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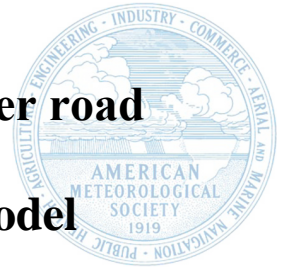
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Examining the viability of the world's busiest winter road to climate change using a process-based lake model

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Abstract

Winter roads play a vital role in linking communities and building economies in the northern high latitudes. With these regions warming two to three times faster than the global average, climate change threatens the long-term viability of these important seasonal transport routes. We examine how climate change will impact the world's busiest heavy-haul winter road – the Tibbitt to Contwoyto Winter Road (TCWR) in northern Canada. The FLake freshwater lake model is used to project ice thickness for a lake at the start of the TCWR – first using observational climate data, and second using modelled future climate scenarios corresponding to varying rates of warming ranging from 1.5°C to 4°C above preindustrial temperatures. Our results suggest that 2°C warming could be a tipping point for the viability of the TCWR, requiring at best costly adaptation and at worst alternative forms of transportation. Containing

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25 warming to the more ambitious temperature target of 1.5°C pledged at the 2016 Paris
26 Agreement may be the only way to keep the TCWR viable – albeit with a shortened annual
27 operational season relative to present. More widely, we show that higher regional winter
28 warming across much of the rest of Arctic North America threatens the long-term viability of
29 winter roads at a continental scale. This underlines the importance of continued global efforts
30 to curb greenhouse gas emissions to avoid many long-term and irreversible impacts of climate
31 change.

32

33 **Capsule**

34 Warming of 2°C may be a tipping point for the world’s busiest winter road, while enhanced
35 winter warming threatens the viability of winter roads across Arctic North America.

36

37 **Introduction**

38 The Arctic has experienced warming two to three times greater than the long-term global mean
39 trend of 0.87°C since preindustrial times (IPCC 2018), resulting in widespread shrinking of the
40 cryosphere (IPCC 2019). This arctic amplification is projected to continue throughout the 21st
41 century, with a 2°C global mean temperature increase (GMTI) projected to result in up to a
42 6°C warming in the Arctic (IPCC 2018). While impacts on ice sheets and glaciers tend to
43 capture the headlines, there are also important consequences for infrastructure in Arctic and
44 sub-Arctic communities, where warming temperatures threaten the physical integrity of
45 overland transport routes and the economies they sustain (Meredith et al. 2019). Infrastructure
46 built over permafrost is particularly vulnerable. Cumulative expenses of USD 5.5 billion are
47 projected for climate-driven damage to public infrastructure in Alaska between 2015 and 2099
48 under high emissions scenarios, with one of the top two costs associated with building damage
49 from near-surface permafrost thaw (Melvin et al. 2017). In a circumpolar study, Hjort et al.

50 (2018) revealed that nearly four million people and 70% of existing infrastructure in the
51 permafrost domain lie in areas with high potential for near-surface permafrost thaw. Winter
52 roads, comprising seasonally frozen sea, land, lakes, rivers, and creeks, are also under
53 considerable threat from a warming climate. These seasonal roads are vital for the affordable
54 transport of heavy equipment, cargo and fuel, but also provide physical connections that foster
55 social and cultural interactions among remote communities (Chiotti and Lavender 2008; Furgal
56 and Prowse 2008). In recent decades, climate change has shortened the operational season of
57 winter roads across the Canadian Arctic, and published studies project future shortening in the
58 James Bay region of Ontario (Hori et al. 2016; 2018); northern Manitoba and Saskatchewan
59 (CIER 2006; Blair and Sauchyn 2010); the Mackenzie River, Northwest Territories (ACIA
60 2005); and the Tibbitt to Contwoyto Winter Road, Northwest Territories (Perrin et al. 2015;
61 Mullan et al. 2017). One commonality in the methods used in these previous studies is that
62 future projections are based on regression models developed between historic climate trends
63 and ice thickness records. While there is merit in this statistical approach, it lacks a process-
64 based incorporation of the multitude of meteorological and lake-specific parameters that
65 influence the development of lake ice (Dibike et al. 2012). Given this limitation, the present
66 study applies – for the first time – a process-based freshwater lake model to simulate the
67 impacts of climate change on winter roads. We do this by examining the future viability of the
68 world’s busiest heavy-haul winter road to GMTIs of 1.5°C, 2°C and 4°C above preindustrial
69 temperatures. We also make inferences for the future viability of other winter roads across
70 Arctic North America based on projected winter warming in the region.

71

72 **Study Region, Materials and Methods**

73 The study region is the Tibbitt to Contwoyto Winter Road (TCWR), Canada – a seasonally
74 operational winter road extending from Tibbitt Lake, Northwest Territories ~ 70 km east of

75 Yellowknife and spanning around 400 km northwards across frozen lakes (85%) and overland
76 portages (15%) to Ekati diamond mine, north of Lac de Gras (JVTC 2020) (Figure 1). The
77 TCWR is of considerable economic importance as the only overland transport route supplying
78 four mines with fuel, cement, tyres, explosives, and other construction and maintenance
79 materials to a value of CAD 500 million yr⁻¹ (JVMC 2015). It is the busiest heavy-haul winter
80 road in the world, with more than 300,000 tonnes transported in over 10,000 loads yr⁻¹ (Perrin
81 et al. 2015). This annual haulage has, on average, been squeezed into a shorter transport season
82 (herein referred to as the operational season) over the past twenty years, at least in part driven
83 by rising air temperatures in the region (Appendix Figure A1).

84

85 *A modelling approach*

86 We simulate ice thickness for Tibbitt Lake (62.56°N, 113.36°W) at the southern limit of the
87 TCWR using the FLake freshwater lake model (<http://www.flake.igb-berlin.de/site/download>)
88 (Kirillin et al. 2011). FLake simulates the vertical temperature structure and mixing conditions
89 of shallow lakes (≤ 50 m) (Huang et al, 2019). It is used as a lake parameterisation module in
90 three-dimensional numerical weather prediction and climate models, but can also run in stand-
91 alone mode as a single-column lake model (Mironov 2008). We apply FLake in stand-alone
92 mode, simulating ice thickness for 20-year simulations at a daily time step representing (1)
93 observed climate, and (2) a set of 15 future climate scenarios. We applied the model on a
94 hydrological year basis – with each year beginning on 1 October and ending on 30 September.
95 This approach is employed to ensure model simulations begin prior to the annual onset of ice
96 freeze up.

