



## Abstract

Lakes comprise a large portion of the surface cover in northern North America forming an important part of the cryosphere. The timing of lake ice phenological events (e.g. break-up/freeze-up) are useful indicators of climate variability and change, which is of particular relevance in environmentally sensitive areas such as the North American Arctic. Further alterations to the present day ice regime could result in major ecosystem changes, such as species shifts and the disappearance of perennial ice cover. Lake ice models are a valuable tool for examining the response of lake ice cover to changing climate conditions. The use of future climate scenario data in these models can provide information on the potential changes in ice phenology, ice thickness and composition. The Canadian Lake Ice Model (CLIMo) was used to simulate lake ice phenology across the North American Arctic from 1961–2100 using climate scenarios produced by the Canadian Regional Climate Model (CRCM). Results from the 1961–1990 time period were validated using 15 locations across the Canadian Arctic, with both in situ ice cover observations from the Canadian Ice Database as well as additional ice cover simulations using nearby weather station data. Projected changes to the ice cover using the 30 yr mean data between 1961–1990 and 2041–2070 suggest a shift towards shorter ice cover durations by an average of just over 3 weeks, with a 25 cm average reduction of the total ice thickness – varying based on location, lake depth and snow cover amounts.

## 1 Introduction

Lakes are a major feature across northern North America, forming an important part of the cryosphere, with their ice cover both playing a role in and responding to climate variability. Future changes in ice cover conditions due to changing climate conditions could impact the role of lakes on energy, water and biogeochemical processes in cold regions as well as socio-economic impacts in terms of transportation (ice roads) and recreation.

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Both long-term and short-term trends have been identified in ice phenology records and are typically associated with variations in air temperatures; while trends in ice thickness tend to be associated more with changes in snow cover (Brown and Duguay, 2010). Generally, lake ice records show trends towards earlier break-up, and later freeze-up (Northern Hemisphere: Magnuson et al., 2000; Europe: e.g., Blenckner et al., 2004; Korhonen, 2006; Palecki and Barry, 1986; Weyhenmeyer et al., 2004; Livingstone, 1999; North American Laurentian Great Lakes region: e.g., Jensen et al., 2007; Johnson and Stefan, 2006; Anderson et al., 1996). However, the statistical significance and magnitude of the trends varies by location and time scale examined (see Brown and Duguay, 2010).

Throughout Canada, from 1951–2000, trends toward earlier water-clear-of-ice dates have been observed for many lakes during the latter part of the 20th century, but complete freeze over dates have shown few significant trends over the same period (Duguay et al., 2006; Latifovic and Pouliot, 2007). Changes in the ice regimes of typically perennially ice-covered lakes on northern Ellesmere Island (Nunavut, Canada) have been related to shifts in the climate regimes in that area and shown to have changed from infrequent to more frequent summer ice loss (Mueller et al., 2009). Past changes to lake ice regimes have also been inferred in the arctic using proxy methods such as diatoms (Smol, 1983, 1988; Douglas and Smol, 1999; Smol et al., 2005; Keatley et al., 2008) and sediment records (Tomkins et al., 2009).

Snow is a very important influencing factor for lake ice. Once the ice has formed, snow accumulation on the ice surface slows the growth of ice below due to the insulating properties as a result of the lower thermal conductivity (thermal conductivity of snow,  $0.08\text{--}0.54\text{ W m}^{-1}\text{ K}^{-1}$  versus  $2.24\text{ W m}^{-1}\text{ K}^{-1}$  for ice, Sturm et al., 1997). Conversely, the mass of the snow can also change the composition of the ice by promoting snow ice development, and hence influence the thickness of the ice cover (Korhonen, 2006; Brown and Duguay, 2011). Recent work using a combination of several datasets by Brown et al. (2010) showed a reduction of the spring snow cover extent throughout the pan-arctic from 1967–2008. Specifically for the North American Arctic, they found



for a detailed comparison). While most work involving ice cover changes has been done for specific locations, Walsh et al. (1998) produced gridded ice phenology for the entire Northern Hemisphere using historical 1931–1960 mean climate data to create the first wide-scale examination of lake ice phenology. A recent study using gridded climate data examining possible changes to the lake ice regime in North America from 40° N to 75° N under future climates suggests break-up will advance by 10–20 days, while freeze-up will be delayed by 5–15 days, resulting in a reduction of the ice cover duration by 15–35 days (Dibike et al., 2011).

In situ data is very sparse throughout northern North America and the majority of the climate stations in the Arctic are typically confined to relatively accessible areas of the mainland or coastal areas in the islands. The use of gridded climate data to drive numerical lake ice models provides the ability for wide-scale assessments of ice cover, as well as the ability to produce predictions of future ice conditions. Several forms of gridded climate data are available such as Global Climate Models (GCMs) (e.g. CGCM3: McFarlane et al., 2005; HadCM3: Gordon et al., 2000), Regional Climate Models (RCMs) (e.g. CRCM: Caya and Laprise, 1999; HIRLAM4: Christensen et al., 1998; MM5: Hernandez et al., 2006) and atmospheric reanalysis data (e.g. ERA-40: Uppala et al., 2005; NARR: Mesinger et al., 2006). GCMs are not particularly well suited to ice phenology studies due to their coarse spatial resolution, however RCMs or reanalysis data with finer resolutions can be quite beneficial. The aim of this paper is to create gridded ice phenology data for North America (greater than 58° N) using gridded input data from the Canadian Regional Climate Model (CRMC) both for present day climate as well as future simulation, while highlighting the importance of snow cover on the potential changes to the lake ice regimes.

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## 2 Study area and methodology

### 2.1 Study area

Canada and Alaska (USA), north of 58° latitude is dominated by discontinuous or continuous permafrost except at the southern reaches of the Yukon and Northwest Territories (NWT), and northern part of the provinces of British Columbia and Alberta (Fig. 1). The area encompasses mainly subarctic and arctic climate, where the temperatures can reach up to 25 °C in the summer in the interior continental areas (e.g., Yellowknife, NWT) to below -40 °C in the winter throughout most of the area. Mean annual temperatures range from 4 °C in the coastal areas of Alaska, to -18 °C on Ellesmere Island. Precipitation varies greatly across the continent with over 3000 mm near the northern coast of the Gulf of Alaska; the interior regions receiving 200–400 mm (higher amounts in the Yukon and NWT mountain areas); decreasing to less than 200 mm per year in the Canadian Arctic Archipelago (CAA). Snow cover amounts through most of the region range from 30–50 cm (higher in the mountains) with less than 30 cm in the western parts of the CAA.

Many mountainous areas are present in the study region: The Western Cordillera extending up the west coast through British Columbia and Alaska with the Alaska Range and the Brooks Range to the north; and the Arctic Cordillera spanning most of the northern areas of the CAA. Across the interior plains and the northern parts of the Canadian Shield is the boreal forest while tundra extends to the north of the tree line.

Many large lakes (> 400 km<sup>2</sup>) are situated north of 58° N (e.g., Nettelling Lake, Amadjuak Lake, Baker Lake) as well as the Northern Great Lakes (Great Bear Lake and Great Slave Lake). Lakes in the northern boreal and tundra areas are numerous, with an estimated coverage in the Arctic and Subarctic regions of North America reaching up to 15–40 % depending on the location (Duguay et al., 2003).

