2). SnowModel (Liston and Elder 2006a, see appendices in Liston *et al* 2020) is a spatially explicit, physics-based modeling system composed of submodules that simulate meteorology (Micromet; Liston and Elder 2006b), surface energy balance (EnBal; Liston *et al* 1999), snowpack evolution (SnowPack; Liston and Mernild 2012), and snow redistribution by wind (SnowTran-3D; Liston *et al* 2007). SnowModel's landcover and topography distributions were defined using 30 m resolution landcover maps from the 2015 North American Land Change Monitoring System (NALCMS; Commission for Environmental Cooperation *et al* 2020) and topography from the United States Geological Survey 3D Elevation Program, 1 arcsecond (∼30 m) spatial resolution dataset (U.S. Geological Survey 2017).

Daily climate inputs (air temperature, relative humidity, precipitation, wind speed, and wind direction) required to drive SnowModel for the time periods of the 511 reports were derived from NASA's Modern Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2; Gelaro *et al* 2017) dataset. Hereafter, SnowModel will be abbreviated as 'SM-M2' when driven by MERRA-2 forcing data. We used SnowModel to simulate a suite of weather and snow variables at a daily timestep and 500 m spatial resolution over the modeling extents presented in figure 1. Several additional variables were derived after simulation by combining SnowModel outputs to produce synthesis variables relevant to our application (table 2). The derived variables in table 2 can be thought of as societally-relevant environmental variables. These synthesis variables are consistent with the 'human-relevant environmental variables' introduced by Fox *et al* (2020).

2.2.2. Future climate projections

To drive SnowModel under potential future climate trajectories, we used climate data derived from downscaled runs of two global climate models (GCMs): NOAA's Geophysical Fluid Dynamics Laboratory Coupled Climate Model 3 (GFDL-CM3), and the National Center for Atmospheric Research's Community Climate System Model 4 (NCAR-CCSM4). Walsh *et al* (2018) found that these two models were among the top performing out of 21 GCMs tested for the Alaska region. Both GCM runs were part of the Coupled Model Inter-comparison Project 5 and were produced using representative concentration pathway 8.5. Dynamically downscaled 20 km versions of these datasets (Lader *et al* 2017, Bieniek *et al* 2018) were available for our study areas at an hourly timestep for the years 2006–2100 from the Scenarios Network for Alaska and Arctic Planning (SNAP; uaf-snap.org).

We used the 15 years of temporal overlap (2006–2020) between MERRA-2 reanalysis data and the GCM future climate datasets to perform a simple bias correction of the GCM data (see supplemental §S3). The bias-corrected GFDL-CM3 and NCAR-CCSM4 future climate datasets were then prepared for use within SnowModel to estimate future snow

Table 1. Hazardous driving conditions modeled for each highway. Values indicate the number of days each hazardous condition was reported somewhere on that highway over the time period of the available records (see text). Dashes indicate that a model was not trained for that condition on that highway. Hazardous condition labels may represent consolidated versions of originally reported conditions; for example, 'poor visibility' also includes conditions described as 'reduced visibility' or 'zero visibility' .

Hazardous condition	Dalton highway	Dempster highway
Blowing & drifting snow	1172	1213
Fog	787	—
High winds	311	—
Icy road surface	1654	—
Poor visibility	559	510
Snowy road surface	—	2248
Wet-icy road surface	781	—
Wet road surface	1280	271

and weather variables (table 2) at a daily timestep. Hereafter, SnowModel runs driven by the downscaled GFDL-CM3 and NCAR-CCSM4 datasets are abbreviated 'SM-GFDL' and 'SM-NCAR', respectively.

2.3. Building predictive models

2.3.1. Merging 511 report data with Snowmodel MERRA-2 output

Building predictive models required linking records of hazardous driving conditions from the 511 reports to the SM-M2 weather data corresponding to the time and location of each report. To accomplish this, we imposed a temporal resolution of one day on the 511 reports, and we imposed a standardized spatial resolution by dividing the highways into arbitrary road sections (figure 1; see supplemental §S4 for details); a hazardous condition was considered to have occurred on a given day in a given road section if it was reported anywhere within that section on that day.

2.3.2. Modeling pipeline

Samples from four complete snow years (approximately 30% of observations) were separated from each of the Dalton and Dempster datasets to be withheld from model training and used for model accuracy assessments. Here, a 'snow year' begins 1 September and ends 31 August of the following year, and is named for the calendar year in which it ends (e.g. snow year 2021 begins 1 September 2020 and ends 31 August 2021). The remaining 70% of observations in each road's dataset comprised the model training datasets.

Although initially we tested several classifiers in our modeling pipeline, Random Forest provided the most consistent performance and stability for multiple hazardous conditions and both highway study areas, so we proceeded with Random Forest alone. The Random Forest algorithm uses an ensemble of classification trees built from randomized subsets of the training data to produce predictions with limited overfitting (Breiman 2001). It naturally models complex interactions, is robust against outliers and non-linear data, requires minimal data preprocessing, and is appropriate when accurate prediction is valued over model interpretability, as in our study. For each highway and each hazardous condition, a Random Forest classifier was trained to predict whether the hazardous condition occurred or did not occur in a given road section on a given day. See supplemental §S5 for modeling pipeline details.

2.3.3. Model accuracy evaluation

Following model training and fitting, final Random Forest models were applied to withheld samples and evaluated for accuracy using precision, recall, F1-score, and the Matthews correlation coefficient (MCC; Chicco and Jurman 2020). Precision reflects the fraction of predicted positive cases that were truly positive; recall represents the fraction of true cases that the model correctly identified. The F1-score is the harmonic mean of precision and recall, and the MCC ranges from -1 to 1 and only approaches 1 when both true positives and true negatives are well predicted.

In the withheld sample data, discrepancies in storm timing between hazardous conditions in the 511 reports and in the SM-M2 datasets were prevalent (see supplemental §S4), which led to noisy labels and reduced accuracy estimates, even when the model was making reasonable predictions. Therefore, we calculated accuracy metrics twice: first on the raw results, and again after applying a simple time-buffering adjustment algorithm that considered observed hazardous conditions within each road section in the two days before and after each hazardous condition prediction. For example, blowing snow wrongly predicted on a day that was reported as calm in the 511 report could be counted as correct if blowing snow did appear on the previous day's 511 report (see supplemental §S6). The time-buffered results better reflected the practical accuracy of the models.