97

98 *Simulations under observed climate*

99 FLake first requires a set of lake-specific parameters. Lake depth (6.7 m) was taken from Crann
100 et al. (2015) and fetch (2000 m) was approximated by maximum lake length, measured using
101 Google Earth™. The extinction coefficient (0.6 m^{-1}) for water transparency was estimated from
102 field notes associated with Galloway et al. (2010) – a number representing clear water. For a
103 $0.5^\circ \times 0.5^\circ$ grid square containing Tibbitt Lake, daily mean temperatures, relative humidity,
104 solar radiation, and wind speed data from 1 October 1985 – 30 September 2005 were taken
105 from the Watch Forcing Dataset Era Interim (WFDEI) (Weedon et al. 2014), accessed through
106 the Earth System Grid Federation (ESGF) (<https://esgf-node.llnl.gov/>). Cloud cover data were
107 unavailable from WFDEI and instead taken from the European Centre for Medium-Range
108 Weather Forecasts (ECMWF) next-generation reanalysis (ERA5) (C3S 2017), accessed
109 through the Copernicus Climate Data Store (CDS) (<https://cds.climate.copernicus.eu/>) for a
110 $0.5^\circ \times 0.5^\circ$ grid square containing Tibbitt Lake. The October 1985 – September 2005 time
111 period was chosen for two reasons: (1) the observational data are required to bias correct future
112 climate scenarios in a later step based on its comparison to a model hindcast period, with most
113 model hindcast periods ending in 2005; and (2) 1986-2005 is the historical baseline period used
114 by the Intergovernmental Panel on Climate Change (IPCC) in their Fifth Assessment Report
115 (AR5) (IPCC 2013). FLake was run under the observed climate, with dates recorded when lake
116 ice thickness exceeded 107 cm (the safe minimum limit for heavy-haul vehicles) (Perrin et al.
117 2015). Since there are no measured ice thickness data for Tibbitt Lake, we compared measured
118 records for four analagous shallow sub-arctic Canadian lakes (locations shown in Figure 1)
119 with FLake simulations for the same lakes. The measured data were taken from Environment
120 and Climate Change Canada (Environment and Climate Change Canada, 2020) and were
121 available for a minimum of 10 years between 1981 and 2000, with FLake simulations run for
122 the same years following an identical approach to input data as described above for Tibbitt
123 Lake. Validation results indicate the model has a tendency to underestimate ice thickness early

124 and late in the lake ice season, while observed ice thickness in the heart of the lake ice season
125 is generally overestimated (Appendix Text A1, Figure A2).

126

127 *Simulations under future climate*

128 FLake was then run under a series of future climate scenarios corresponding to GMTIs of
129 1.5°C, 2°C and 4°C. The former two rates of warming reflect pledges made by 195 countries
130 under the 2016 Paris Agreement (UNFCCC 2015) and are therefore considered mitigation
131 scenarios, whereas the latter represents something approximating a no-mitigation scenario – a
132 rate of warming evaluated as being *as likely as not* to be exceeded by the end of the 21st century
133 under the highest representative concentration pathway (RCP) 8.5 (IPCC 2013). To account
134 for arctic amplification we examined how the selected GMTIs corresponded to warming in the
135 study region and found that 1.5°C, 2°C and 4°C equated to 2.9°C, 3.9°C and 7.8°C (Appendix
136 Text A2). These are herein referred to as regional mean temperature increases (RMTIs). For
137 each RMTI, we shortlisted five climate scenarios (n=15) from an initial pool of 82 available,
138 based on how closely they compared to observations at a monthly temporal resolution for a
139 hindcast period from 1986-2005 (Appendix Text A3, Table A1). Daily mean temperatures from
140 the 15 model scenarios were then downloaded from the ESGF and CDS for the grid square
141 containing Tibbitt Lake. All scenarios are part of the Coupled Model Intercomparison Project
142 (CMIP5) (Taylor et al. 2012), forced with RCP8.5 (van Vuuren et al. 2011) – a high radiative
143 forcing scenario necessary to capture RMTIs up to 7.8°C. For each scenario, we extracted the
144 20-year future time period when projected temperatures reached 2.9°C, 3.9°C and 7.8°C above
145 preindustrial temperatures. Projected temperatures were bias corrected using the change factor
146 methodology used in Ho et al. (2012) (Appendix Text A4). Only temperatures were modified
147 from the baseline FLake simulations, with the other meteorological parameters left constant.
148 This reflects the dominant role that air temperatures play in changing lake ice conditions

149 (Brown and Duguay 2010), but also the fact that some of the other meteorological parameters
150 are unavailable from many of the selected climate models. FLake was then run under each
151 projected climate scenario and the dates recorded when lake ice thickness exceeded the 107 cm
152 threshold. The projected operational season of the TCWR for each model was adjusted to
153 reflect the difference between the baseline simulations and the historical operational season of
154 the TCWR (JVTC 2020) (Appendix Text A5). We also downloaded temperatures for the period
155 1 October 2000 – 31 September 2020 from ERA5 (C3S 2017) to capture years post-2005 and
156 allow us to relate these to the TCWR operational season observations. Present and future
157 operational season length was then colour coded in a traffic light system based on an economic
158 analysis conducted by Perrin et al. (2015). Green indicates ≥ 50 days – a viable season; amber
159 indicates 45-49 days – an ‘adaptive scenario’ where flexible scheduling is required to meet
160 season demands at a high cost of around USD 1.57 million yr⁻¹; and red indicates < 45 days –
161 a ‘critical conditions scenario’ representative of an unviable season and the need for alternative
162 transportation at a cost of around USD 6.09 million yr⁻¹.

163

164 *Providing wider geographical context*

165 In order to set our results for the TCWR within a wider geographical context, we downloaded
166 monthly observed temperatures from ERA5 (C3S 2017) and monthly CMIP5 climate model
167 scenarios for each of the 15 future scenarios used in the FLake simulations for the northern half
168 of North America (40°N – 90°N, 55° – 180°W). Future scenarios were interpolated to the same
169 resolution as the observed data and then bias corrected using a change factor approach, by
170 subtracting the hindcast period of the model from the future period and adding the result to
171 observations (Hawkins et al. 2013).

172

173 **Results and Discussion**

174 Projected changes in the TCWR operational season relative to the present are shown in Figure
175 2. The mean length of the operational season is projected to decrease for all but one of the 15
176 future scenarios, from 61 days at present to 56-61 days under 1.5°C, 47-55 days under 2°C and
177 20-31 days under 4°C. The range reflects differences in climate model scenarios. Although not
178 directly comparable because we focus on rates of warming rather than set time periods, changes
179 are broadly in line with previous projections for the TCWR. Perrin et al. (2015) projected a
180 mean operational season of 58 days by the 2020s and 49 days by the 2050s, while a much
181 shorter operational season of 21, 5 and 2 days was projected by Mullan et al. (2017) for the
182 2020s, 2050s and 2080s respectively. The particularly extreme scenarios in the latter may
183 reflect limitations in the regression modelling methodology, lending support to the process-
184 based lake modelling conducted here. According to the Perrin et al. (2015) classification, our
185 results suggest that warming of 1.5°C permits a viable TCWR operational season, but an
186 increase to 2°C leads to costly adaptation under two scenarios. A warming of 4°C shows a
187 mean operational season well below the unviable threshold, indicating no future for the TCWR
188 before this level of warming is reached. These findings suggest that, for an average year, an
189 increase from 1.5°C to 2°C is the tipping point at which costly adaptation is required. An
190 increase from 1.5°C to 2°C GMTI was also found to impose higher risks for a number of other
191 natural and human systems, including in some cases long-lasting or irreversible impacts such
192 as the loss of some ecosystems (IPCC 2018).