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## 2.2 Lake ice model

The model used is the Canadian Lake Ice Model (CLIMo), a one-dimensional thermodynamic model used for freshwater ice cover studies (e.g., Ménard et al., 2002; Duguay et al., 2003; Jeffries et al., 2005, Morris et al., 2005) capable of simulating ice on and off, thickness and composition of the ice cover (clear or snow ice). CLIMo has been shown to perform very well at simulating lake ice phenology when using input data that well represents the climate for the lake, for example from nearby meteorological towers (Duguay et al., 2003; Jeffries et al., 2005; Brown and Duguay, 2011). CLIMo has been modified from the one-dimensional sea ice model of Flato and Brown (1996), which was based on the one-dimensional unsteady heat conduction equation, with penetrating solar radiation, of Maykut and Untersteiner (1971), i.e.

$$\rho C_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial z} k \frac{\partial T}{\partial z} + F_{sw} I_o (1 - \alpha) K e^{-kz} \quad (1)$$

where  $\rho$  ( $\text{kg m}^{-3}$ ) is the density,  $C_p$  ( $\text{J kg}^{-1} \text{K}^{-1}$ ) is the specific heat capacity,  $T$  (K) is the temperature,  $t$  (s) is the time,  $k$  ( $\text{W m}^{-1} \text{K}^{-1}$ ) is the thermal conductivity,  $z$  (m) is the vertical coordinate, positive downward,  $F_{sw}$  ( $\text{W m}^{-2}$ ) is the downwelling shortwave radiative energy flux,  $I_o$  ( $\text{W m}^{-2}$ ) is the fraction of shortwave radiation flux that penetrates the surface,  $\alpha$  is the surface albedo, and  $K$  is the bulk extinction coefficient for penetrating shortwave radiation.

From this, the surface energy budget can then be calculated:

$$F_o = F_{lw} - \varepsilon \sigma T^4(0, t) + (1 - \alpha)(1 - I_o)F_{sw} + F_{lat} + F_{sens} \quad (2)$$

where  $F_o$  ( $\text{W m}^{-2}$ ) is the net downward heat flux absorbed at the surface,  $\varepsilon$  is the surface emissivity,  $\sigma$  is the Stefan–Boltzmann constant ( $5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$ ),  $F_{lw}$  ( $\text{W m}^{-2}$ ) is the downwelling longwave radiative energy flux,  $F_{lat}$  ( $\text{W m}^{-2}$ ) is the downward latent heat flux, and  $F_{sens}$  ( $\text{W m}^{-2}$ ) is the downward sensible heat flux (Ménard et al., 2002; Jeffries et al., 2005).

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CLIMo includes a fixed-depth mixed layer in order to represent an annual cycle. When ice is present, the mixed layer is fixed at the freezing point and when ice is absent, the mixed layer temperature is computed from the surface energy budget and hence represents a measure of the heat storage in the lake. The water column of shallow lakes is typically well-mixed and isothermal from top to bottom during the ice-free period, permitting the mixed layer depth to be a good approximation of the effect of lake depth leading to autumn freeze-up (Duguay et al., 2003). Snow ice is created by the model if there is a sufficient amount of snow to depress the ice surface below the water level. The added mass of the water filled snow pores (slush) is added to the ice thickness as snow ice. A more detailed description of CLIMo can be found in Duguay et al. (2003).

In order to account for redistribution of snow across the ice surface, simulations were run with both a full snow cover and no snow cover (see Sect. 3.1 for details). Three sets of simulations were run with respect to mixing depth: 3 m (to represent shallow lakes, e.g. in the North Slope area of Alaska; the Hudson Bay Lowlands), 10 m (to represent medium deep lakes, near-shore areas where observations would be taken on larger lakes, or lakes of unknown depth following Samuelsson et al., 2010) and 30 m (to represent large, deep lakes).

### 2.3 Gridded climate data

CLIMo was driven by gridded climate data produced from the Canadian Regional Climate Model (CRCM 4.2.0) (45 km true at 60° N) provided by Consortium Ouranos. CRCM is a limited-area model, originally developed at Université du Québec à Montréal (UQAM), driven at the boundaries by GCMs or reanalysis data. CRCM uses the Canadian LAnd Surface Scheme (CLASS 2.7; Verseghy 1991; Verseghy et al., 1993) to describe the water and energy exchanges between land surface and atmosphere (Muscic and Caya, 2007). For a detailed description of CRCM see Caya and Laprise (1999) and Laprise (2008).





the majority of the study area, correcting the large bias in the mountainous Ellesmere Island areas using coastal station data (Alert) could potentially introduce a warm bias over the glaciated mountains. Conversely, since this study aims to examine changes in the lake ice cover, the adjusted temperature data would be suitable to represent the areas where lakes would be more likely to be situated (e.g. lowland areas, valleys, rather than in high altitude glaciated areas). The mean monthly bias was determined from the 1961–1990 data and then adjusted accordingly. Snow amounts from the gridded climate scenarios were compared to station data (see Sect. 3.1) and were found to be suitably comparable. Other variables play a lesser role in the model and no bias correction was undertaken. The adjusted temperature data was then able to produce simulation results comparable to those run using observation data. An assumption was made that the bias present from 1961–1990 is consistent into the future.

## 2.4 In situ data

Fifteen lakes were selected as validation sites for the CRCM simulations (Fig. 3, Table 1). Each lake chosen has observation data available for ice break-up and freeze-up in the Canadian Ice Database (CID) during the contemporary climate (1961–1990). The 1961–1990 climate mean was chosen rather than the more recent 1979–2000 climate mean as the earlier set coincides with the peak years of in situ lake ice observations. The CID is a national historical database of in situ ice cover (lake ice, river ice, landfast sea ice) from 1822 for 757 sites across Canada (259 Lakes) (Lenormand et al., 2002). For clarity, the two unnamed lakes will be referred to by their area (Mould Bay and Sachs Harbour). To assess the performance of the CRCM simulations of freeze/break-up, simulations were also run for each of the validation sites using data from nearby weather stations operated by the Meteorological Service of Canada (MSC) (air temperature, relative humidity, wind speed, and cloud cover). Snow depth and density were obtained from the Canada Snow CD (MSC, 2000), a database of quality controlled and reconstructed snow data from Meteorological Service of Canada stations throughout Canada (Brown and Braaten, 1998). Snow density was obtained as

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a seasonal average from bi-weekly gridded snow density normals, created from snow course data and interpolated to a 200 km grid (MSC, 2000). Six of the selected validation sites had on-ice snow depths measurements recorded by the Canadian Ice Service (CIS) as part of the Canadian Ice Thickness Program (<http://www.ec.gc.ca/glaces-ice/default.asp?lang=En&n=E1B3129D-1>). Ice thickness and snow depths are available for 195 Lake/River/Sea ice sites throughout Canada from 1947 to present, with varying completeness of years. Snow depths on the lake ice surface were compared with snow depths at the MSC stations and the corresponding CRCM tile in order to examine the effects of snow depth on the ice cover simulations. Table 1 provides a summary of the available observation data from the validation lakes, along with the years of available meteorological data and on-ice snow depths where available. A statistical comparison was done for the validation results using the Mean Bias Error (MBE) or Absolute Error (AE).

### 3 Results

#### 3.1 Comparison of snow cover on the lakes

Representing the snow cover on the lake surface well is important for accurate simulations of the ice evolution throughout the winter (e.g., Brown and Duguay, 2011) as the snow cover can both provide insulation and in areas with adequate snowfall, contribute to thickness in terms of snow ice growth. Redistribution of the snow across the lake ice surface can result in a non-uniform snow cover, typically less than what would be measured nearby on-land. For example, in northern Alaska, the ratio of snow-on-ice over the lakes to snow-on-land was found to be an average of 56 % (Sturm and Liston, 2003). In order to represent the range of potential snow conditions on the lake ice surface, simulations are run with a “full snow cover” to represent 100 % of the snowfall accumulating on the ice, as well as a “no snow cover” simulation to represent the opposite conditions. Comparison of the full snow scenarios is dependent on the equivalency

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of the snow conditions between the input data sets. Table 2 presents the comparison of the snow cover between the gridded climate data sets with respect to the measured snow at the MSC stations nearest to the lakes where on-ice snow measurements were available. Although it is not advised to compare a CRCM tile with a weather station (Gagnon et al., 2009) an assessment of the amounts of snow in each data set is important to determine the ability of the CRCM tile to represent the snow cover of the lakes within it.