2.4. Estimating future trends in hazardous driving conditions

Based on model accuracy assessments, we selected a final suite of hazardous condition models to be applied to the SM-GFDL and SM-NCAR future climate simulations for each road corridor. As with the SM-M2 data, output from SM-GFDL and SM-NCAR were summarized over pixels within each road

Table 2. Descriptions and units of SnowModel outputs and derived variables used in modeling.

Variable	Description
SnowModel output variables	
Air temperature	Daily mean air temperature at 10 m height (°C)
Precipitation	Daily total precipitation (m)
Rainfall	Daily total liquid precipitation (m)
Relative humidity	Daily mean relative humidity (%)
Snowfall SWE	Daily total snow precipitation (m)
Snowpack SWE	Snow water equivalent depth (m)
Snowmelt	Daily total snowmelt (m)
Wind speed	Daily mean wind speed (m s^{-1})
Derived SnowModel variables	
3 day cumulative air temperature >0 °C	Rolling prior three-day sum of daily mean air temperatures greater than 0 °C (°C)
3 day cumulative precipitation	Rolling prior three-day sum of daily total precipitation (m)
3 day cumulative rainfall	Rolling prior three-day sum of daily total rainfall (m)
3 day cumulative snowfall SWE	Rolling prior three-day sum of daily total snowfall SWE (m)
3 day cumulative snowmelt	Rolling prior three-day sum of snowmelt (m)
Storm index	Unbounded indicator of storm severity: 100 * precipitation (m) + wind speed $(\mathrm{m\ s^{-1}})^3$
3 day cumulative storm index	Rolling prior three-day sum of storm index
Surface-air temperature difference	Difference between surface (skin) temperature and air temperature (°C)

section in each road corridor at a daily timestep, then were used as new weather and climate input datasets for prediction using the Random Forest hazardous condition models. We summarized daily predictions of hazardous conditions for each road corridor under each future climate dataset at monthly, annual (snow year), and 20 year intervals for comparison over space and time. Annual summaries include values from all months, although only September–May are shown in monthly results. We also applied the predictive models pixelwise over each complete study area to produce a spatial visualization of future changes in conditions that likely would be hazardous for travel in the study area around each highway.

3. Results

3.1. Future trends in SnowModel climate variables

Annual trends in future climate simulated by SM-GFDL and SM-NCAR were similar overall (figure S1) and led to broadly similar future estimates of hazardous driving conditions for both highway corridors (compare figures 2 and S2). Therefore, in the main text we report only results derived from SM-GFDL; see supplemental §S8 for SM-NCAR results. In the SM-GFDL simulation, the mean annual air temperature during the 2080–2100 period was 7.5 °C higher than during the 2006–2021 period along the Dalton Highway, and 6.1° higher along the Dempster (figure S1). Comparing the same two time periods, total annual precipitation increased along both highways, by 1.5 cm (+5%) along the Dalton and 1.6 cm (+6%) along the Dempster. Along the Dalton, this increase reflected an increase in mean annual snowfall (+2.5 cm or +11%) and a decrease in mean annual rainfall (−1.0 cm or −24%), while along the Dempster there was both a slight increase in snowfall (+0.4 cm or +1%) and a more dramatic increase in rainfall (+1.2 cm or +37%). (Note that all snowfall values shown are snow water equivalent; see table 2). Along both highways, annual mean wind speed also increased between these two periods, by 0.16 m s^{-1} (+7%) along the Dalton and 0.11 m s^{-1} (5%) along the Dempster.

3.2. Predictive model performance

Random Forest model performance was mixed, and a few models were deemed too weak to use for estimating future hazardous driving conditions (table 3). Hazardous conditions that tend to be common and persistent were best predicted; for example, 'icy road surface' was well predicted on the Dalton (F1 = 0.88), as was the roughly equivalent 'snowy road surface' on the Dempster (F1 = 0.96). Relative to persistent conditions, ephemeral conditions like 'high winds' were less well predicted (Dalton F1 = 0.70) and tended to

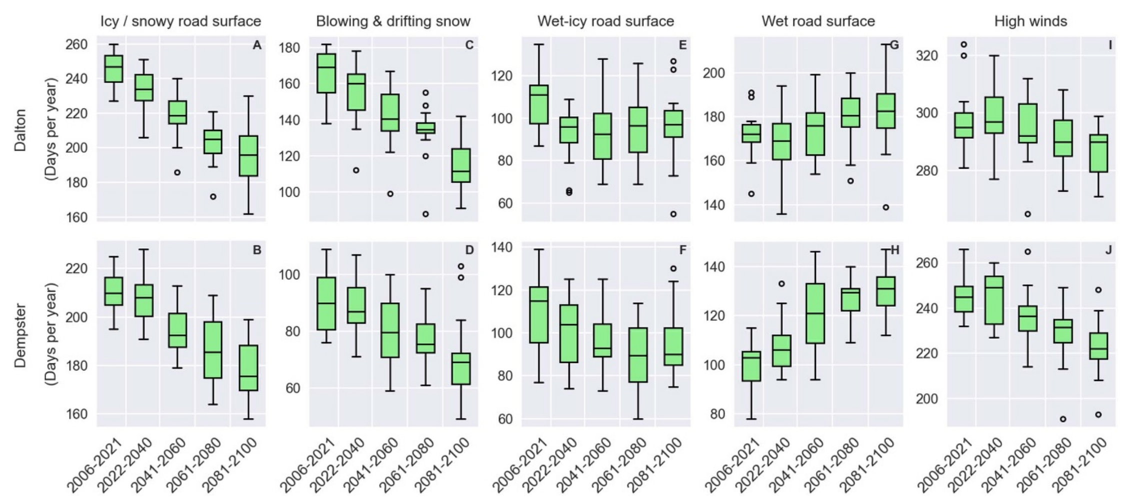

Figure 2. Projected trends in total number of days per snow year with hazardous driving conditions predicted to occur within the Dalton and Dempster Highway corridors from the time periods 2006–2021 through 2081–2100. Boxes span the 25th to 75th quartiles; whisker length is 1.5 times the interquartile range; line marks the median; circles mark outliers. Note that the *Y*-axis range is not shared across subplots.

show larger differences between accuracy metrics calculated with and without the two-day temporal buffer, suggesting that they were more prone to timing mismatches. The Dalton model for 'wet-icy road surface' had relatively weak precision (0.54), but because the model recall was acceptable (0.71) and the condition is particularly hazardous and relevant in a warming climate (Hanesiak and Wang 2005), the model was retained. The 'wet road surface' model for the Dempster Highway had similarly weak precision, potentially because the condition was rarely reported before 2017 and consequently there were limited samples with which to build and validate the model (table 1).