193

194 ***Enhanced December warming and impacts on late opening***

195 From the present mean operational season of 31 January to 1 April, future changes in the mean
196 operational season length translates to 30 January-3 February to 29-31 March under 1.5°C, 4-
197 10 February to 26-30 March under 2°C and 18-27 February to 17-20 March under 4°C (Figure
198 2). These dates reveal there is a general trend towards a larger proportion of the change coming

199 from a delayed opening – particularly at 4°C – with a slower rate of change in an earlier closure.
200 Jensen et al. (2007) found a similar pattern across 65 water bodies in the Great Lakes region
201 between Minnesota and New York, USA – with lake freeze up occurring 3.3 days decade⁻¹
202 later and lake breakup occurring at a slower rate of 2.1 days decade⁻¹ earlier from 1975-2004.
203 Figure 3 explains the trend towards a greater proportion of change from a delayed opening in
204 this study, with November-January temperatures projected to warm at a rate far in excess of
205 February-April temperatures. For example, under a GMTI of 4°C, December temperatures in
206 the Tibbit Lake region are projected to warm by 11.5°C compared to a 6.1°C rise in March.
207 Temperatures in the autumn months generally act as the dominant control on lake and river ice
208 freeze up, with reduced autumn cooling known to prolong the period of above zero water
209 temperatures and delay the onset of freeze up (Prowse et al. 2007). Hori et al. (2018) refer to
210 these months, primarily October-December in the high latitudes, as the preconditioning period
211 of winter roads – essential for providing a more climatically favourable construction period
212 and contributing to earlier opening dates. When warming of the magnitude projected here
213 occurs during this preconditioning period, it is unsurprising that a considerable delay in the
214 opening of the TCWR follows. Figure 3 reveals this pattern could be expected to an even larger
215 degree across much of the rest of Arctic North America, with a GMTI of 1.5°C, 2°C and 4°C
216 resulting in regional December warming in excess of 5°C, 8°C and 15°C across parts of the
217 Prudhoe Bay coast of Alaska, the Northwest Territories, Nunavut, and the Hudson Bay coastal
218 regions of Manitoba, Ontario and Quebec. With a number of prominent winter roads in these
219 regions, a widespread shift towards costly adaptation or route closure seems likely.

220

221 The levels of winter warming projected here – in places over three times the global average –
222 are consistent with projections for the Arctic by the end of the 21st century (IPCC 2013; 2019).
223 These high rates of warming can be explained by a projected continuation of arctic

224 amplification, where observed records in recent decades show a warming signal that has been
225 strongest over the Arctic Ocean in autumn and winter (Cohen et al. 2014; Horton et al. 2015).
226 A number of mechanisms are thought to be responsible for enhanced sensitivity to warming in
227 the Arctic, but chief among them is the change in sea ice albedo owing to the stark difference
228 in reflective properties of an ice-free ocean and snow-covered sea ice surfaces (*ca.* 7% vs 80%
229 reflectance respectively) (Cohen et al. 2019). This likely explains the high degree of warming
230 particularly along the Arctic coastal regions in autumn and winter (Figure 3). Other more
231 localised arctic amplification mechanisms may contribute to enhanced autumn and winter
232 warming in the study region, located ~ 500 km south of the Arctic coast. Local forcings include
233 snow, cloud and ice insulation feedbacks (Kwok et al. 2009; Lee et al. 2011; Yang and
234 Magnusdottir 2018), while increased vegetation over Arctic land contributes to surface
235 darkening at high latitudes (Overland et al. 2015). It is thought that local and remote forcing
236 mechanisms may interact and amplify one another (Yang and Magnusdottir 2018), meaning
237 some combination of all the above factors is likely at play in amplifying warming in the wider
238 TCWR region. Attribution studies indicate that increasing anthropogenic greenhouse gases
239 play a vital role in driving Arctic surface temperature increases (Fyfe et al. 2013; Najafi et al.
240 2015), leading to a high confidence in projections of further Arctic warming (Overland et al.
241 2018).

242

243 *Interannual variability*

244 The interannual variability within the 20-year observations and simulation periods reveals that
245 mean patterns are subject to considerable divergence from year to year, as shown in Figure 4.
246 During the observed period, the TCWR opened as late as 9 February in 2016 (9 days later than
247 the mean), while it closed as early as 21 March in 2010 (11 days earlier than the mean). As
248 seen in Figure 4 and in Figure A1, shortened seasons are often associated with anomalously

249 warm years, partly due to large-scale teleconnections that correlate most strongly with
250 Canadian climate during winter (Bonsal and Shabbar 2011). Anomalous heating in the Eastern
251 tropical Pacific associated with El Niño results in a positive Pacific-North American (PNA)
252 pattern over North America (Wallace and Gutzler 1981) and consequently warmer than average
253 temperatures from late autumn to early spring (Shabbar and Khandekar 1996). The two shortest
254 operational seasons on record (2010: 46 days; and 2016: 44 days) follow two of the strongest
255 El Niño events in recent decades: 2009/10 and 2015/16 (Timmermann et al. 2018). Shorter
256 operational seasons in some cases may also be associated with increased winter storminess.
257 Major storms with high wind speeds and blowing snow can cause temporary closures on the
258 road, as occurred in March 2012 (Rodan 2012). Where anomalously warm or stormy winters
259 cause the ice to break open in a ‘blowout’ (Ashbury 2006), winter roads may shut for
260 maintenance or may even close for the season. The short 50-day season in 2006 occurred in
261 such a way, with a blowout on Waite Lake late in the season (14 March) before the season was
262 complete (Perrin et al. 2015). Consequently, approximately 1,200 loads were flown into mines
263 in the summer and autumn of 2006 at a cost of CAD 100-150 million (JVMC 2014; Perrin et
264 al. 2015). A poleward shift in extratropical cyclone activity is projected to result in increased
265 atmospheric moisture and greater winter precipitation over the northern half of North America
266 (Christensen et al. 2013). This indicates the clear future potential for an increase in blowing
267 snow and hazardous blizzards that further threaten the operational season of the TCWR.
268 Conversely, longer operational seasons are typically associated with colder than average years.
269 For example, the longest operational season on record (26 January – 16 April 2002: 81 days)
270 occurred when 2001/02 winter and early 2002 spring temperatures were considerably colder
271 than average. Cooler years are typically associated with modes of variability in opposite phases
272 to anomalously warm years. A switch towards La Niña events and a negative phase of the PNA
273 are associated with earlier freeze up and later breakup of lake and river ice across much of