The ratio of on-ice snow depth to on-shore snow depth at the MSC stations were all less than 1 (Table 2). The lakes have an average of 41–82 % of the snow measured at the MSC stations on their surface, with the exception of Baker Lake, which had only 9 % of the recorded snow measured on the ice surface. The CRCM tiles over these lakes had fairly comparable ratios between them, and were within 80–122 % of the snow amounts measured at the MSC stations, excluding Upper Dumbell Lake. CRCM snow cover in the region near Upper Dumbell Lake is consistently overestimated due to perpetual snow cover in the CRCM data after the snow has melted at the station. The CRCM tile over Upper Dumbell Lake covers both land and ocean; however, the climate in this tile is more likely representative of the surrounding high altitude regions.

### 3.2 Ice cover during 1961–1990 climate

The two CRCM scenarios are similar for the contemporary climate years (1961–1990). The similar input data results in similar simulated ice cover patterns with the primary difference between them occurring in the areas predicted to have perennial ice cover. The ice cover figures produced for the 1961–1990 climate use scenario 1 and are meant to represent hypothetical lakes at the given depths (3, 10 and 30 m), since many different lakes sizes and shape could exist within a given grid cell.

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### 3.2.1 Ice cover duration 1961–1990

Break-up of the ice cover ranges from March in the Gulf of Alaska coastal areas to August in the High Arctic (yd 102–yd 241), with perennial ice cover on Ellesmere Island and other regions of the CAA; as well as northern Baffin Island with the no snow scenarios (Fig. 4). Mean break-up dates for entire study region range from yd 162–165 for all simulations with snow cover (mean yd 163) and yd 171–174 (mean yd 172) for no snow. Both climate scenarios show break-up to be similar for all depth simulations (not shown), however changes are evident based on snow cover (mean difference of 9 days between snow and no snow cover) and are more pronounced in the high latitude areas of perennial ice cover. Freeze-up however, is dependent on the depth of the lake rather than the snow cover scenario (Fig. 5). Freeze-up ranges from September to December (yd 245–yd 358), with a mean freeze-up date for 3 m lakes of yd 281, 10 m lakes freezing an average of 11 days later (yd 292), and 30 m lakes freezing an average of a further 20 days after the 10 m lakes (yd 313). The resulting ice cover durations vary for both depth and snow cover, ranging from 90 to 365 days (Fig. 6), with the longest ice cover duration (ICD) on shallow snow-free lakes (average of 255 days) and shortest for large snow-covered lakes (average 215 days).

In the far northern areas, break-up does not always occur on an annual basis resulting in occasional summer ice cover. All simulations encountered occasional summer ice cover on the lakes in the far northern areas, however only grid cells where no break-up occurred during the 30 yr mean were designated as “perennial ice cover”. Perennial ice cover is simulated the same regardless of lake depth but is slightly different between the two climate scenarios. Scenario 1 produces 40 grid cells (81 000 km<sup>2</sup>) where perennial ice is simulated on snow-free lakes (versus 33 (66 825 km<sup>2</sup>) for scenario 2) and 19 grid cells (38 475 km<sup>2</sup>) for snow-covered lakes (versus 10 (20 250 km<sup>2</sup>) for scenario 2).

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### 3.2.2 Ice cover thickness 1961–1990

Lake ice thickness is known to be influenced by snow cover on the ice (e.g., Ménard et al., 2003; Morris et al., 2005; Brown and Duguay, 2011) as shown in Fig. 7, with a substantial difference between the spatial pattern of thickness in snow-free versus snow-covered lakes. Since CLIMo uses the mixing depth rather than absolute lake depth the areas where perennial ice cover occurs continue to thicken each year and are hence, capped at 3 m to avoid unrealistically thick ice. Both CRCM scenarios produce similar mean maximum ice thickness (MMT) (within 2 cm of each other) ranging from an average of 1.91 m to 2.03 m for the snow-free scenarios, and 1.44 to 1.51 m for the snow-covered scenarios for all depths. The difference in MMT between the snow-free and snow-covered scenarios differs by depth, with an average of 58 cm thicker ice for snow free 3 m lakes, 53 cm thicker ice for snow free 10 m lakes and 42 cm thicker for snow free 30 m lakes.

The composition of the ice (snow ice/clear ice) can affect the strength of the ice as well as the melt rates due to albedo differences between the snow versus clear ice. Figure 8 shows the distribution of snow ice (as a ratio to total ice thickness), highlighting the areas where enough snowfall is received to depress the ice cover enough for snow ice to form. Cold temperatures and low snowfall amounts through most of the Arctic limit the amount of snow ice that forms, however throughout the mountainous areas and northern Quebec/southern Baffin Island some snow ice is simulated.

### 3.3 Validation of ice phenology and thickness

Validation of modelled ice phenology and thickness in Northern Canada and Alaska presents challenges as the observational network for lake ice is very sparse. Simulations using CLIMo typically compare well to observation data when run using climate data that adequately represents the lake observed (i.e. nearby weather stations) (e.g., Duguay et al., 2003; Brown and Duguay, 2010; Jefferies et al., 2005). To examine how

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representative the CRCM simulations are compared to observations, simulation results from the containing CRCM tiles were compared to 15 locations that had both observation data and MSC station data available. If CLIMo is not able to accurately capture the break-up/freeze-up dates using nearby MSC station data, then the same would be expected of the CRCM data. This allows for distinguishing between limitations with the model rather than the CRCM data.

Table 3 presents the Mean Bias Error (MBE) for the simulations compared to observations. Looking at the MSC simulations results for the validation sites, all but six had a MBE of less than one week for the simulations compared to observations, with most being slightly early. Break-up for Mould Bay was simulated 13 days late compared to the observations, suggesting either the snow conditions are not well represented or a factor not captured by the 1-D model. Break-up for Dewar Lakes was simulated 20 days too late, again suggesting other factors that are not captured by the 1-D model – in this case likely a result of the morphometry as this locations is part of a long narrow series of lakes. Break-up at Charlton Bay and Ennadai Lake was two weeks early, however the dates vary in phase. This same early tendency for break-up was also found at Charlton Bay by Ménard et al. (2002), who suggested that this might in part be due to the sheltered location creating a favourable environment for a longer ice cover. Lake Athabasca was the only lake where freeze-up could not be adequately simulated, being 38 days too early compared to observations. The in situ data for this lake is from Fort Chipewyan, situated beside the Peace-Athabasca Delta (PAD), in a very shallow area of Lake Athabasca. The mean depth of the lake is 20 m however the lake is 3 m or shallower at the western end near the PAD. The PAD is a hydrologically complicated area, where reversal of flow is known to occur (Peters and Buttle, 2010), and the additional heat inputs to the lake from the PAD and surrounding rivers in this area likely contributed to the discrepancy between the observed and simulated freeze-up. Since CLIMo usually represent freeze-up quite well a test was run adjusting the mixing depth in the simulations in order to match the observations. A mixing depth of 30 m was required for simulations for Lake Athabasca to match observations – suggesting that the

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heat added from the surround inputs to this area has the equivalent heat storage of an extra 27 m of water.