Two important hazardous conditions—"wet-icy road surface" and 'high winds'—were well represented in 511 reports from the Dalton Highway but not the Dempster Highway, meaning we could not build Dempster-specific predictive models for these conditions. However, given the similarity between the ecological settings, latitude range, road surfaces, and traffic characteristics of the two highways, we proceeded to apply the Dalton models to the Dempster Highway corridor to estimate future trends in those same two conditions on the Dempster Highway. However, we note that we cannot evaluate the accuracy of these models when applied to the Dempster.

3.3. Future trends in hazardous driving conditions

3.3.1. Ice- and snow-covered roads

For both highways, the mean number of days per year when the road is ice- and snow-covered was projected to shrink considerably between the 2006–2021 and 2081–2100 time periods, decreasing by 51 d (−21%) on the Dalton and 31 d (–15%) on the Dempster (figures 2(A) and (B)). The biggest changes were predicted to occur in September, October, April, and May (figures 3(A) and (B)). For example, the number of October days with snow- and ice-covered roads was projected to decrease by 19 d (−63%) on the Dalton and 16 d (−56%) on the Dempster. In May, the Dalton was projected to have 13 fewer ice- and snow-covered days (−66%) by 2081–2100. In addition to these Dalton- and Dempster-wide trends, we found trends related to latitude and topography along each highway (figures 4 and 5). For example, figure 4 (top row) suggests that decreases in the frequency of icy roads along the Dalton during fall and spring months will be most prevalent in northern road sections, while decreases in icy road frequency during winter (December through March) will be more prevalent in southern sections. Spatial trends in additional future hazardous driving conditions along each highway are shown in supplemental §S8.

3.3.2. Wet road surface

The decreasing number of days per year with icy- and snow-covered road surfaces is partly matched by an increasing number of days with wet road surfaces. Between the 2006–2021 and 2081–2100 time periods, the mean number of days per year when the surface is wet was expected to increase by 11 d (+6%) on the Dalton and 31 d (+32%) on the Dempster (figures 2(G) and (H)). On the Dalton, this manifested as a much wetter October (+11 d or +120%), November (+5 d or +580%), and March (+11 d or +145%); meanwhile May had fewer days with a wet road surface (−9 d or −28%) (figure 3(G)). Similarly, by the 2081–2100 time period the Dempster was expected to have a wetter October (+14 d or +722%) and drier May (−3 d or −16%) (figure 3(H)).

3.3.3. Blowing and drifting snow

The diminishing cold season was also projected to reduce the number of days per year impacted by blowing and drifting snow. By the 2081–2100 time period,

Table 3. Accuracy metrics for Random Forest models evaluated on withheld data. MCC = Matthews correlation coefficient. Parentheses enclose values calculated without a two-day buffer. Models for hazardous conditions marked by an asterisk were not considered strong enough to apply to future projections, based on F1 score.

Hazardous condition	Precision	Recall	F1-score	MCC
Dalton Highway				
Blowing & drifting snow	0.72 (0.48)	0.79 (0.59)	0.75 (0.53)	0.70 (0.43)
* Fog	0.43 (0.28)	0.39 (0.27)	0.41 (0.28)	0.37 (0.22)
High winds	0.70 (0.46)	0.71 (0.48)	0.70 (0.47)	0.55 (0.20)
Icy road surface	0.83 (0.71)	0.94 (0.90)	0.88 (0.79)	0.79 (0.61)
* Poor visibility	0.47 (0.26)	0.39 (0.23)	0.42 (0.25)	0.39 (0.20)
Wet-icy road surface	0.54 (0.36)	0.71 (0.53)	0.61 (0.43)	0.57 (0.36)
Wet road surface	0.68 (0.48)	0.81 (0.65)	0.74 (0.55)	0.66 (0.40)
Dempster Highway				
Blowing & drifting snow	0.61 (0.38)	0.75 (0.46)	0.67 (0.42)	0.58 (0.25)
* Poor visibility	0.26 (0.12)	0.57 (0.24)	0.36 (0.16)	0.35 (0.11)
Snowy road surface	0.97 (0.91)	0.94 (0.90)	0.96 (0.91)	0.87 (0.69)
Wet road surface	0.52 (0.40)	0.81 (0.65)	0.63 (0.49)	0.60 (0.44)

the mean number of days per year with blowing and drifting snow declined by 51 d (−31%) on the Dalton and 21 d (−24%) on the Dempster (figures 2(C) and (D)). This decrease was evident during most months between September and May (figures 3(C) and (D)), with the most consistent decreases in the fall and spring. For example, along the Dalton, the mean number of days per year with blowing snow decreased by approximately 12 d (−97%) in October and 14 d (−51%) in November between the 2006–2021 and 2081–2100 time periods. However, December and January showed slight increases in frequency, particularly in mountainous areas (Dalton Highway, figure 4) and northern road sections (Dempster Highway, figure 5).

3.3.4. High winds

The number of days per year with reports of high winds was also projected to decline along both highways between the 2006–2021 and 2081–2100 time periods, by 11 d (−4%) along the Dalton and 22 d (−9%) along the Dempster (figures 2(I) and (J)). This decrease occurred during all months from September through April; however, the frequency of high winds in May was projected to increase by 4 d along both the Dalton (+19%) and the Dempster (+25%) (figures 3(I) and (J)).

3.3.5. Storm conditions

The predicted decline in the frequency of days with blowing and drifting snow and with high winds (§3.3.3 and §3.3.4; figure 2) initially appeared inconsistent with the overall projected increase in snowfall and wind speed (§3.3.1; figure S1). However, when we isolated ‘stormy’ days (i.e. days with blowing and drifting snow predicted), we found that the mean daily snowfall and wind speed on those days were expected to increase over time (figure 6) so, although there were fewer stormy days in the future, they became more intense. By the 2081–2100 time period, mean annual storm snowfall totals increased by 0.3 cm (36%) relative to the 2006–2020 time period along the Dalton and by 0.2 cm (24%) along the Dempster. The biggest changes were seasonal, especially along the Dalton, where mean December storm snowfall totals increased by more than 1.1 cm (217%) relative to the 2006–2021 period (figure 6(A)). Wind speed on stormy days tended to increase more in the fall and early spring: October mean storm wind speed on the Dalton increased by more than 1.4 m s^{-1} (44%) between the 2006–2021 and 2081–2100 time periods (figure 6(C)).