274 Canada (Bonsal et al. 2006). Figure 4 shows that interannual variability in temperatures and
275 the winter road operational season are projected to continue in future, indicating that natural
276 variability will continue to result in considerable year to year divergence from the mean. Figure
277 2 shows that the year with the longest projected operational season under 1.5°C (69-79 days)
278 and 2°C (63-72 days) is always longer than the mean observed season (61 days) and reflective
279 of a viable season in the Perrin et al. (2015) classification. In addition, Figure 2 shows that the
280 mean projected operational season is always longer at 1.5°C (56-61 days) and 2°C (47-55 days)
281 than it is during the shortest year of the observed record (44 days). Figure 5 reveals the reason
282 for this, as temperature anomalies during the warmest observed year are higher than the mean
283 temperature anomalies for 1.5°C and 2°C for all months under most future scenarios (note this
284 refers to the warmest observed year out of 20 simulated years, where the actual year may differ
285 between months). Furthermore, the year with the longest projected operational season at 4°C
286 (37-50 days) is for two models greater than the shortest observed operational season (44 days).
287 Figure 5 again shows why, since the year with coldest projected temperatures under 4°C is
288 colder than the warmest observed year during January-April. In this sense, greater future
289 variability may offer hope that colder than average years could permit some fully operational
290 seasons, even when the mean suggests otherwise. For example, under the least extreme 2°C
291 model – where a mean operational season of 55 days is projected – there are 12 years out of 20
292 where a fully viable season up to the longest year of 72 days is projected.

293

294 However, greater future variability also means there are several years that fall below the mean.
295 The same 2°C scenario referred to above has a shortest season length of 36 days and eight out
296 of 20 years that fall below the 50-day threshold. Considering the shortened 50-day season and
297 associated high costs in 2006, it is clear that scenarios such as the one identified above do not
298 lend support to a viable TCWR without at least considerable adaptation. Even under 1.5°C

299 scenarios, where the mean operational seasons of all five models exceed the 50-day threshold,
300 shortest seasons lie below 40 days – with several years among the 20-year projections falling
301 below the viable threshold. For example, under the least extreme 1.5°C model – where the
302 mean season length is 61 days – there are still four years out of 20 where the operational season
303 is less than 50 days. Falling short of a viable season length at a frequency of once every five
304 years may raise important questions among planners about the long-term viability of the
305 TCWR. That outlook becomes even bleaker when we examine the most extreme 1.5°C and
306 2°C scenarios, with seven out of 20 years below the 50-day threshold for the former, and 11
307 years for the latter. At 4°C, the TCWR is unequivocally unviable. Three out of five models
308 under the 4°C scenarios project all 20 years to fall below the 50-day threshold, with the other
309 two models projecting only one or two years respectively above this threshold. As shown in
310 Figure 5, temperatures rising above freezing in November and April under these scenarios
311 indicates why such large reductions in the operational season are simulated.

312

313 *Adaptation*

314 Before considering costly large-scale adaptation options, there are first adaptations to present-
315 day practices that may help ensure the TCWR remains viable for longer. Sladen et al. (2020)
316 investigated threshold requirements for the initiation of winter road operations along the
317 TCWR and found that the current practice of planning construction by calendar dates rather
318 than by evaluation of air-freezing indices results in a conservative approach to the start of the
319 construction season. In the interests of ‘winning back’ some time as the climate reduces the
320 length of the operational season, it may be necessary to adapt a more methods-based approach
321 to the dates of winter road construction, by installing equipment to calculate freezing indices
322 or measure frozen ground depths and temperatures. It is also clear, however, that such an
323 approach incurs expense, logistical challenges and issues with mobilising equipment and

324 personnel at short notice (Sladen et al. 2020). Amending the nature of annual haulage on the
325 TCWR may also represent a low-cost adaptation measure in the face of shortening operational
326 seasons. For winter roads linking remote communities, the desire is to ensure as long a season
327 as possible. This is not the case for the TCWR, where the goal is to ensure specified tonnages
328 of materials to mines are provided during the operational season. Where the season length is
329 reduced, lost service may be recovered by increasing the number of daily loads (Perrin et al.
330 2015). We see evidence of this in the historical records (Appendix Table A2) – years with a
331 reduced operational season but higher freight statistics than years with a longer season. For
332 example, 2016 ranks third out of 20 years for highest number of loads (8,766) and tonnes
333 transported (262,261), despite being the shortest operational year (44 days) on record. This
334 clearly shows there is some scheduling flexibility that can help offset a shortened operational
335 season. The limiting factor in this scenario is the number of trucks and drivers available (Perrin
336 et al. 2015). Increasing their provision to facilitate maximising the daily use of the TCWR may
337 therefore avoid more costly adaptation. The above adaptations may help under the less extreme
338 scenarios highlighted in this study, but larger-scale higher-cost alternatives may be needed
339 under more extreme scenarios. Options already considered for the TCWR include construction
340 of an all-season gravel-surface overland route along the most vulnerable southern portion;
341 construction of a deep sea port at Bathurst Inlet, Nunavut, with a road to the mines across colder
342 Arctic tundra; and construction of 600 km of power lines to expand hydroelectric power and
343 reduce reliance of the mines on diesel – the most transported commodity in the TCWR (Perrin
344 et al. 2015). If pledges to reduce greenhouse gas emissions are not met, there may be little
345 alternative but to implement one or more of these measures to protect economic activity in the
346 region.

347

348 **Conclusions, Limitations and Future Work**

349 Unlike previous studies, use of a process-based freshwater lake model has allowed us to
350 incorporate more of the factors influencing the development and evolution of lake ice along
351 the TCWR. Despite this, there are a number of limitations that must be considered when
352 interpreting the results. FLake has been found to overestimate ice thickness (e.g. Kheyrollah
353 Pour et al., 2012) – a trend clearly evident in our validation (Figure A2) during the peak cold
354 season between January and March. We also identified an underestimation of ice thickness in
355 November/December and in April/May, corresponding with slightly later than observed
356 freezeup (by 3 days on average) and earlier breakup (by 9 days on average). These
357 freezeup/breakup trends are similar to some studies (e.g. Kheyrollah Pour et al., 2012; Rontu
358 et al., 2019) and opposite in sign to others (e.g. Yang et al., 2013; Kourzeneva, 2014;
359 Peitikäinen et al., 2018). Timing of overestimation and underestimation in our validation results
360 likely points to difficulties in simulating the accumulation of snow on lake ice (Rontu et al.,
361 2019). FLake does not account for the insulating effect of snow, meaning ice is able to thicken
362 more rapidly but also melt faster without snow buffering ice from the cold air above (Jeffries
363 and Morris, 2006). Although provision is made to model parametrically the evolution of snow
364 cover above lake ice in FLake, the model has not been sufficiently tested in this regard and is
365 highlighted as an area requiring development (FLake, 2020). It is not possible to quantify in
366 days the potential impact this limitation has on the operational season length of the TCWR, but
367 we highlight this as a particular point of caution when interpreting the projected dates shown
368 in Figure 2. The daily time step may be too temporally coarse to take account of important
369 processes relating to ice formation, including low wind speeds and calm events creating the
370 potential for complete lake freeze within hours (Bernhardt et al., 2011). This highlights another
371 important issue – only air temperatures were modified in the future simulations owing to data
372 availability. This limits the reliability of future projections since interactions with other
373 changing meteorological properties including wind speed are essential components in ensuring

