Projections of declining outdoor skating availability in Montreal due to global warming

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Abstract
Outdoor skating is a valued and culturally important winter activity in Canada that is vulnerable to warming winter temperatures resulting from anthropogenic climate change. Changes to the outdoor skating season (OSS) due to climate change have been estimated from historical weather records using the occurrence of daily temperatures below a particular temperature threshold as a proxy for rink availability. However, research on the actual weather conditions needed for outdoor rinks to be maintained in reasonable condition is limited. In this study, we used historical weather data and daily reports on outdoor rinks in Montréal to identify which daily or multi-day temperature variable can best act as an indicator of outdoor ice rink availability. We evaluated a series of temperature variables using a logistic regression to predict the likelihood of open rinks during each day of the season. Using AIC scores to select the best model, we found that the mean of the preceding six-day maximum temperature was the best predictor of skating availability. Using this temperature predictor, we then projected changes in the duration of the future OSS in Montréal based on global climate model data, downscaled to the island of Montréal using the MarkSim Weather Generator. Our results showed that the mean OSS duration in Montréal would range from a 15% to a >75% decline by 2090 depending on which future emissions scenario we follow. In a scenario that limits global temperature rise to below 2.0 °C (RCP 2.6), we projected a 41 day mean OSS duration at the end of this century. By contrast, under a business-as-usual emissions pathway (RCP 8.5), the average length of the OSS in Montréal could decline to only 11 days per year. Our results suggest that very ambitious climate change mitigation will be required to preserve outdoor skating in Montréal in the face of ongoing global climate change.

Introduction
As a high-latitude country, Canada has experienced a considerably faster rate of warming due to anthropogenic climate change as compared to the rest of the world. Average temperatures have increased by approximately 0.25 °C per decade from 1948–2016, while the average global temperature has only risen 0.12 °C per decade over a similar period from 1951–2012 (Serreze and Barry 2011, IPCC, Contribution of Working Groups I 2014, Environment and Climate Change Canada 2017). Winter temperatures specifically have risen by 3.3 degrees Celsius in the past 70 years (Environment and Climate Change Canada 2016). In addition to warming, Canada has experienced increased variability in weather in the form of more frequent and longer lasting warm spells during winter (Shabbar and Bonsal 2003). Climatic changes have also had an effect on river and lake ice cover. In an analysis of freeze and thaw dates of rivers and lakes in the Northern Hemisphere from 1846 to 1995, Magnuson et al (2000) found trends towards later freeze and earlier breakup dates, with freeze dates coming 5.8 days/100 years later and breakup dates coming 6.5 days/100 years earlier. There has also been increased interannual variability of freeze and thaw dates for lakes and rivers in the Northern Hemisphere (Magnuson et al 2000).
As a result of this high rate of warming and changes to winter climate conditions, the outdoor skating season (OSS hereinafter) has become shorter and increasingly variable across most of Canada (Damyanov et al 2012, Brammer et al 2015). Damyanov et al (2012) found that most climatic regions in Canada experienced trends towards later OSS start dates and earlier OSS end dates from 1951 to 2005—both trends were evident in eastern Canada where Montréal is located. A study focused on the Rideau Canal in Ottawa from 1972 to 2013 found the OSS length to be declining by \(-5.2 \pm 2.9\) days per decade (Brammer et al 2015). Decreased availability of outdoor skating has also been recorded in other northern regions, such as in the Netherlands and in China (Visser & Petersen 2009, Liu et al 2017).

Changes to the OSS could potentially have far reaching social implications in Canada given outdoor hockey and outdoor skating are strongly associated with national identity for many Canadians (Johnson and Ali 2017). If the OSS in Canada becomes shorter, outdoor rinks will have decreased capacity to act as an ecosystem service as they have historically. Communities of lower socio-economic status—the communities who benefit most from free recreational activities—would likely lose access to affordable hockey given the high costs of playing organized club hockey (Johnson and Ali 2017). Furthermore, outdoor hockey and outdoor skating, which have a capacity for community development through their free and inclusive nature, would become less effective tools for community development (Johnson and Ali 2017).

Research to date on the OSS in Canada has demonstrated spatial and temporal variability through the analysis of the OSS start and end dates, as well as through the analysis of days in which outdoor skating is possible by region using daily temperatures (Damyanov et al 2012, Brammer et al 2015). Additionally, projections of the OSS length based on daily temperatures have also been conducted (Brammer et al 2015, Robertson et al 2015). However, research focused on the availability of skating in relation to multi-day temperatures remains unexplored.