The CRCM simulations were within 1 week of observations for 6 of the 15 lakes simulated (Table 3). As expected from the MSC simulations, the CRCM simulations for break-up at Mould Bay and Dewar lakes were too late, and freeze-up at Lake Athabasca was too early. The five lakes with the greatest MBE for early break-up (Charlton Bay (GSL), Lake Athabasca, Ennadai Lake, Baker Lake and Resolute Lake: 10–18 days, with the exception of Resolute Lake for scenario 2, which matched observations) also had early break-up seen in the MSC simulations (5–14 days). The only anomaly between the CRCM and MSC simulations occurred at Upper Dumbell Lake for freeze-up, while the station data resulted in freeze-up being captured within 3 days of observations, CRCM simulations for scenario 1 and 2 were both over a week late.

Overall, the absolute error compared to observations for all fifteen lakes combined was 8 days for break-up and 6 days for freeze-up (4 days excluding Lake Athabasca), indicating that CLIMo produces satisfactory simulations for break/freez-up using CRCM gridded climate data.

A comparison of mean maximum thickness (MMT) was possible at five of the validation lakes (Table 4). Simulating the ice thickness correctly is dependent on accurately representing the snow cover depth and density on the lake ice surface where the measurements were taken. Also, since the in situ thickness measurements are generally taken weekly (but not always) there is a small possibility of missing the maximum thickness during the sampling. For Back Bay (GSL) the MSC simulations had a MBE of 10 cm too thin, while the CRCM simulations here were 20 cm too thick. Ennadai Lake was also too thin with MSC (12 cm) however in this instance the CRCM simulations were closer to the observations (< 4 cm MBE). MMT was underestimated at Baker Lake as well with the MSC simulations 14 cm too thin, and the CRCM simulations 11 cm too thin. Break-up was not simulated well at Charlton Bay (GSL) so the likelihood of representing the thickness well here is reduced with all simulations being too thick. The large discrepancy for the thickness of Upper Dumbell Lake for the CRCM

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simulations is due to the snow cover being poorly represented here (MSC simulations captured the thickness well with a MBE of 6 cm)

The average absolute error for the simulated MMT compared to observations is 10 cm for the MSC simulations and 25/23 cm for the CRCM simulations using the best estimate for snow cover amounts. Excluding Charlton Bay where the MSC simulations did not capture the observations well (and hence CRCM would not be expected to either), and Upper Dumbell Lake where snow cover amounts are inaccurate, the average absolute error for the remaining three lakes is within 12 cm of observations for both scenarios.

Snow ice measurements are not recorded in the historical archives, however a study on Baffin Island near Iqaluit, Nunavut, found a 7% ratio of snow ice to maximum ice thickness during the 2005–2006 winter (Dyck, 2007). The 1961–1990 mean ratio in this area was ~6%.

### 3.4 Ice cover during future climate

The dominant climatic variables in terms of ice cover changes are air temperature and the snow conditions (both depth and density). Although the two scenarios begin with similar conditions and both show warming throughout (Fig. 9a), by the 2041–2070 mean they have evolved different temperature patterns. Temperatures in scenario 1 show the greatest change in the winter seasons (December, January, February) ranging from 5–9°C warmer over the land areas. Spring (March, April, May) shows an increase mainly in the 3–5°C degree range; summer (June–August) only 1–3°C, and fall (September–November) a 2–6°C change. Temperatures in scenario 2 however are cooler and show less warming to 2041–2070. Winter in scenario 2 does not have warming in the Alaskan area seen in scenario 1, and the bulk of the NWT shows less warming in the spring. Summer is quite similar for both, while fall is also cooler for the NE (Alaska).

Precipitation is expected to increase throughout the northern regions in future climate scenarios (see figures available on the NARCCAP website using similar scenario data:

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http://www.narccap.ucar.edu/results/crcm-cgcm3-results.html), however, in terms of snow water equivalent (SWE) the CRCM data shows spatially varying changes in the future (Fig. 9b). The majority of the northern areas show an increase of SWE consistent with increasing precipitation, however the Alaskan coastal regions and the tip of Labrador show a decrease in SWE – which would be attributed to changes from snow-fall to rainfall in these areas. The two scenarios are more similar in terms of SWE than temperature, and the amount of change is mainly in the range of  $\pm 10\%$ , with some winter SWE increases up to 30%. Snow depths compared at the lake validation sites tend to increase, however based on a sensitivity study for Back Bay (GSL) by Ménard et al. (2003) increasing the snow depth on the ice does little to affect the ice cover duration and only slightly affect the thickness as compared to the effects of reducing the snow cover on the ice. While increased snow depth on the ice surface may not have a large impact on the duration, the ice composition is likely to be affected by the increased formation of snow-ice in the areas where the mass of the snow (or SWE) on the ice increases.

### 3.4.1 Ice cover duration 2041–2070

Comparing the mean break-up dates for 2041–2070 to the mean 1961–1990 dates show later break-up across the entire study area (Fig. 10a,b) with the exception of 1 small area on Baffin Island in the snow free scenario 1 simulation where the increased frequency of summer break-up resulted in a slightly earlier date. Break-up ranges from late February to mid-August (yd 51–yd 232) for all simulations, with the mean break-up date now yd 150 (151 for scenario 2) for full snow scenarios and 156 (157 for scenario 2) for no snow scenarios – a shift of mean break-up date 7 days earlier for the snow scenario and 14 days earlier for no snow scenario. No perennial ice cover remains in scenario 2 and only 5 grid cells remain in scenario 1 for the no snow scenarios (compared to 19 and 40 for snow/no snow in 1961–1990). Although in most areas scenario 2 is cooler than scenario 1, the far northern parts of Ellesmere and Baffin Islands where the perennial ice was located, experience warmer temperatures

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than scenario 1 during the winter and spring, likely contributing to the differences in the perennial ice cover.

Comparing the results from the two future scenarios can provide some insight on the possible range of dates predicted by this CRCM scenario data (Fig. 10c). Examining the snow-free scenarios, the majority of the study area has mean 2041–2070 break-up dates for both CRCM scenarios within 5 days of each other. Scenario 2 is mainly 0–5 days later than scenario 1; not unexpected as slightly cooler temperatures persist in most areas of scenario 2. Only a few areas show a difference of more than 5 days between the scenarios, with a few smaller areas dispersed around the southern reaches of the study area showing 5–10 days later break-up. The northwestern coastal and southern coastal areas of Alaska (and northern British Columbia) show 10–30 days earlier break up with scenario 2. The northern and eastern parts of the CAA show earlier break-up for scenario 2, again the result of warmer temperatures in this area. The areas with greater than 30 days differences in break-up dates on Ellesmere Island result from the lack of any remaining perennial ice cover in scenario 2. For the snow-covered scenarios, break-up for the two CRCM scenarios is still mainly within 5 days, with a larger portion of the study area shifting to 0–5 days earlier break-up, particularly in the north eastern areas.

Freeze-up for 2041–2070 now ranges from late August until the end of December (yd 240–yd 365 for scenario 1 and yd 245–yd 364 for scenario 2), with mean freeze-up dates the same for both scenarios: 289 (3 m), 301 (10 m) and 325 (30 m). Mean freeze-up dates show a shift of 6–11 days later than those from 1961–1990, less of a change than break-up. Figure 11a,b presents the changes in freeze-up dates from 1961–1990 to 2041–2070. Scenario 1 has the greatest changes for freeze-up in Alaska and the High Arctic while scenario 2 has the greatest changes in the High Arctic and eastern areas (Baffin Island and northern Quebec). The areas with greater than 40 days change in freeze-up on Ellesmere Island are the areas where the perennial ice cover changed to seasonal ice cover. There are more pronounced differences between the scenarios for freeze-up than break-up (Fig. 11c). The central section of the study area

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is still  $\pm 5$  days between the scenarios, however northern Quebec and Baffin Island show 5–20 days later freeze-up with scenario 2, while freeze-up in Alaska is 5–10 days earlier with some section in the shallower lakes  $> 10$  days earlier (not shown).