3.3.6. Wet-icy road surfaces

On both highways, the number of days per year with wet-icy road surfaces declined between the 2006–2021 and 2081–2100 time periods, by 12 d (−11%) on the Dalton and 14 d (−13%) on the Dempster (figures 2(E) and (F)). However, the annual periods with the highest frequency of wet-icy conditions occur when temperatures are near 0 °C, and the timing of these periods was predicted to shift considerably over time (figures 3(E) and (F)). Along the Dalton, for example, the fall-season month of peak frequency for wet-icy conditions was predicted to first shift from September (in the 2006–2021 time period) to October (2022–2080), and then to November (2081–2100) (figure 3(E)), as freezing temperatures occurred progressively later in the fall season. The earlier onset of spring warmth along the Dalton was evident in the March results, when the mean number of days with wet-icy conditions doubled from 13 d during 2006–2021 to 25 d during 2081–2100 (figure 2). And, while wet-icy conditions in April remained relatively unchanged over the study period, values for May decreased dramatically, losing a mean of 16 d (−53%) of wet-icy conditions by the 2081–2100 time period, as the onset of thawing temperatures shifted earlier in the spring.

Additionally, the core winter months of December, January, and February, which currently experience few, if any, wet-icy days, showed small

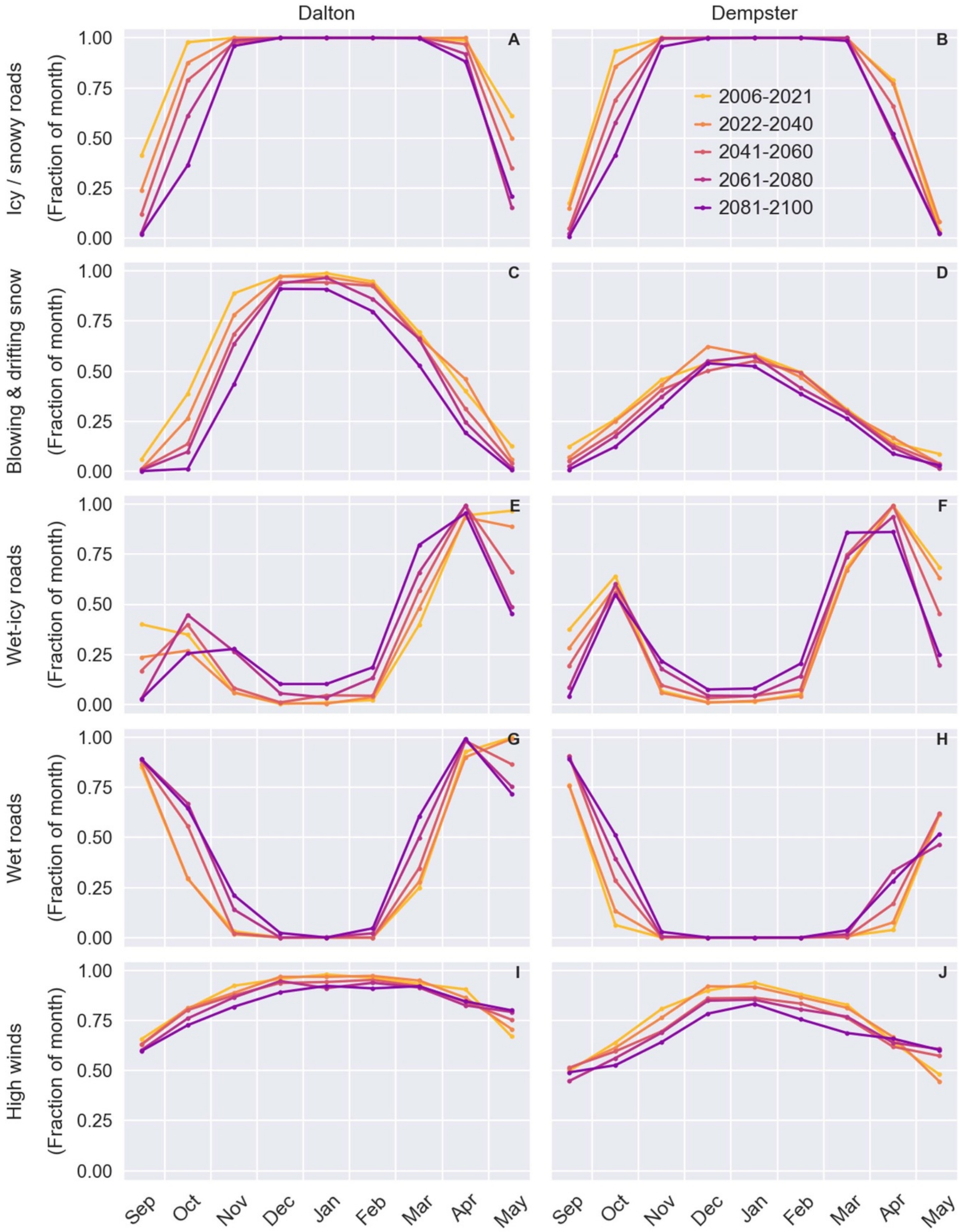

Figure 3. Mean fraction of days per month that hazardous driving conditions were predicted to occur during September through May of future time periods for the Dalton and Dempster highway corridors. Y-axis values are standardized to avoid misleading effects due to differing month lengths, but note that each Y-axis increment of 0.25 roughly corresponds to one week.

but potentially important increases in the frequency of these conditions along both highways. On the Dalton, the number of days with wet-icy conditions in December and January was predicted to increase from a mean of less than 1 d to more than 3 d, and the number of wet-icy days in February was predicted to increase from a mean of less than 1 d to 5 d by the 2081–2100 time period. These increases were most apparent on south-facing aspects on the southern portion of the road (figure 4), although they also occurred to a lesser extent on the coastal plain in the north. Along the Dempster, spatial patterns of changes between the 2006–2021 and 2081–2100 time periods depended somewhat on latitude, with the largest winter increases occurring south of the mountains near the southern end of the road and on south-facing aspects north of the mountains (figure 5).