Here, we expand on these previous analyses with two primary objectives. First, we aim to identify the best predictor of daily outdoor skating availability in Montréal from a range of multi-day and single-day temperature variables. Second, we use this temperature predictor to project changes to the OSS under a range of future greenhouse gas emissions scenarios.

**Methods**

We retrieved rink data from four skating seasons between 2013 and 2017 from patinermontreal.ca—a website used by the city of Montréal to report on the condition of outdoor ice rinks. The data included daily open and closed reports from an average of 247 rinks each year across the island of Montreal, with each rink having an average of 45 reports per season, totalling 45,000 daily rink reports over the four seasons. Refrigerated rinks and rinks that were not reported as open at all during a particular season were removed from the dataset. On inspection of the data, it was clear that there were some inconsistencies in the reporting of rinks in some municipalities—for example some municipalities would have a small number of rinks listed as ‘open’ when weather conditions were clearly not favourable to outdoor skating and all other rinks were listed as ‘closed’. Therefore, to minimize the effect of poor reporting in certain municipalities, we followed the approach of Robertson et al (2015) by classifying each day as an ‘open’ skating day if the ratio of open rinks to total rinks reported was greater than or equal to 0.5 (i.e. at least 50% of reported rinks for that day were reported as open). We selected this 50% criteria for consistency with previous analyses, though found also that adopting a lower or higher threshold (i.e. a 40 to 60% ‘open’ reporting requirement), did not have a large effect on our analysis. All other days in the dataset were classified as ‘closed’ for skating (i.e. where fewer than 50% of reported rinks were listed as ‘open’).

We retrieved historical weather data for the island of Montréal from Environment Canada (Environment and Climate Change Canada 2018). For our analysis, we used historical daily minimum, maximum and mean temperatures for all days included in our rink dataset. In addition, we calculated multi-day mean temperatures using each of the three temperature variables, over periods ranging from two to seven days prior to (and including) a particular date. For example, the six-day maximum temperature variable was calculated as the average of the daily maximum temperatures from the current and five preceding days. We focused on daily temperature (and its variants; see full list in table 1) rather than other potential climate variables, given that previous studies have shown this variable to be the most important predictor of skating conditions (Damyanov et al 2012). We argue also that deriving a relationship with temperature only rather than other potential climate variables, given that precipitation, strengthens our future projection given that temperature is generally better simulated by global climate models as compared to other daily climate variables.

Using a logistic regression model, we tested the ability of each single and multi-day temperature variable to predict the likelihood of rinks being open on a given day. Here, the availability of skating (i.e. open/closed days) from our 4-season dataset was used as the dependant variable and each temperature variable was used...
sequentially as the independent variable in the model. By selecting the model with the smallest Akaike information criterion (AIC) value, we determined that the preceding six-day maximum temperature was the best predictor of skating availability on a particular day across the island of Montreal (table 1).

To project future changes in the OSS, we used the MarkSim Weather Generator to obtain future daily temperature data for the island of Montréal (Jones and Thornton 2013). The MarkSim Weather Generator includes data from 17 global climate models from the Coupled Model Intercomparison Project Phase 5 (CMIP5); here we used the ensemble average of all models to generate future projections of daily temperature data for Montréal. For each of the four Representative Concentration Pathways (RCPs) used in the IPCC in the Fifth Assessment Report (AR5) (IPCC 2014), we generated 99 replications of the full year at 2020, and then repeated this at 10-year intervals up to the year 2090; this is consistent with the approach taken by Robertson et al (2015) and Brammer et al (2015) in similar studies.

Using the daily maximum temperatures produced with the MarkSim Weather Generator, we calculated the six-day maximum temperature for each of the 99 replications of the 8 annual time slices from the 4 emission scenarios. The fitted regression model for six-day maximum temperature generated from the observed data was then used to predict the probability of skating availability for all projected weather data. We used a likelihood threshold of 0.43 to designate days as open or closed to best align the beginning of the model predictions with the mean of the observed four seasons. We then used the number of open days in each of the 99 replications for each year to calculate the minimum, maximum, mean and standard deviation of open days among all replications of a particular annual time slice and RCP scenario. Finally, we used these values to project changes in the OSS length in Montréal between 2020 and 2090 for each RCP scenario.