374 vertical heat transfer is sufficient to cool surface water temperatures to 0°C (Leppäranta, 2010;
375 Nõges and Nõges, 2014). Perturbing other meteorological variables in the model in addition to
376 mean temperatures would build a fuller picture of the impacts of climate change on the TCWR.
377 No ice thickness measurements were available for Tibbitt Lake, so it is not possible to fully
378 evaluate model performance for the lake simulated in this study. Future studies could also build
379 on our progress by accounting for the ~ 15% of the TCWR route crossing overland portages,
380 which primarily comprise permafrost peatlands (Sladen et al. 2020). With rapid thawing of
381 permafrost peatlands in the Canadian Arctic (Swindles et al. 2015; Sim et al. 2019), it is
382 currently unclear if these sections of the TCWR are more or less vulnerable to warming than
383 lakes. Finally, a continental or hemispheric-scale study simulating the impacts of climate
384 change on other winter roads across the high latitudes, beyond the inferences we have made,
385 would be highly valuable. In the meantime, our work represents a considerable advance on
386 previous studies and highlights the escalating threat that climate change poses to the future
387 viability of the TCWR and most likely other North American winter roads. The identification
388 of a tipping point at 2°C GMTI illustrates that the actions of current and future generations in
389 cutting greenhouse gas emissions is critical to the future viability of winter roads and the vital
390 role they provide in building economies and linking communities in the northern high latitudes.

391

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394 Geological Survey of Canada.

395

396 **Data Availability Statement**

397 References to the datasets used in this study and the web addresses for the data repositories
398 they were downloaded from can be found in the Datasets, Materials and Methods sections (and
399 in Appendix Text A1 and A2). All data are freely and openly available.

400

401 **Appendix Text**

402

403 **Text A1. FLake Model Validation**

404 Ice thickness data for four lakes in Canada were downloaded from Environment and Climate
405 Change Canada. We selected the four lakes following a careful screening process that started
406 by examining all available lake ice records from Environment and Climate Change Canada and
407 including those lakes that fulfilled the following criteria: (1) latitude $> 52.5^\circ$ (to ensure lakes
408 are within 10° of the study lake); (2) > 10 years of data between 1981-2000 (to correspond with
409 the modelling time period for the study lake); and (3) lakes with a mean depth < 50 m (as
410 determined from the Global Lake Database) – note 50 m depth is considered the upper limit of
411 suitability for FLake modelling. This generated a validation database comprising four lakes –
412 the details of which are provided in Figure A2. Measurements for these four lakes exist at
413 approximately a weekly temporal resolution and were measured to the nearest centimetre using
414 a special auger kit or hot wire ice thickness gauge (Environment Canada, 2020). FLake
415 simulations were run from 1 October 1981 – 30 September 2000 and were then compared to
416 the observed ice thickness records by extracting modelled ice thickness only for the precise
417 dates where measured data existed during the 19-year comparison period. The two sets of data
418 were then compared for the (inclusive) months November-May, with the absolute error, mean
419 absolute error and percentage error calculated to determine the degree to which the model under
420 or overestimated ice thickness during these months (Figure A2). We also downloaded observed
421 freezeup and breakup dates for each validation lake from the Global Lake and River Ice

422 Phenology Database Version 1 (Benson et al., 2020) and compared these records with FLake
423 simulated freezeup and breakup dates for the same years as the data used to calculate absolute
424 error (Figure A2).

425

426 **Text A2. Calculating RMTIs**

427 To calculate RMTIs for the study area, monthly mean temperatures were downloaded from
428 KNMI Climate Explorer (<https://climexp.knmi.nl/>). Historical monthly mean temperatures for
429 the period 1986-2005 were subtracted from the 2006-2100 period forced with RCP8.5 for the
430 mean of all CMIP5 models and ensembles. This was done for the global average (resulting in
431 2.0°C) and subsequently for the grid square containing Tibbitt Lake (resulting in 3.9°C). This
432 global : regional ratio of 2.0 : 3.9 was subsequently used to correct GMTIs of 1.5°C, 2°C and
433 4°C by simply dividing 3.9 by 2.0 and multiplying by the relevant GMTI. This produced
434 RMTIs of 2.9°C 3.9°C and 7.8°C. We deducted 0.6 from each RMTI to reflect the fact that the
435 1986-2005 period was 0.6°C warmer than preindustrial temperatures, and then calculated the
436 mean 20-year period when temperatures were 2.3°C, 3.3°C and 7.2°C higher than the 1986-
437 2005 hindcast period for each model.

438

439 **Text A3. Shortlisting climate models**

440 We downloaded all available CMIP5 models and ensembles at a monthly temporal resolution
441 under RCP8.5 (n=82) for the grid square containing Tibbitt Lake. For all 82 scenarios, we
442 calculated the root mean squared error (RMSE) from the difference between the 1986-2005
443 historical temperatures for that scenario and the 1986-2005 observed temperatures for Tibbitt
444 Lake. The 82 scenarios were ranked by their RMSE and the top five for each GMTI shortlisted
445 for subsequent FLake modelling. In several cases, a different 20 year future time period from

446 the same scenario was used among the final 15 scenarios. The full list of selected scenarios and
447 extracted time periods is given in Table A1.

448

449 **Text A4. Bias Correction**

450 Daily temperature projections for each scenario were bias corrected using a change factor (CF)
451 methodology that uses observed daily variability and changes the mean and daily variance as
452 simulated by the model (e.g. Arnell et al. 2003, Gosling et al. 2009). Outlined in Ho et al (2012),
453 this method takes the form:

454

$$455 \quad T_{CF}(t) = \overline{T_{RAW}} + \frac{\sigma T_{RAW}}{\sigma T_{REF}} (O_{REF}(t) - \overline{T_{REF}})$$

456

457 Where T_{RAW} represents daily raw model output for the future period, T_{REF} represents daily raw
458 model output for the historical period, O_{REF} represents daily observed output, time (t) represents
459 a daily time step, the bar above a symbol denotes the mean, and σ represents standard deviation.

460

461 **Text A5. Operational Season Adjustment**

462 Projected operational season dates were adjusted using the following equation:

463

$$464 \quad D_{AdjOBS} = \left(\frac{D_{REF}}{D_{OBS}} \right) (D_{FUT} - D_{OBS})$$

465

466 Where D_{AdjOBS} represents adjusted projected operational season dates, D_{REF} represents
467 projected operational dates for the baseline simulations, D_{OBS} represents operational dates from
468 historical records (2001-2020), and D_{FUT} represents projected operational dates from future
469 simulations.