The changes in ICD from 1961–1990 to 2041–2070 are presented in Fig. 12a,b.

Scenario 1 shows a change in ICD ranging from 10 to more than 40 days shorter by 2041–2070. The areas of the most change are the Alaska coast and the High Arctic islands (25 to  $> 40$  days shorter ICD); and northern Quebec (20–30 days shorter ICD). The ICD throughout the rest of the region is mainly 10–25 days shorter ICD and the effect of snow cover can also be seen in the simulations, with the snow-covered simulations producing slightly less change in ICD than the snow-free simulations.

Although scenario 1 and 2 appear quite different in terms of spatial pattern (Fig. 12a,b) this is in part due to the broad 5 day categorization. Scenario 2 shows the same range of ICD changes as scenario 1, however, there are much larger areas with less change due to the smaller changes in break-up and freeze-up. Of note here is the areas of most change – scenario 1 focusing over the Alaskan coast and scenario 2 focusing over the Arctic islands as well as northern Quebec and Southern Baffin Island rather than the Alaskan coast (as seen in scenario 1). Similar to break-up and freeze-up, the ICD differences for the two CRCM scenarios (Fig. 12c) is mainly  $\pm 5$  days, with more areas in the 5–10 day differences from the combined effect of break-up and freeze-up differences.

Both future scenarios show a loss of perennial ice cover as well as large reductions to the area where occasional summer ice cover is predicted to occur (Fig. 13). There is a larger reduction of grid cells where occasional summer ice occurs with the no-snow scenarios than with snow. However, a smaller area remains with occasional summer ice when snow is taken into account, reflecting the insulating effects of the snow, leading to thinner ice, leading to fewer summers where any ice persists in the lakes. Using the 10 m hypothetical lakes as an example, a reduction of 192 grid cells where perennial or occasional ice would occur ( $388\,880\text{ km}^2$ ) was seen with no-snow and reduction of 91 grid cells ( $184\,427\text{ km}^2$ ) was seen with snow. Also, while scenario 2

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begins with slightly more occasional summer ice, due to the greater warming in the high latitude areas by the 2041–2070 mean in this scenario, a greater reduction in the summer ice cover is seen.

### 3.4.2 Ice cover thickness 2041–2070

5 Along with a reduction in the ICD for the future scenarios, the mean maximum thickness of the ice cover on the lakes is also shown to decrease. Scenario 1 shows an average of 25 cm less ice for the snow simulations, and 32 cm less ice for the snow-free simulations. Spatially, the snow cover scenarios produce quite different results (Fig. 14a,b). With the snow-free simulations, the deeper the lake, the more change in thickness predicted (30 m lakes mainly greater than 30 cm reduction in ice thickness).  
10 With snow added on top of the ice cover however, the 10 m deep lakes show slightly less loss of thickness than the 3 m lakes, the most change occurring in the 30 m lakes.

Scenario 2, being generally cooler than scenario 1 for the majority of the study area shows less predicted loss of thickness, with 21 cm less (mean) for snow covered and 24 cm less for snow free. Again the deeper the lake, the more change in thickness seen, but less change than scenario 1. In this case, most of the changes to the ice thicknesses are in the 10–30 cm, except for some areas of the CAA and northern Quebec/southern Baffin Island where this increases to 30–40 cm.

15 Comparing the two scenarios (Fig. 14c), most of the area has less than 10 cm difference between them, with the exception of the northern Western Alaskan coastal areas in the same areas the differences in ICD were seen. With snow covered scenarios the difference is less than 20 cm (with scenario 2 being thicker) however with the snow free scenarios this difference increased to up to 25 cm.

25 Mean maximum thickness amounts include both snow ice and black ice in the total amounts. Looking at the changes in to the snow ratio ice from 1961–1990 to 2041–2070 most of the study area experiences some increase, though in the central regions this increase is less than 1 % (Fig. 15). Also, with the shallower lakes, increased snow ice ratios are seen around Hudson Bay and up into the High Arctic that are not evident

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with the deeper 30 m lakes. Areas of decreased snow ice ratio are along the warmer coastal areas of Alaska (and a small area of northern Quebec/Labrador), corresponding to areas of decreased SWE (Fig. 9b) where increased amounts of precipitation would be expected to fall as rain rather than snow, reducing the chance for snow to accumulate on the ice surface to form snow ice.

#### 4 Summary and conclusions

Ice phenology simulations using the lake ice model CLIMo driven by gridded input climate data from CRCM scenarios for 1961–1990 had an average absolute error of less than 1 week compared to observation data at 15 validation sites across Northern Canada. For three validation lakes where CLIMo was able to represent the phenology well, the mean maximum ice thickness had an average absolute error of 12 cm compared to the measured ice thickness. Capturing the correct ice thickness in the simulations depends on how well the snow cover on the ice surface is represented both in terms of depth and density.

By 2041–2070, the mean break-up date was shown to shift 7 days earlier with snow cover on the lakes and 14 days earlier with no snow cover. Most of the northern areas show a change in the range of 10–25 days earlier for break-up (excluding the areas of maximum change discussed later). Mean freeze-up for the north was shown to shift 7, 8 and 11 days later (3, 10 and 30 m depths, respectively) with shifts ranging from 0–15 days later, a smaller change than seen in break-up. These ranges are comparable to those identified by Dibike et al. (2011), using the MyLake model (Saloranta and Anderson, 2007) to examine future changes over a broader and more southern area of North America. Ice cover durations ranged from 10 to more than 40 days shorter, with the areas of greatest change in scenario 1 located near the Alaskan coast, the far northern Arctic islands, and northern Quebec; while scenario 2 had the greatest changes in the north eastern section of the study area (the CAA and southern Baffin Island/northern Quebec). In the remainder of the study area (away from the areas of

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maximum change) the shallower lakes (3 and 10 m) show mainly 10–25 days shorter ICD (5–25 days shorter for scenario 2), while the 30 m lakes show primarily 15–30 days shorter ICD (10–30 days shorter for scenario 2). The areas of maximum change identified in this study were more extreme than those in the results produced by Dibike et al. (2011) for reduction in ICD, however the spatial patterns in their results were most similar to scenario 1. River ice durations were also estimated to be approximately 20 days shorter (2040–2069) over most of Canada, based on projected changes to the 0° isotherm (Prowse et al., 2007).

Both scenarios show a drastic reduction in the number of grid cells with perennial ice cover, with none remaining in scenario 2. The areas of occasional summer ice cover are also reduced, with greater losses when no snow cover is on the ice (though a smaller area remains when snow cover is taken into account).

Changes to the mean maximum thickness show an average of 25 cm less ice for the snow simulations (21 cm less for scenario 2), and 32 cm (24 cm) less ice for the snow-free simulations. Overall, scenario 1 shows more reduction in ice thickness than scenario 2 with the maximum loss reaching over 40 cm in the Alaskan coast areas (scenario 1) and up to 40 cm reduction in the CAA and Northern Quebec/Southern Baffin Island (scenario 2). The ratio of snow ice to total maximum ice thickness was also shown to increase throughout the study area, with the exception of the Alaskan coastal areas, where a reduction in the SWE was also observed. Dibike et al. (2011) show the area with the thickness changes along the northern coast lines at the upper extent of their study area (up to 25 cm reduction), which is again, most comparable to the full snow simulations in scenario 1.