### Results and discussion

Daily temperature variables and the proportion of open rinks in Montreal varied considerably across the four seasons in our dataset (figure 1). In general, the OSS in Montreal extends from late December to early March, and the beginning of the season is typically marked by the first multi-day cold spell of the season, where daily temperatures remain well below zero for several consecutive days. Once established, rinks are usually able to tolerate periodic temperature swings, including days with maximum temperatures above zero. However, several consecutive days with maximum temperatures above 0 °C, or instances of mean temperatures above zero, typically lead to the closure of rinks until daily temperatures return below zero. Where this occurs late in the season, this typically marks the end of the skating season in Montreal. Of the four seasons in our dataset, the 2014–2015 skating season was the most consistent with respect to the availability of skating, with close to 55

| Temperature variable | AIC      | P        |
|----------------------|----------|----------|
| Mean of preceding six-day max | 410.797 404 | 5.71E-21 |
| Mean of preceding five-day max | 416.134 022 | 1.55E-20 |
| Mean of preceding four-day max | 418.221 941 | 2.26E-20 |
| Mean of preceding six-day mean | 421.696 343 | 1.53E-20 |
| Mean of preceding four-day mean | 422.888 831 | 1.95E-20 |
| Mean of preceding three-day max | 423.314 952 | 3.39E-20 |
| Mean of preceding three-day mean | 426.059 904 | 2.61E-20 |
| Mean of preceding six-day min | 433.333 189 | 1.18E-19 |
| Mean of preceding two-day mean | 434.630 045 | 9.63E-20 |
| Mean of preceding five-day min | 435.031 925 | 1.46E-19 |
| Mean of preceding four-day min | 436.240 484 | 1.73E-19 |
| Mean of preceding two-day max | 437.240 793 | 3.65E-19 |
| Mean of preceding three-day min | 439.101 488 | 2.60E-19 |
| Mean of preceding seven-day max | 442.522 955 | 2.74E-18 |
| Mean of preceding day min | 444.576 716 | 7.05E-19 |
| Mean of preceding seven-day mean | 449.507 184 | 5.55E-18 |
| Daily mean | 453.437 551 | 6.77E-18 |
| Daily min | 458.635 993 | 1.90E-17 |
| Mean of preceding seven-day min | 461.653 034 | 8.29E-17 |
| Daily max | 463.760 84 | 2.36E-16 |

Table 1. Results of the logistic regression model for each temperature variable. The availability of skating (i.e. open/closed days) from our 4-season dataset was used as the dependant variable and each temperature variable was used sequentially as the independent variable in the model.
uninterrupted skating days between mid-January and early-March. Skating days in the other three seasons ranged from 33 to 64, though were marked by considerably more interruptions as a result of daily temperature variability within the season (figure 1).

Across all of the temperature variables that we tested, we found that the 6-day maximum temperature was the best predictor of the availability of outdoor skating in our dataset (table 1). The results of this model are shown in figure 2, for all seasons combined (back line) and each season individually (dashed lines). Across all seasons, a six-day maximum temperature of 5 °C was associated with a 6% likelihood of rinks being open, increasing to 26% likelihood at 0 °C and 66% likelihood at −5 °C. For a 50% or higher chance of rinks being open, this required six-day maximum temperatures of less than −3 °C. This temperature threshold for 50% likelihood of open rinks varied somewhat across individual seasons, however, from −5 °C for the 2016–2017 season, to −2.5 °C for the 2015–2016 season.

Our analysis also revealed across all models with multi-day temperature variables from three days to seven days, the models with the maximum temperature variable as the independent variable were consistently better predictors of daily skating availability (table 1). For example, the models using the three-day mean and minimum temperature variables performed worse (resulting in a higher AIC score) than the model using the three-day maximum temperature variable. This finding suggests that daily maximum temperatures are in general a more important determinant of outdoor rink availability than daily minimum and mean temperature. This is consistent with the analysis of Damyanov et al (2012) who also used maximum daily temperatures to assess historical changes in the outdoor skating season across Canada.