470

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679 **Appendix Tables**

680

Model Ensemble	RMSE	1.5°C	2°C	4°C
IPSL-CM5A-LR r1i1p1	1.16	2033-2053	2039-2059	2074-2094
ICHEC EC-Earth r2i1p1	1.42	2029-2049	2047-2067	
NOAA GFDL-ESM2G r1i1p1	1.52	2037-2057	2058-2078	
CSIRO-QCCCE CSIRO-Mk3-6-0 r9i1p1	1.54	2031-2051	2043-2063	
IPSL-CM5A-LR r4i1p1	1.37	2027-2047		
CSIRO-QCCCE CSIRO-Mk3-6-0 r8i1p1	1.46		2048-2068	
IPSL-CM5A-LR r3i1p1	1.78			2075-2095
MIROC5 r2i1p1	1.82			2066-2086
MIROC5 r3i1p1	1.90			2069-2089
CSIRO-QCCCE CSIRO-Mk-3-6-0 r1i1p1	1.92			2079-2099

681

682 **Table A1.** All 15 shortlisted scenarios as used for FLake modelling. Root Mean Square Error
 683 (RMSE) is provided, along with the extracted years for each scenario. Twenty-year time
 684 periods were taken from 1 October on the start year to 30 September on the end year to conform
 685 to the temporal basis of FLake modelling and represent the 20-year mean period when
 686 temperatures first exceed the RMTI associated with each of the three GMTIs.

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Year	Open Date	Close Date	Duration (Days)	No. Loads	Tonnes
2001	1 Feb	13 Apr	72	7,981	245,586
2002	26 Jan	16 Apr	81	7,735	256,915
2003	1 Feb	2 Apr	61	5,243	198,818
2004	28 Jan	31 Mar	63	5,091	179,144
2005	26 Jan	5 Apr	70	7,607	252,533
2006	4 Feb	26 Mar	50	6,841	177,674
2007	27 Jan	9 Apr	73	10,922	330,002
2008	29 Jan	7 Apr	62	7,484	245,585
2009	1 Feb	25 Mar	50	5,377	173,195
2010	4 Feb	24 Mar	46	3,508	120,020
2011	28 Jan	31 Mar	63	6,832	239,000
2012	1 Feb	28 Mar	59	6,551	210,188
2013	30 Jan	31 Mar	61	6,017	223,206
2014	30 Jan	1 Apr	62	7,069	243,928
2015	30 Jan	31 Mar	61	8,915	305,215
2016	9 Feb	24 Mar	44	8,766	262,261
2017	1 Feb	29 Mar	57	8,241	279,484
2018	1 Feb	31 Mar	61	8,209	303,725
2019	1 Feb	31 Mar	59	7,489	257,176
2020	31 Jan	8 Apr	68	7,072	230,497

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694 **Table A2.** Historical Operational Season Statistics for the TCWR (JVTC, 2020).

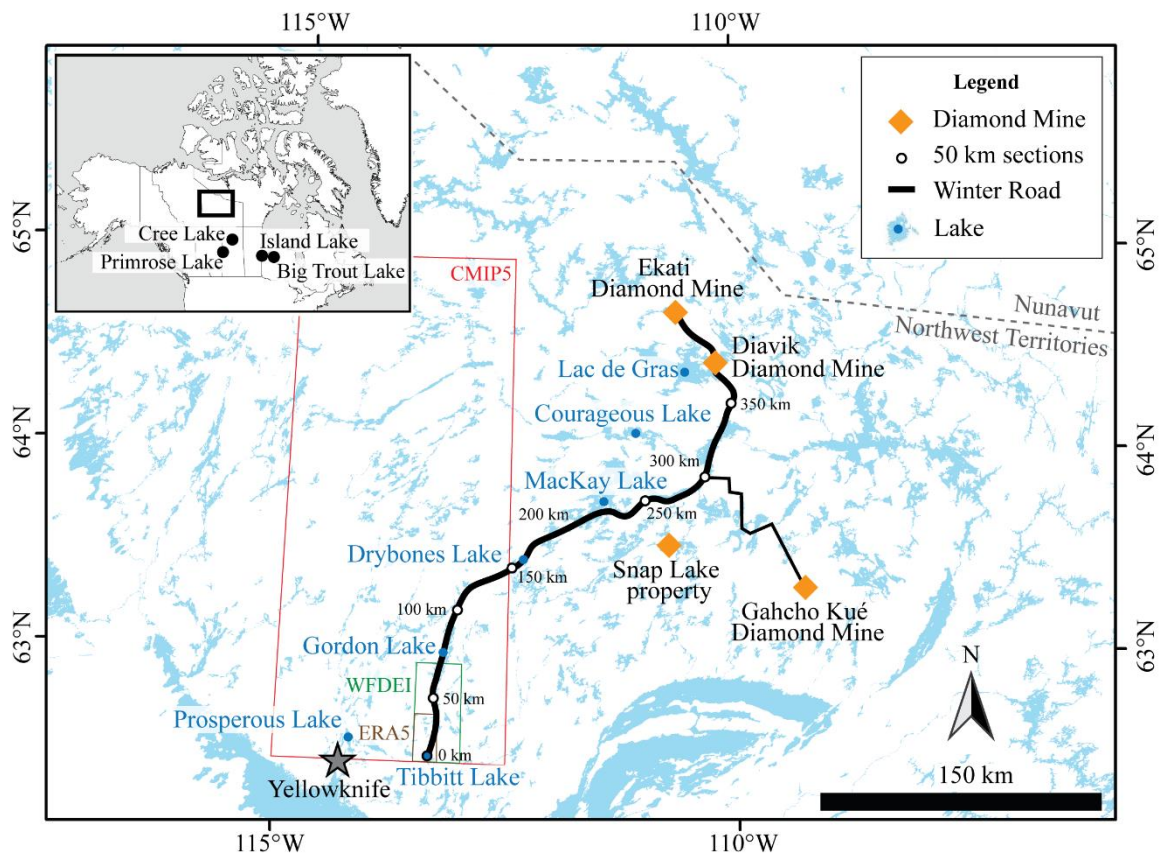
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697 **Figures**

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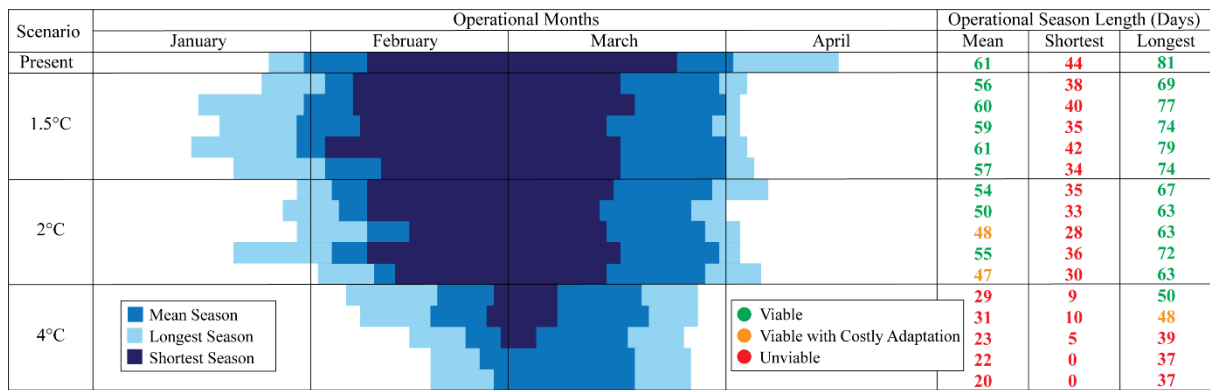


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701 **Figure 1.** The TCWR study region. The three transparent boxes show the spatial resolution of
702 the ERA5 ($0.25^\circ \times 0.25^\circ$) and WFDEI ($0.5^\circ \times 0.5^\circ$) climate observations, as well as the CMIP5
703 climate model scenarios (*ca.* $2.5^\circ \times 2.5^\circ$ but variable from model to model). The locations of
704 the four lakes used for model validation are also shown in the inset map.