The use of two variations of the CRCM data allows for some measure of uncertainty in the range of dates produced by the simulations. Break-up and freeze-up dates were generally within 5 days for the two scenarios, except in three key areas where the most variability is seen throughout, around the coasts in: Alaska, the far north on Ellesmere island and Northern Quebec/Southern Baffin Island (and to a lesser extent a localised area on the coast of the NWT). In these areas, differences between the scenarios for

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freeze-up range up to  $\pm 16$  days (the very large values ranging up to  $\sim 100$  days in the far north are due to the different amounts of perennial ice cover). Thickness typically varied less than 10 cm between the scenarios except for Alaska, where the snow free simulations were up to 20 cm different (snow covered up to 25 cm) in the same areas of maximum differences seen in ICD. The variations in these areas are a reflection of the different patterns of temperature change between the scenarios by the time they evolve to 2041–2070. Scenario 1 shows the greatest warming over the Alaska region in the fall and winter, while scenario 2 has the greatest warming in the Quebec/Baffin region in the winter and the CAA in the fall. Higher temperatures throughout in the spring for scenario 1 would affect the break-up, and the warmer winter temperatures would lead to less ice thickening and earlier spring break-up.

Changes to northern lakes as a result of a shorter ice cover season (longer open water season) and thinner ice covers are already being seen in the Arctic and would be expected to continue. In terms of ecology, shorter and thinner ice cover durations are expected to increase the availability of under ice habitat and productivity, warmer water temperatures will result in a longer productivity period (ACIA, 2005) and increased amounts of light and UV radiation would be expected to reach the water inducing changes to the habitats and species (e.g., Reist et al., 2006). Longer open water seasons will result in change to the stratification and circulation patterns in the lakes (Wrona et al., 2005), and previously stratified perennial ice covered lakes that have changed to seasonally ice free will experience wind-driven mixing, changing the water column regime (Mueller et al., 2009). Longer open water seasons will also lead to increased evaporation from lakes, and while ponds in the High Arctic are drying out as the climate warms (Smol and Douglas, 2007) the shrinking/drying of lakes and ponds will likely be mitigated in some areas by increases in precipitation (Duguay et al., 2009).

A shortened ice covered season is also expected to have a detrimental effect on the duration and stability of the winter ice roads in Northern Canada and Alaska. Winter ice roads in Alaska's North Slope have already seen a reduced duration in some areas



from over 200 to just over 100 days since the 1970s (Hinzman et al., 2005). By mid century, Canada is predicted to lose access to 13% of the northern areas currently accessible via ice roads, while Alaska is predicted to lose access to 29%, with most of the changes occurring in April and November (Stephenson et al. 2011).

5 Gridded climate data specifically created for the arctic regions could provide more reliable predictions as most gridded data for the lower latitudes experience biases towards the far northern regions. Alternatively, the use of model ensemble data for future ice cover simulations could be beneficial as the largest source of uncertainty can come from the section of the model used (e.g., Prudhomme and Davis, 2009). Downscaling projects to examine regional changes to the future climate are underway through  
10 programs such as CORDEX: (COordinated Regional climate Downscaling Experiment, regional climate change scenarios) and high resolution climate change scenarios are being studied at NARCCAP (North American Regional Climate Change Assessment Program) to better assess the uncertainties in the various model simulations.

15 The gridded phenology maps produced herein highlight the important effects that both snow cover and lake depth have on lake ice regimes, and that snow cover tends to mitigate the changes in to the ice cover. As well, the use of the two scenarios suggests areas of the greatest uncertainty in the phenology and thickness changes, primarily the Alaska coastal areas, the Eastern CAA and the Baffin Island/northern  
20 Quebec region.

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**Table 1.** Summary of the lake ice observation data, corresponding climate station and the years used.

Lake observations (CID)	Nearby climate station (MSC)	Years	Years of ice observations BU/FU	Years of snow depth on ice
Watson Lake	Watson Lake	1961–1990	28/25	
Unnamed Lake	Sachs Harbour	1961–1986	18/18	
Unnamed Lake	Mould Bay	1961–1990	18/21	
Module Lake	Kugluktuk	1980–1990	7/9	
Back Bay	Yellowknife	1961–1990	28/27	1961–1990
Charlton Bay	Fort Reliance	1961–1990	26/29	1961–1990
Lake Athabasca	Fort Chipewyan	1968–1990	20/17	1962–1990
Beaverlodge Lake	Uranium City	1963–1982	20/16	
Ennadai Lake	Ennadai Lake	1961–1979	19/19	1961–1979
Farnworth Lake	Churchill	1961–1990	22/22	
Baker Lake	Baker Lake	1961–1990	29/29	1961–1990
Resolute Lake	Resolute	1961–1990	10/18	
Upper Dumbell Lake	Alert	1961–1990	3/24	1961–1990
Fenor Lake	Hall Beach	1961–1990	4/6	
Dewar Lakes	Dewar Lakes	1961–1990	21/23	

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**Table 2.** Ratio of snow depths measured on-ice and snow depth from the CRCM gridded data with respect to the amounts measured at the MSC weather stations.

Lake (MSC Station)	Ratio of on-ice snow depth to MSC station	Ratio of CRCM gridded snow depth to nearest MSC station	
		S 1	S 2
Back Bay, GSL (Yellowknife)	0.68	0.89	1.04
Charlton Bay, GSL (Fort Reliance)	0.48	0.80	0.88
Lake Athabasca (Fort Chipewyan)	0.41	0.83	0.83
Ennadai Lake	0.67	1.21	1.22
Baker Lake	0.09	0.85	0.81
Upper Dumbell Lake	0.82	2.34	2.35

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**Table 3.** Mean bias error in break-up and freeze-up dates for the validation sites along with the mean observed break-up and freeze-up (dates as indicated in Table 1).

Lake	Snow cover (%)	Mixing depth (m)	Break-up				Freeze-up			
			CID yd	MSC (MBE days)	S 1	S 2	CID yd	MSC (MBE days)	S 1	S 2
Watson Lake*	0 <sup>+</sup>	10	141	5	0	-2	314	1	1	2
Unnamed lake – Sachs Harbour*	100 <sup>+</sup>	3	188	1	5	4	269	1	-5	-6
Unnamed lake – Mould Bay*	100 <sup>+</sup>	2	191	13	13	16	247	2	6	2
Module Lake*	100 <sup>+</sup>	3	181	-4	-2	-6	278	-5	1	-2
Back Bay	68	10	151	-2	-3	-3	302	3	5	4
Charlton Bay	48	20	172	-14	-16	-15	321	-2	-3	-4
Lake Athabasca**	41	3	145	-9	-11	-6	339	-38	-37	-38
Beaverlodge Lake*	0 <sup>+</sup>	20	151	-4	-8	-8	329	-2	-2	-4
Ennadai Lake*	62	10	183	-14	-18	-15	295	0	6	4
Farnworth Lake	0 <sup>+</sup>	2	171	0.5	-7	-4	291	-1	2	4
Baker Lake	9	20	200	-9	-14	-13	297	0	4	1
Resolute Lake	50 <sup>+</sup>	10	212	-6	-10	0	262	-2	5	3
Upper Dumbell Lake	82	15	218 <sup>++</sup>				251	-3	9	12
Fenor Lake*	50 <sup>+</sup>	10	203	-5	-3	-5	280	-3	4	-1
Dewar Lakes*	0	10	185	20	10	10	275	-3	1	2

\* Assumed mixing depth based on most suitable fit to observations when lake depth was not available.