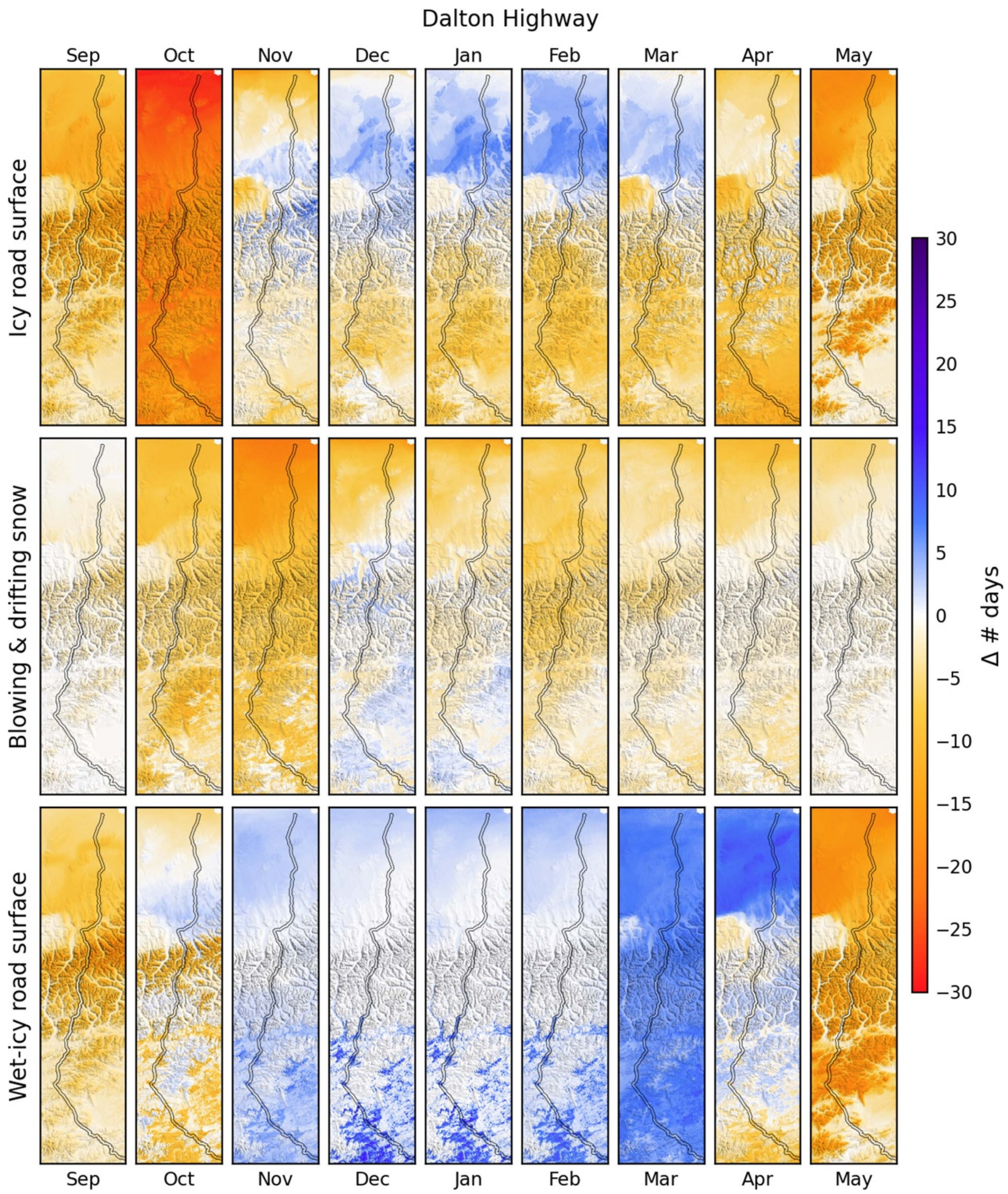

Figure 4. Monthly difference (2081–2100 monthly means minus 2006–2021 monthly means) in the number of days with selected hazardous driving conditions predicted to occur for the complete Dalton Highway study area. The Dalton Highway is shown with a 2 km buffer for reference.

4. Discussion

4.1. Future cold-season driving conditions will become wetter

Unsurprisingly, a shorter future cold season is expected to lead to a shorter period each year with snow- and ice-covered roads, and a correspondingly longer period when the roads are wet instead. Along the Dempster, for example, the projected decrease in the mean number of days per year with snow-covered roads (−31 d) was exactly balanced by an increase in the expected number of days with wet roads (+31 d). Wet roads may be less dangerous than icy roads, but they also present challenges that could require shifts in driver behavior and road maintenance priorities, particularly given the gravel surfaces found on most all-season roads in ABRs. For example, drivers may find the darker color of wet roads more challenging to navigate compared to white snow- and ice-covered roads, especially in low light conditions, and may be surprised by occasional wet conditions occurring during previously dependably frozen months like December or February.