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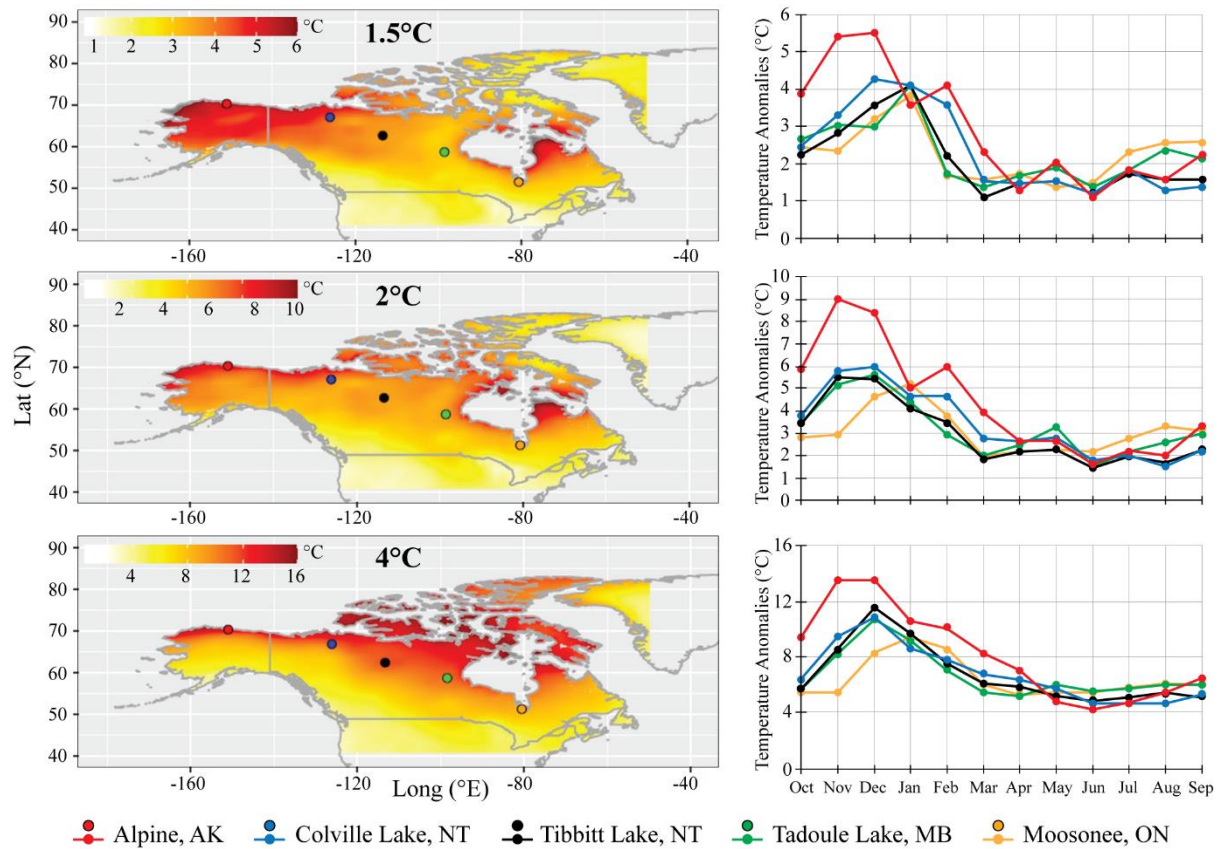
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708 **Figure 2.** TCWR operational season as observed for the present (mean of 2001-2020
709 observations taken from JVTC (2020)) (n=1) and simulated by FLake for the future under 15
710 climate scenarios corresponding to a GMTI of 1.5°C (n=5), 2°C (n=5) and 4°C (n=5). The
711 mean of the 20-year observations / simulations is shown in medium blue, while the year with
712 the shortest (longest) season is shown in dark (light) blue. Also shown is the operational season
713 length (days) for the mean, shortest and longest years in a traffic light colour system following
714 the scenarios outlined in Perrin et al. (2015): ≥ 50 days = green (viable); 45-49 days = amber
715 (viable with costly adaptation); < 45 days = red (unviable).