\*\* Freeze up simulated poorly due to hydrological factors not captured by the 1-dimensional model.

<sup>+</sup> Snow cover percentage estimated based on best fit to observations when on ice snow depth measurements not available.

<sup>++</sup> Only 3 break-up observations available.

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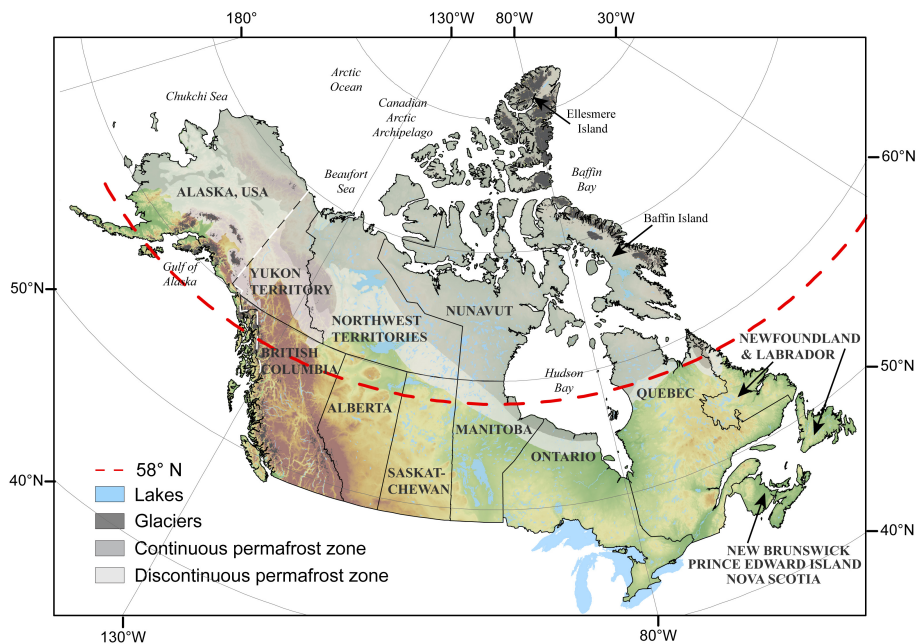
**Table 4.** Mean bias error in mean maximum thickness for the validation sites along with the mean maximum thicknesses (dates as indicated in Table 1).

Lake	Snow cover (%)	Mean maximum ice thickness (m)				MBE (m)		
		CIS	MSC	S1	S2	MSC	S1	S2
Back Bay (GSL)	68	1.32	1.23	1.54	1.50	-0.10	0.22	0.18
Charlton Bay (GSL)	48	1.28	1.36	1.60	1.62	0.09	0.32	0.35
Ennadai Lake	62	1.68	1.56	1.64	1.68	-0.12	-0.04	-0.00
Baker Lake	9	2.27	2.13	2.16	2.16	-0.14	-0.11	-0.11
Upper Dumbell Lake	82	1.96	1.90	2.51	2.48	-0.06	0.55	0.52

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**Fig. 1.** Canada with provincial and territorial boundaries and the state of Alaska (USA), highlighting the area above 58°N used for this study. Also shown are areas of permafrost and glacier.

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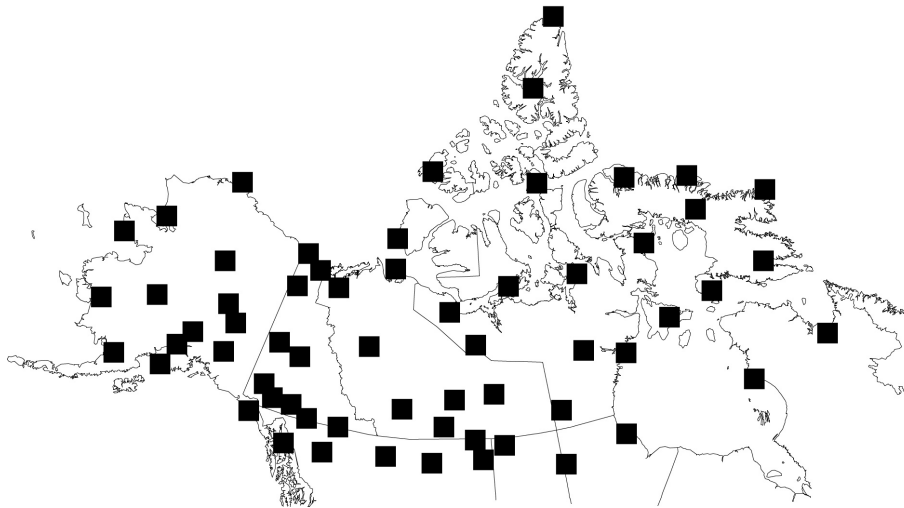
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**Fig. 2.** Locations of stations used for CRCM temperature adjustment; 15 stations within Alaska and 47 stations within Canada.

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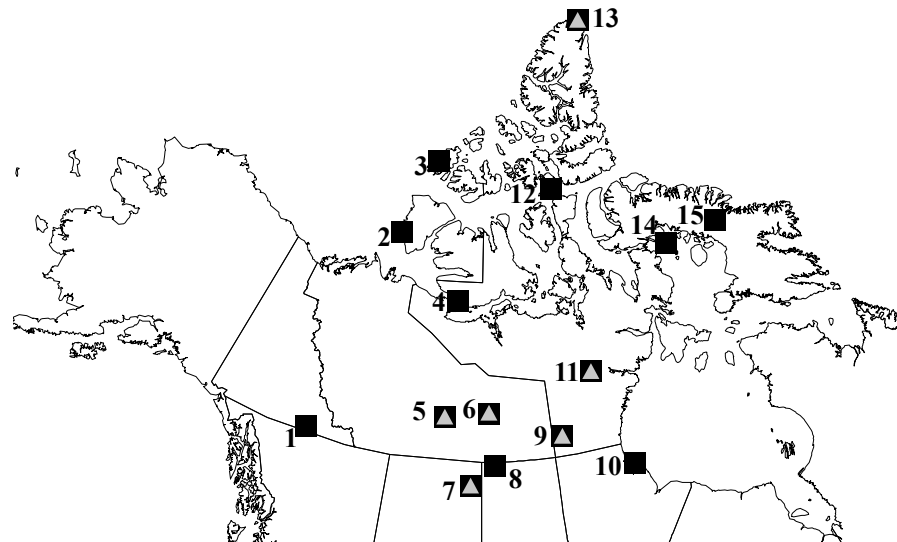
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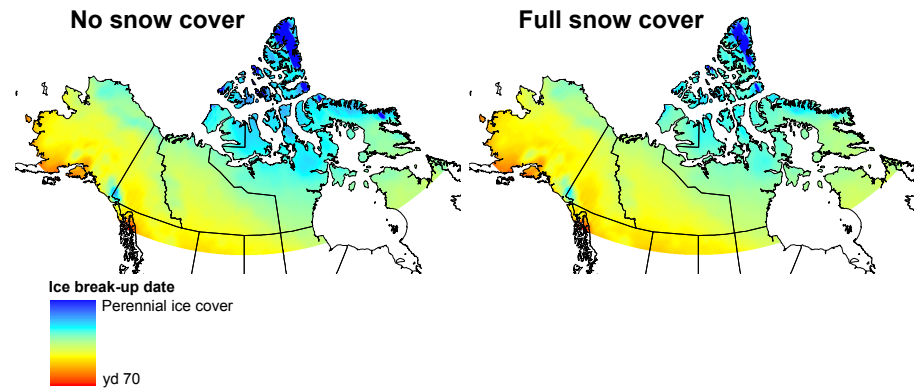
- |                                   |                        |
|-----------------------------------|------------------------|
| 1. Watson Lake                    | 9. Ennadai Lake        |
| 2. Unnamed Lake (Sachs Harbour)   | 10. Farnworth Lake     |
| 3. Unnamed Lake (Mould Bay)       | 11. Baker Lake         |
| 4. Modulo Lake                    | 12. Rolute Lake        |
| 5. Back Bay, Great Slave Lake     | 13. Upper Dumbell Lake |
| 6. Charlton Bay, Great Slave Lake | 14. Fenor Lake         |
| 7. Lake Athabasca                 | 15. Dewar Lakes        |
| 8. Beaverlodge Lake               |                        |

**Fig. 3.** Lakes used as validation sites for the model simulations. Squares represent the lakes used for ice phenology validation, triangles represent the lakes where snow depth on ice and ice thickness data was also available.