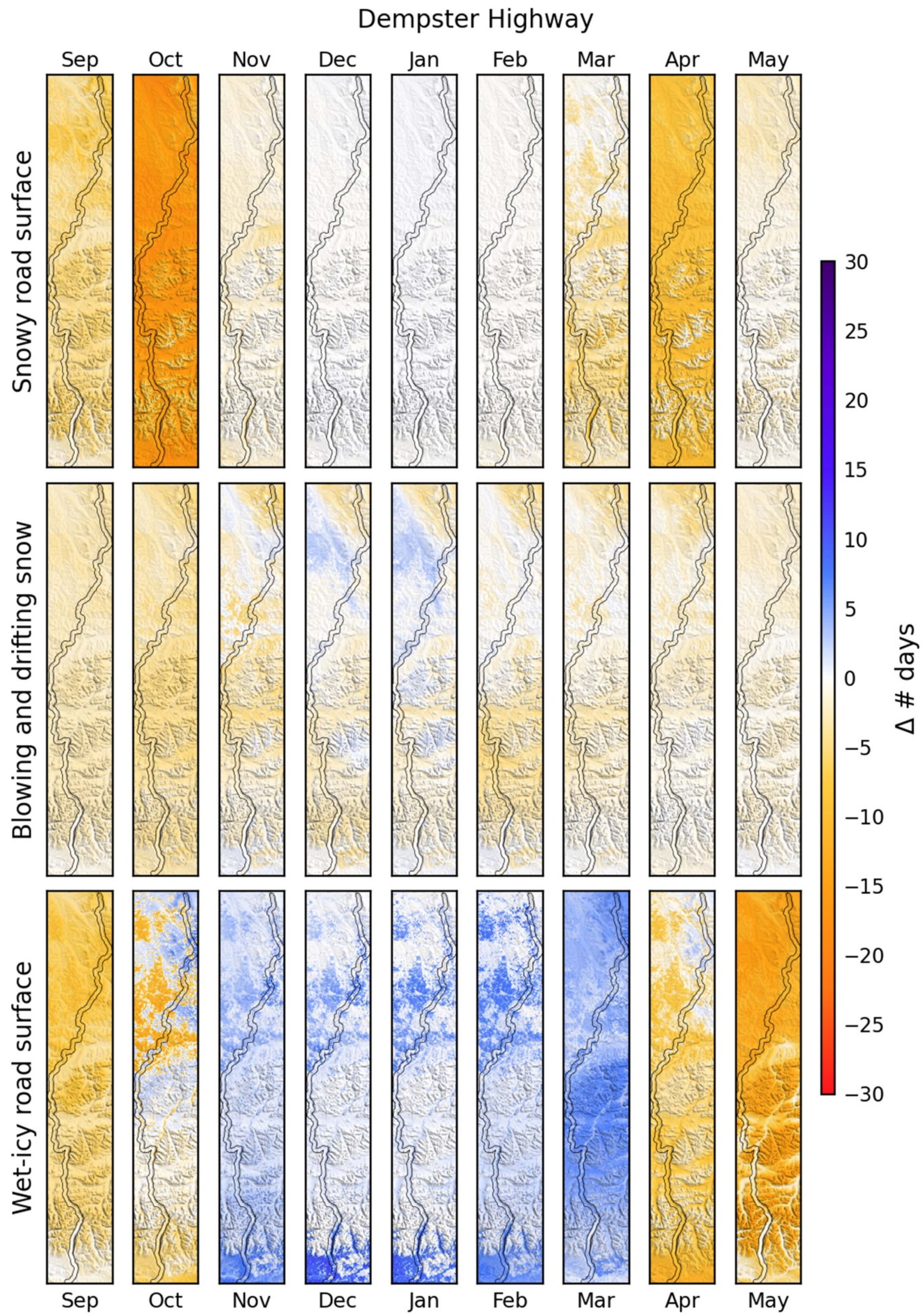

Figure 5. Monthly difference (2081–2100 monthly means minus 2006–2021 monthly means) in the number of days selected hazardous driving conditions are predicted to occur for the complete Dempster Highway study area. The Dempster Highway is shown with a 2 km buffer for reference.

4.2. Wet-icy conditions may occur more often in darkness

Previous work has found that freezing rain and similar events that cause wet-icy conditions create the most dangerous driving conditions (Norrman *et al* 2000, Andrey *et al* 2003, Malin *et al* 2019), and we showed that the annual frequency of these hazardous conditions may decrease in the future. However, we also found that the seasonality of frequent wet-icy road surfaces will shift to later in the fall season

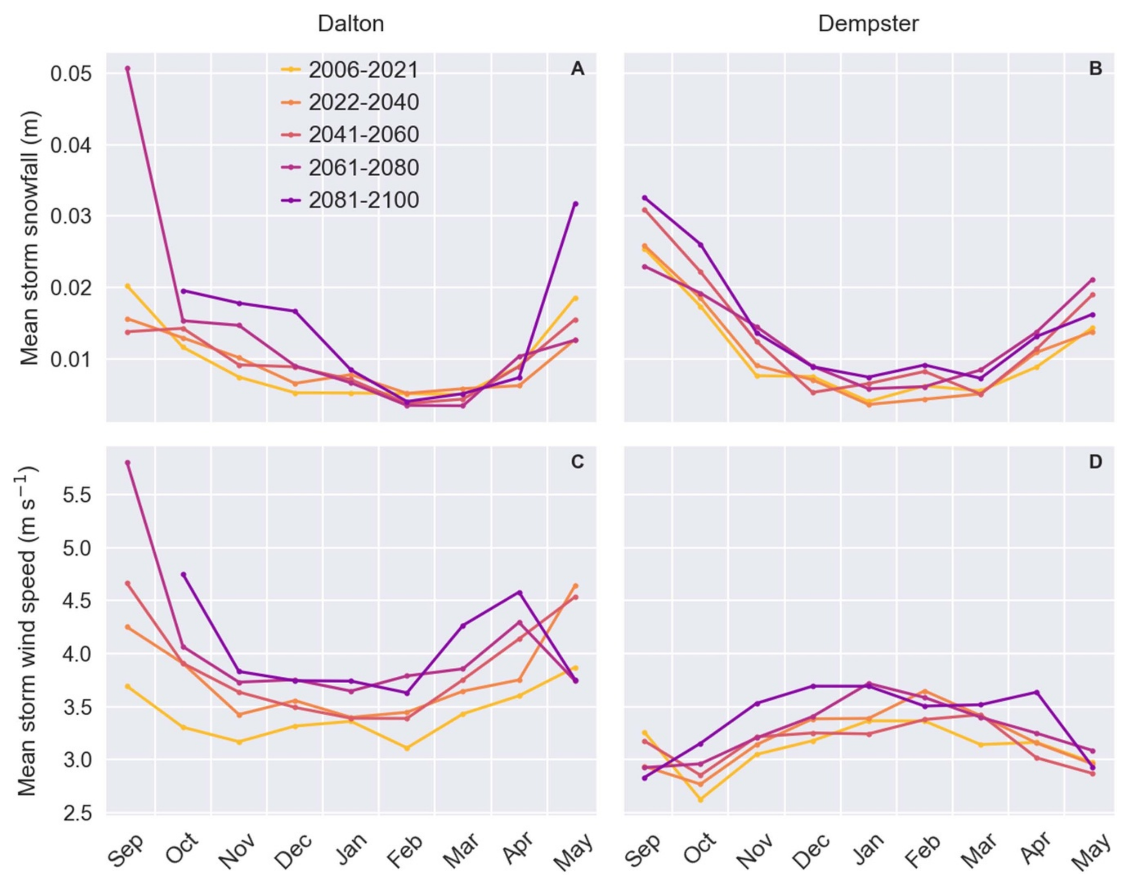

Figure 6. Predicted mean total snowfall (top row) and mean wind speed (bottom row) during September–May blowing snow events along the Dalton and Dempster highway corridors, 2006–2100. There are no datapoints for September 2081–2100 on the Dalton because no days with blowing and drifting snow were predicted in September during that time period.

and earlier in the spring, with some wet-icy events arising even in the core winter months of December, January, and February. This change in seasonality also pushes the most frequent wet-icy conditions toward the darkest period of the year, potentially compounding the safety hazard they represent. On the Dalton highway, for example, the days predicted to have wet-icy conditions had almost 2.5 fewer hours of daylight in the 2081–2100 time period compared to wet-icy days in the 2006–2021 time period, on average. Naturally, this effect will be most pronounced in the northernmost road sections, where seasonal changes in daylight hours are greatest; for example, the mean daylength of days with wet-icy conditions decreased by four hours on the northernmost section of the Dalton (milepost 365–414). This suggests that increases in safety conferred by an overall reduction in the frequency of wet-icy conditions may be offset by their increased occurrence on darker days when drivers may not be able to identify and account for the hazard.