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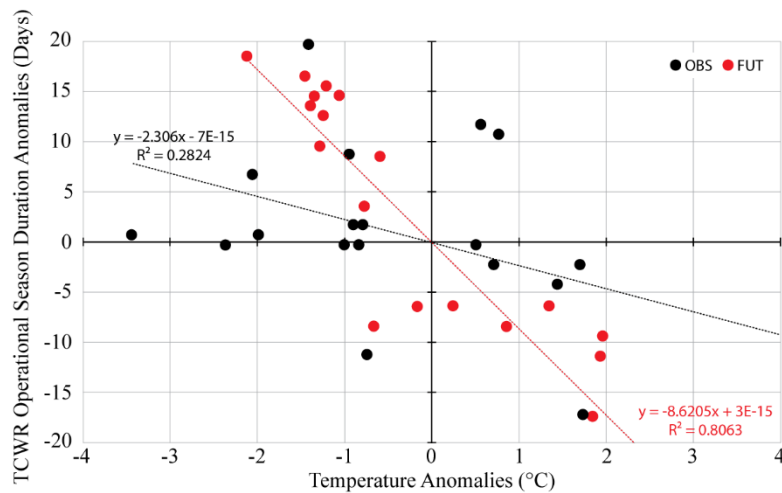
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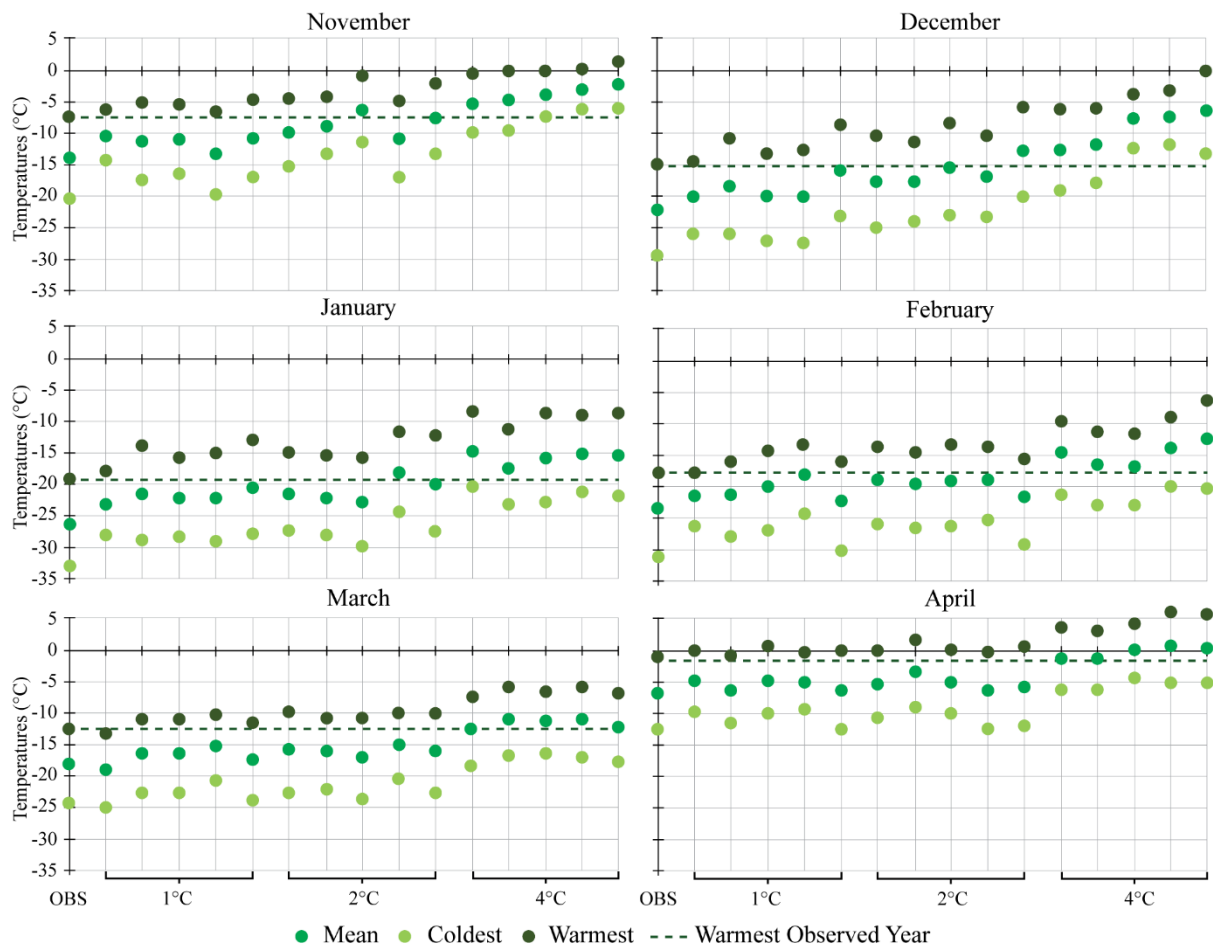
Figure 3. Map panels: mean projected December temperature anomalies for the northern half of North America. Temperature anomalies are expressed as the mean of the models analysed in this study at a GMTI of 1.5°C, 2°C and 4°C from the mean 1986-2005 observed period. Graph panels: Temperature anomalies (calculated in the same way as above) for each month of the year for five winter roads in North America (including the TCWR, as represented by Tibbitt Lake, NT). Two-letter state/province/territory codes are used for the five winter road locations – AK: Alaska; MB: Manitoba; NT: Northwest Territories; ON: Ontario.



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727 **Figure 4. November-April mean** temperature (°C) and TCWR seasonal duration (days)
 728 anomalies for the Tibbit Lake region of the TCWR. Anomalies for each year of the 20-year
 729 observed record / model simulations are expressed as changes relative to the mean of that same
 730 20-year period. Black points represent observations (OBS) for 2000-2020 and red points
 731 represent the most extreme model simulation (FUT) under a 4°C GMTI – in this case for 2079-
 732 2099 – the 20-year period when temperatures first rise the RMTI equivalent of 4°C GMTI
 733 above preindustrial temperatures.

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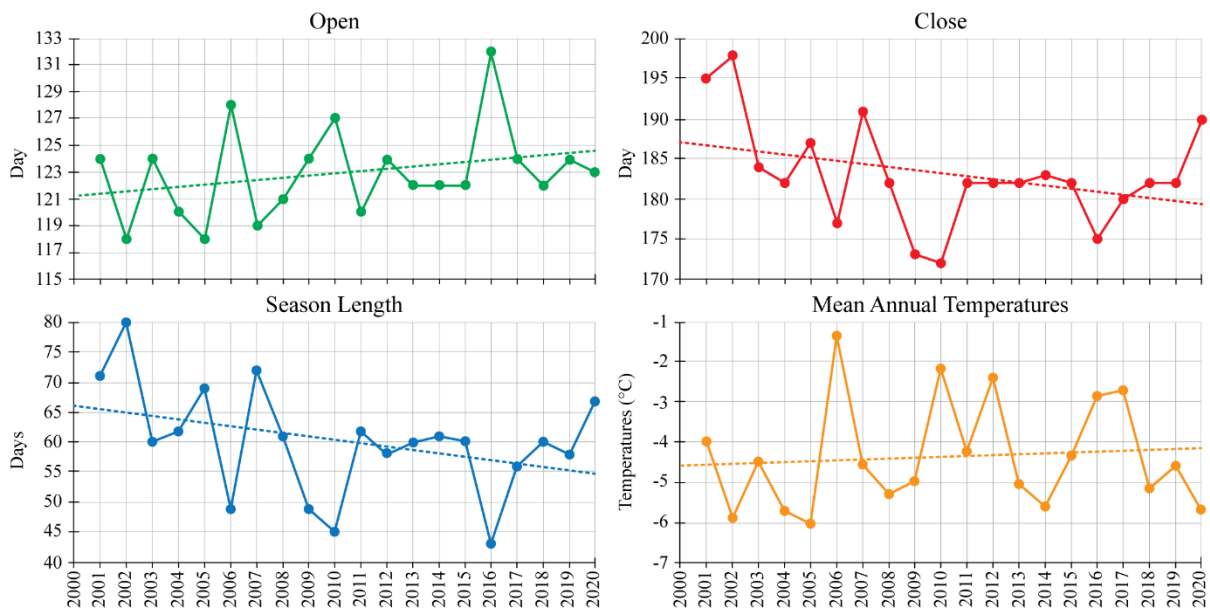
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Figure 5. November-April temperatures at Tibbitt Lake as observed (OBS) for the present (n=1) and simulated for the future under 15 climate scenarios corresponding to a GMTI of 1.5°C (n=5), 2°C (n=5) and 4°C (n=5). The mean of the 20-year observations / simulations is shown in medium green, while the year with the coldest (warmest) temperatures for each particular month is shown in light (dark) green. The dashed line represents observed temperatures during the warmest year (mean of November-April).

748 **Appendix Figures**

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752 **Figure A1.** Changes in the TCWR open date (top left) and close date (top right) from 2001-
753 2020 (JVTC, 2020) and mean annual air temperatures for Tibbitt Lake from 2001-2020. For
754 the top panels and the bottom left panel, dates are expressed as days since the start of the
755 hydrological year on 1 October. Mean annual air temperatures are calculated for hydrological
756 years, starting on 1 October and ending on 30 September the next year.

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