We also found that the average six-day maximum temperature across each full OSS was negatively correlated with the number of open days within that OSS, again demonstrating a robust relationship between daily maximum temperatures and skating availability (figure 3(a)). There was also a particularly strong negative correlation between OSS skating days and the number of occurrences with each season of six-day maximum temperatures rising above five degrees Celsius (figure 3(b)). Although our analysis is only based on four OSSs, this finding would suggest that increased intra-season temperature variability, leading to more occurrences of six-day maximum temperatures >5 °C, would in general decreases the number of viable skating days within a particular OSS. If variability in temperature is to increase with climate change, a more thorough understanding of how outdoor rinks respond to variability in temperature would allow for more precise forecasts.

Using the results of our logistic regression model and projected future daily maximum temperatures for Montreal from the MarkSim weather generator, we found that the OSS in Montreal is expected to decrease between now and the end of this century as a result of continued climate warming (figure 4). Under the RCP 8.5 (business-as-usual)
emissions scenario, we project a rapid decrease in the length of the skating season, from 45 ± 12 days per year in 2020 to only 11 ± 7 days per year in 2090 (black line in figure 4(d)). This would result in a >40% loss of skating days in Montreal by 2060 and a >75% decline in the length of the skating season by the end of the century as a result of unmitigated global warming. Furthermore, in this scenario, there are also individual years among the replications of the model that we ran, with zero skating days in Montreal as early as 2070 (blue line in figure 4(d)).

By contrast, the ambitious mitigation scenario (RCP2.6)—in which anthropogenic greenhouse gas emissions are decreased rapidly to limit global temperature rise to below 2 degrees Celsius in accordance with the Paris Climate Agreement—maintained stable outdoor skating conditions during the second half of the century. In the scenario, the number of skating days at 2090 levelled out at 41 ± 12 days, which represents only a 7-day (15%) decrease in the mean number of skating days per year between 2020 and 2090. The intermediate scenarios

Figure 2. Likelihood of daily rinks availability as a function of the average maximum temperature of the preceding 6 days, based on the results of a logistic regression model of open/closed skating days in Montreal during 4 skating seasons between 2013 and 2017. The solid black line shows the result of the model applied to the combined data from all four seasons, with individual year models shown in coloured dashed lines. Individual data points showing the distribution of open and closed skating days are shown with open circles at the top and bottom of the plot (where values of 1 and 0 indicate days with open and closed rinks, respectively).

Figure 3. (a) The number of open days in each OSS plotted against the seasonal average value of the six-day maximum temperature; (b) the number of open days in each OSS plotted against the number of occurrences of six-day maximum temperatures above 5 °C during the season.
RCP 4.5 and RCP 6 showed larger skating day decreases of 39% and 49% respectively between 2020 and 2090. This suggests that very ambitious mitigation scenarios, leading to global temperature changes of less than 2 °C by the end of the century, will be required to maintain outdoor skating conditions in Montreal at a level that is at all similar to current conditions.

There are only two previous studies that have projected future changes in outdoor skating conditions in Canada, and it is notable that both projected less dramatic OSS declines in comparison with our results. Using the A2 business-as-usual emissions scenario from the IPCC Special Report on Emissions Scenarios (2000)—a scenario that is comparable to the RCP 8.5 scenario we used—Brammer et al (2015) found that the OSS on the Rideau Canal would decline to 14.7 ± 16.4 days per OSS by 2090, representing a 67% or 30 day decline from observed data. With the same emissions scenario, Robertson et al (2015) predicted that by 2090 the OSS length in Montreal be 43 ± 13 days, which represents a 34% or 22 day decline from their predicted OSS length by 2020. Brammer et al (2015) also estimated only a 5-day (11%) decrease in skating days on the Rideau Canal for a scenario where global temperatures are limited to 2 °C, which is also smaller than the decrease we simulated for the RCP 2.6 scenario. Some of these differences from our results can be attributed to different datasets that reflect different geographic locations and current skating conditions. For example, the analysis by Brammer et al (2015) was applied to skating conditions on the Rideau Canal in Ottawa, which typically requires different (and generally colder) temperature conditions to freeze sufficiently to allow skating as compared to outdoor rinks that are built on the ground. The study by Robertson et al (2015) was more comparable in terms of the types of rinks analysed, though was based on fewer years and total rink reports that were spread over a much larger geographic area. It is also possible that their method of collecting rink condition data via citizen reports resulted in more variability in data quality as compared to the city-reported data for Montreal.