Unfortunately, wet-icy driving conditions are particularly difficult to detect and foresee (Norrman *et al* 2000, Hanesiak and Wang 2005, Malin *et al* 2019) largely because they occur in a narrow temperature range around the freeze-thaw threshold, which can be a brief transient state and may arise in response to temperature inversions, local topographic effects like shading, and transitory cold-air drainage events that are beyond the spatial and temporal precision of climate datasets like those used to drive SnowModel. Our results predict that the frequency of wet-icy conditions will decline overall, but previous research indicates that frequency of freezing precipitation events has increased recently, and may continue to increase in the future (Hanesiak and Wang 2005, Bieniek *et al* 2018). Given this context, it is possible our models underestimate the future frequency of wet-icy driving conditions.

4.3. Effects of changing driving conditions on accident risk are uncertain

A shorter cold season on high-latitude all-season roads is expected to reduce the frequency of hazardous driving conditions created by snow, ice, and weather, but translating the predicted occurrence of hazardous conditions into accident risk is not straightforward. A Swedish study found that weather-related traffic accidents are not expected to decrease in the future, despite warmer and less icy conditions (Andersson and Chapman 2011)—potentially because drivers adjust their behavior in complex, unpredictable ways, or because the warming climate produces novel or unusually intense conditions. In our results, for example, fewer days are predicted to be disrupted by winter storms, an outcome that could be expected to decrease storm-related accidents and road-closure delays overall. However, it is possible that despite an overall reduction in the number of winter storms, increased intensity of individual storm events may instead increase the risk of accidents when storms do occur, or may actually increase the number or length of road-closure delays as maintenance crews contend with more challenging storm conditions. Additionally, the frequency of intense convective summer and fall storms (Poujol *et al* 2020) and of extreme fall, winter, and spring rain events (Bieniek *et al* 2018) is expected to increase in Alaska in the future, meaning that a reduced number of cold-season storms each year may be offset by an increase in extreme rain events that also create hazardous driving conditions.

4.4. Expanding monitoring networks could improve hazard predictions and driving safety

To improve prediction of dangerous driving conditions, and especially to identify the narrow window of conditions that produce wet-icy road surfaces, installation of more road surface temperature sensors and other more advanced road weather information systems (RWIS) may be useful. Currently, the Dalton and Dempster highways each have only one or two road surface temperature sensors installed. Additional sensors, potentially including mini-RWIS such as those currently being tested in Alaska (Karandreas and Burton 2022), would provide data enabling improved modeling of current and future hazardous driving conditions along these remote but socially and economically important high-latitude roads. Alternatively, it is possible that instantaneous computer vision analysis of imagery from additional traffic cameras could provide real-time road condition updates when there is sufficient daylight (Ramanna *et al* 2021). Sensors like these are difficult and expensive to install, power, and maintain in remote ABRs, but information derived from them could enable the installation of dynamic real-time traffic warning signs that have been shown to reduce accident risk (Malin *et al* 2019). The need for such mitigation measures may become especially urgent as increasing temperatures produce shorter but more intense and unpredictable winter driving seasons.

5. Conclusions

As a warming climate reduces the annual duration of freezing temperatures, the overall frequency of ice- and snow-related driving hazards on all-season roads in ABRs will decrease, but this may not always translate to less hazardous conditions. In particular, we found that although winter storm events that cause blowing and drifting snow may become less frequent, they could also become more severe, with higher storm snowfall totals and higher average wind speeds that may make road driving more hazardous. Additionally, although the frequency of days with slippery wet-icy road surfaces may decrease, the shortening of the cold winter period will lead to these slippery conditions occurring more frequently on days with limited daylight hours, when drivers may be less able to identify the hazard.

Changing seasonality and the encroachment of fall- and spring-like conditions into core winter months are likely to produce substantial changes in the experience of travelers and maintenance needs on all-season roads in ABRs. Drivers accustomed to hard-frozen winter roads with white snow-packed surfaces that are visible even in the twilight of Arctic-boreal winter may instead find slick wet-icy roads—or soft, muddy roads with darker surfaces that are more difficult to see, as the annual period with reliably firm winter road surfaces contracts over time. Meanwhile, the period of the year when snow plowing and ice maintenance are needed may shrink, although that period will likely be punctuated by more severe winter storms that individually require more plowing and maintenance. Additionally, roads that remain unfrozen for a longer period each year may be prone to more frequent washouts and slumping, while gravel surfaces may require additional grading—or paving—to manage potholes and maintain a trafficable surface to reduce delays. Adjustments in both maintenance patterns and driver expectations and behavior will be needed to minimize accident risk on all-season Arctic-boreal roads in the future.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Acknowledgments

This work was funded under NASA ABoVE grant 80NSSC19M0109 and NASA EPSCoR grant 80NSSC21M0321. Archived 511 road condition reports for the Dalton Highway were kindly provided by Caitlyn Frye and Alicia Stevens at the Alaska Department of Transportation and Public Facilities. Archived 511 road condition reports for the Dempster Highway within the Yukon were provided by Amanda Price at the Yukon Department of Highways and Public Works. Assistance and advice from Peter Bieniek at the University of Alaska Fairbanks regarding the downscaled GCM data were greatly appreciated.