Importantly, however, both of these previous studies used single-day temperature values to predict daily skating conditions, whereas in our analysis, we found that single-day values were not the best predictor of skating conditions, as compared to multi-day temperatures. In the context of future climate, it is likely that even considerably warmer winter climates will nevertheless always have some instances of very cold individual days. However, in the absence of sustained cold days (as captured by our six-day maximum temperature variable), individual cold days by themselves will not be sufficient to allow the creation and maintenance of outdoor rinks. Our results therefore suggest that projecting future skating conditions using only single-day temperatures would likely overestimate the number of skating days under future warmer winter conditions.

Figure 4. Projected future skating days in Montreal in response to 4 scenarios of future climate change, ranging from ambitious mitigation (RCP 2.6) to business-as-usual (RCP 8.5). The mean number of skating days (black circles and line) and standard deviation (grey shaded region) are derived from 99 replications of each year’s daily temperature values for individual years at 10-year intervals from 2020 to 2090. The minimum (blue) and maximum (red) values similarly represent the extreme cases among each 99-member ensemble. This figure illustrates that the OSS in Montreal will decrease across all scenarios, though with larger and sustained decreases seen only in the scenarios without successful greenhouse gas mitigation efforts.
It should be noted that our dataset better reflects the realities of municipal operations, such as bureaucratic delays, or difficulties in preparing and maintaining all rinks within a given neighbourhood simultaneously. For instance, there were extended cold periods in mid-December during both the 2013–2014 and 2016–2017 seasons that did not trigger the widespread opening of rinks in the city; this may simply reflect municipal delays or pre-determined schedules of operations, rather than any indication of the suitability of this window of the season for skating in Montreal. Consequently, we recognize that the record of daily skating conditions in Montreal that we have access to is not an exact reflection of the true temperature conditions that are required to create and maintain rinks. It is possible that rinks in other locations or municipalities that are maintained by individuals or smaller organizations could be more responsive to daily climate conditions, and may therefore be able to maintain more days of skating in a given year as compared to what we see in our dataset. However, there is also likely some inherent limitation to the viability of rink creation and maintenance: notably, if the number of consecutive skating days declines as a result of continued winter warming, we will likely reach a threshold where both individuals and municipalities decide that the effort of creating and maintaining a rink can no longer be justified for only a small number of potential skating days. Consequently, the effective skating season in Montreal will likely end long before the actual number of potential skating days reaches zero.

Our forecast of future OSSs suggests that global warming represents a larger threat for outdoor skating than has been suggested by previous research. If warming continues at its current pace, we anticipated that winter climate in Montreal will no longer be able to support consistently-available outdoor skating during the second half of this century. If outdoor skating is to be preserved in Montréal (and other similar locations across Canada), very ambitious climate change mitigation will be required. However, even were we to successfully achieve the temperature goals of the Paris Agreement, we can nevertheless expect some continued decline in the length and quality of the OSS in Montreal over the coming decades.

Changes to the outdoor skating season have important social and cultural implications given that outdoor skating and hockey are such prominent winter recreational activities in Canada. A shorter season would result in less opportunity for Canadians, notably low-income youth, to participate in physical activity, and it decreases the capacity for outdoor rinks to act as venues for community building (Johnson and Ali 2017). These findings are similarly relevant to other countries where outdoor skating is a culturally important winter recreational activity and where future outdoor skating season length has also been studied—for instance in the Netherlands and in China (Visser and Petersen 2009, Liu et al 2017). We do acknowledge that in comparison to other dangerous and widespread expected impacts of climate change, these impacts of climate change on outdoor skating may be seen as relatively benign. However, because of the cultural importance of outdoor skating and hockey in Canada, research into historical changes and future conditions for outdoor skating across Canada could act as a tool for climate change education and climate change awareness on a national level. Drawing a clear link between climate change and outdoor ice skating, something many Canadians care about, is particularly meaningful given that belief in anthropogenic climate change amongst the Canadian public is only at 70%, despite the fact that Canada has been a major contributor to historical emissions (Matthews et al 2014, Abascus Data 2018). Identifying an effect of climate change that is perceptible to Canadians such as a decrease in the availability of outdoor skating—a decrease that could see outdoor skating be severely limited in Montréal and other Canadian cities during the second half of this century—may help to encourage both belief in and action to mitigate anthropogenic climate change.

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