ORCID iDs

Heather E Greaves https://orcid.org/0000-0002-8800-019X
Natalie T Boelman https://orcid.org/0000-0003-3716-2372

Todd J Brinkman https://orcid.org/0000-0001-5375-4840
Glen E Liston https://orcid.org/0000-0001-5743-035X
Laura R Prugh https://orcid.org/0000-0001-9045-3107
Adele K Reinking https://orcid.org/0000-0002-9082-4315

References

Andersson A and Chapman L 2011 The use of a temporal analogue to predict future traffic accidents and winter road conditions in Sweden *Meteorol. Appl.* **18** 125–36

Andrey J, Mills B, Leahy M and Suggett J 2003 Weather as a chronic hazard for road transportation in Canadian cities *Nat. Hazards* **28** 319–43

Bieniek P A, Bhatt U S, Walsh J E, Lader R, Griffith B, Roach J K and Thoman R L 2018 Assessment of Alaska rain-on-snow events using dynamical downscaling *J. Appl. Meteorol. Climatol.* **57** 1847–63

Bird H 2017 As Inuvik-Tuktoyaktuk Highway opens, will the $300M price tag be worth it? *CBC News* (available at: www.cbc.ca/news/canada/north/inuvik-tuktoyaktuk-nwt-road-worth-it-1.4395052)

Bokhorst S *et al* 2016 Changing Arctic snow cover: a review of recent developments and assessment of future needs for observations, modelling, and impacts *Ambio* **45** 516–37

Breiman L 2001 Random forests *Mach. Learn.* **45** 5–32

Brown D R N, Brinkman T J, Verbyla D L, Brown C L, Cold H S and Hollingsworth T N 2018 Changing river ice seasonality and impacts on interior Alaskan communities *Weather Clim. Soc.* **10** 625–40

Chicco D and Jurman G 2020 The advantages of the Matthews correlation coefficient (MCC) over F1 score and accuracy in binary classification evaluation *BMC Genom.* **21** 1–13

Cold H S, Brinkman T J, Brown C L, Hollingsworth T N, Brown D R N and Heeringa K M 2020 Assessing vulnerability of subsistence travel to effects of environmental change in interior Alaska *Ecol. Soc.* **25** 20

Commission for Environmental Cooperation Observation C C for R S C for M and E, Comisión Nacional para el Conocimiento y Uso de la Biodiversidad, Comisión Nacional Forestal, Instituto Nacional de Estadística y Geografía and Survey U S G 2020 2015 Land Cover of North America at 30 meters, edition 2.0 (available at: www.cec.org/nalcms)

Datla S, Sahu P, Roh H-J and Sharma S 2013 A comprehensive analysis of the association of highway traffic with winter weather conditions *Proc. Soc. Behav. Sci.* **104** 497–506

Fox S, Qillaq E, Angutikjuak I, Tigullaraq D J, Kautuk R, Huntington H, Liston G E and Elder K 2020 Connecting understandings of weather and climate: steps towards co-production of knowledge and collaborative environmental management in Inuit Nunangat *Arct. Sci.* **6** 267–78

Gelaro R, McCarty W, Suárez M J, Todling R, Molod A, Takacs L and Al E 2017 The modern-era retrospective analysis for research and applications, version 2 (MERRA-2) *J. Clim.* **30** 5419–54

Hanesiak J M and Wang X L 2005 Adverse-weather trends in the Canadian Arctic *J. Clim.* **18** 3140–56

Herman-Mercer N, Schuster P and Maracle K 2011 Indigenous observations of climate change in the lower Yukon River Basin, Alaska *Hum. Organ.* **70** 244–52

Hinzman L D *et al* 2005 Evidence and implications of recent climate change in northern Alaska and other Arctic regions *Clim. Change* **72** 251–98

Karandreas A and Burton M 2022 Filling gaps in remote locations with low power RWIS *Proc. 20 SIRWEC Conf.* vol 20 (*Druskininkai, Lithuania, 14–16 June 2022*) pp 113–9

Lader R, Walsh J E, Bhatt U S and Bieniek P A 2017 Projections of twenty-first-century climate extremes for Alaska via dynamical downscaling and quantile mapping *J. Appl. Meteorol. Climatol.* **56** 2393–409

Lader R, Walsh J E, Bhatt U S and Bieniek P A 2020 Anticipated changes to the snow season in Alaska: elevation dependency, timing and extremes *Int. J. Climatol.* **40** 169–87

Liston G E and Elder K 2006a A distributed snow-evolution modeling system (snowmodel) *J. Hydrometeorol.* **7** 1259–76

Liston G E and Elder K 2006b A meteorological distribution system for high-resolution terrestrial modeling (micromet) *J. Hydrometeorol.* **7** 217–34

Liston G E, Haehnel R B, Sturm M, Hiemstra C A, Berezovskaya S and Tabler R D 2007 Simulating complex snow distributions in windy environments using SnowTran-3D *J. Glaciol.* **53** 241–56

Liston G E and Hiemstra C A 2011 The changing cryosphere: pan-Arctic snow trends (1979–2009) *J. Clim.* **24** 5691–712

Liston G E, Itkin P, Stroeve J, Tschudi M, Stewart J S, Pedersen S H, Reinking A K and Elder K 2020 A lagrangian snow-evolution system for sea-ice applications (SnowModel-LG): part I—model description *J. Geophys. Res. Ocean* **125** e2019JC015913

Liston G E and Mernild S H 2012 Greenland freshwater runoff. Part I: a runoff routing model for glaciated and nonglaciated landscapes (hydroflow) *J. Clim.* **25** 5997–6014

Liston G E, Winther J-G, Bruland O, Elvehøy H and Sand K 1999 Below-surface ice melt on the coastal Antarctic ice sheet *J. Glaciol.* **45** 273–85

Malin F, Norros I and Innamaa S 2019 Accident risk of road and weather conditions on different road types *Accid. Anal. Prev.* **122** 181–8

Norrman J, Eriksson M and Lindqvist S 2000 Relationships between road slipperiness, traffic accident risk and winter road maintenance activity *Clim. Res.* **15** 185–93

Partlow J 2022 Biden administration suspends right of way for Alaska mining road advanced by Trump officials *Washington Post* (available at: www.washingtonpost.com/climate-environment/2022/02/22/ambler-road-alaska/)

Poujol B, Prein A F and Newman A J 2020 Kilometer-scale modeling projects a tripling of Alaskan convective storms in future climate *Clim. Dyn.* **55** 3543–64

Prowse T *et al* 2011 Effects of changes in arctic lake and river ice *Ambio* **40** 63–74

Ramanna S, Sengoz C, Kehler S and Pham D 2021 Near real-time map building with multi-class image set labeling and classification of road conditions using convolutional neural networks *Appl. Artif. Intell.* **35** 803–33

U.S. Geological Survey 2017 *1 Arc-second Digital Elevation Models (DEMs)—USGS National Map 3DEP Downloadable Data Collection* (U.S. Geological Survey)

Walsh J E, Bhatt U S, Littell J S, Leonawicz M, Lindgren M, Kurkowski T A, Bieniek P A, Thoman R, Gray S and Rupp T S 2018 Downscaling of climate model output for Alaskan stakeholders *Environ. Model. Softw.* **110** 38–51

Wilson N J, Todd Walter M and Waterhouse J 2015 Indigenous knowledge of hydrologic change in the Yukon river basin: a case study of Ruby, Alaska *Arctic* **68** 93–106