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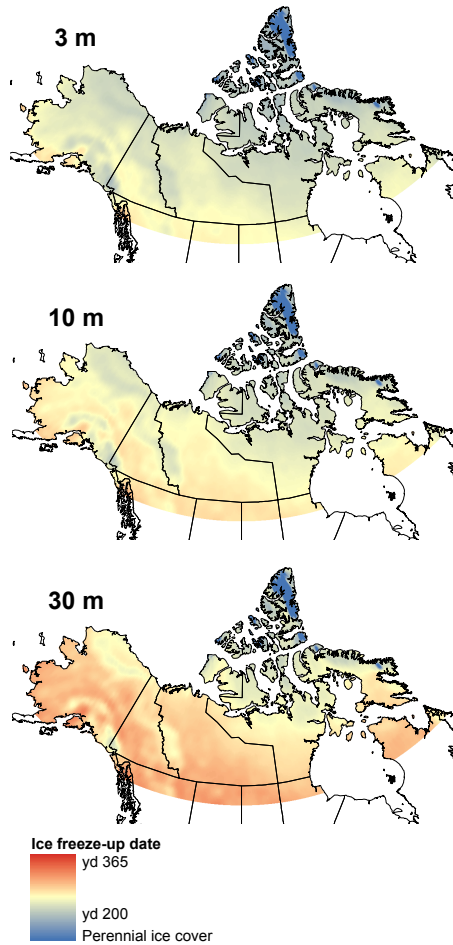


**Fig. 4.** Mean simulated break-up dates for 1961–1990 for hypothetical 10 m lakes, for both no snow and full snow scenarios.

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**Fig. 5.** Mean freeze-up dates for 1961–1990 for the three depth simulations, highlighting the effect of depth on freeze-up dates.

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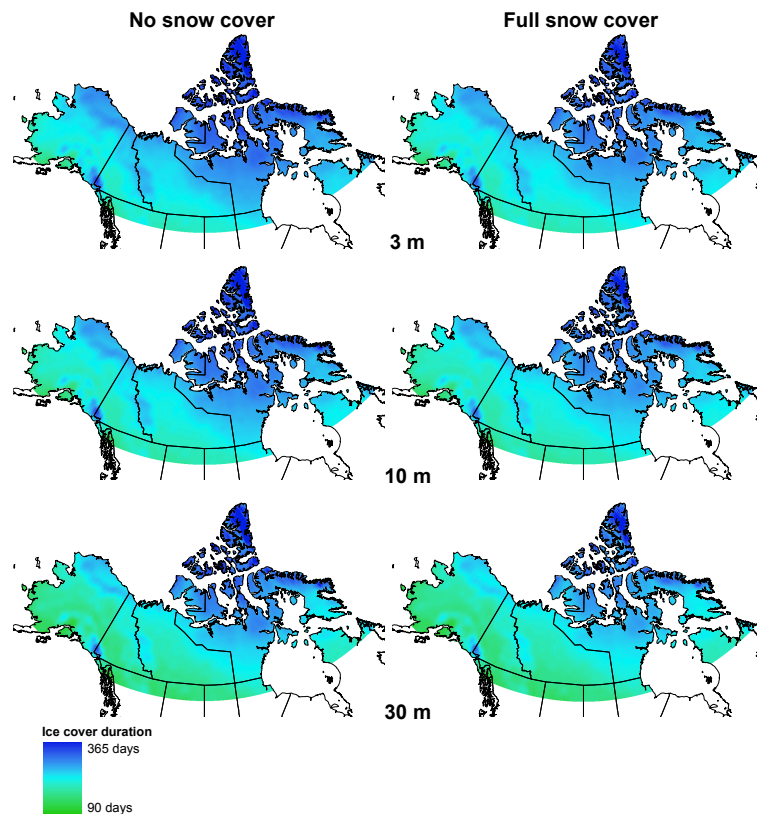
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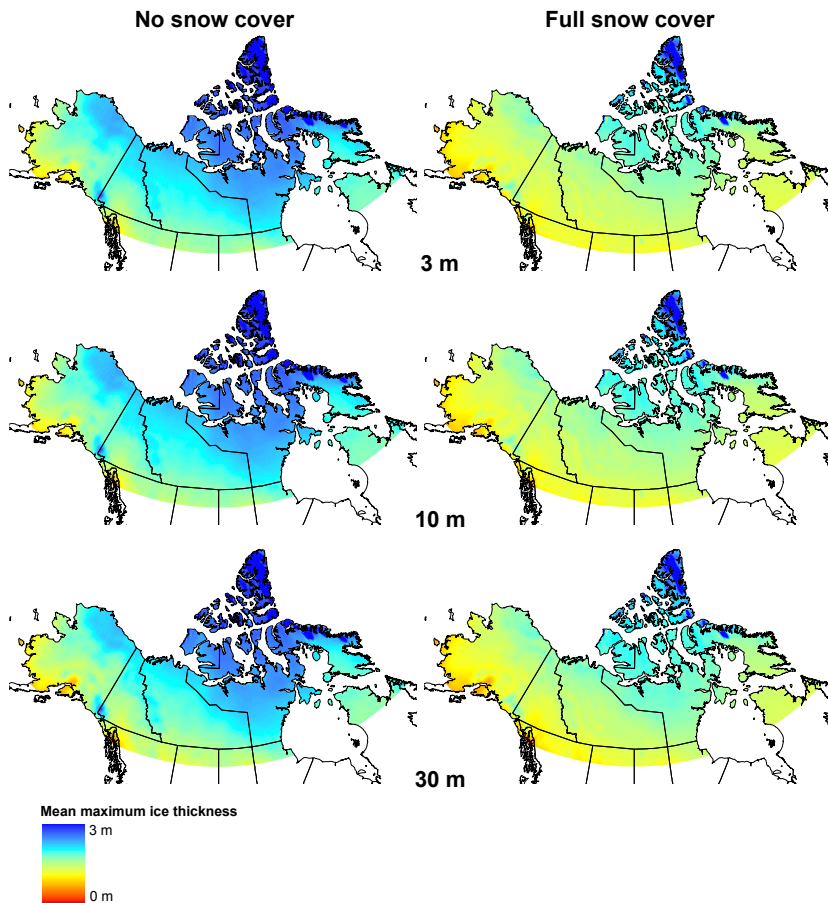
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**Fig. 6.** Mean ice cover duration for 1961–1990 for the three depth simulations, for both the no snow and full snow scenarios.

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**Fig. 7.** Mean maximum ice thickness for 1961–1990, for three depth simulations, and both the no snow and full snow scenarios. Ice thickness capped at 3 m in areas where perennial ice cover growth continued due to the model structure of CLIMo.

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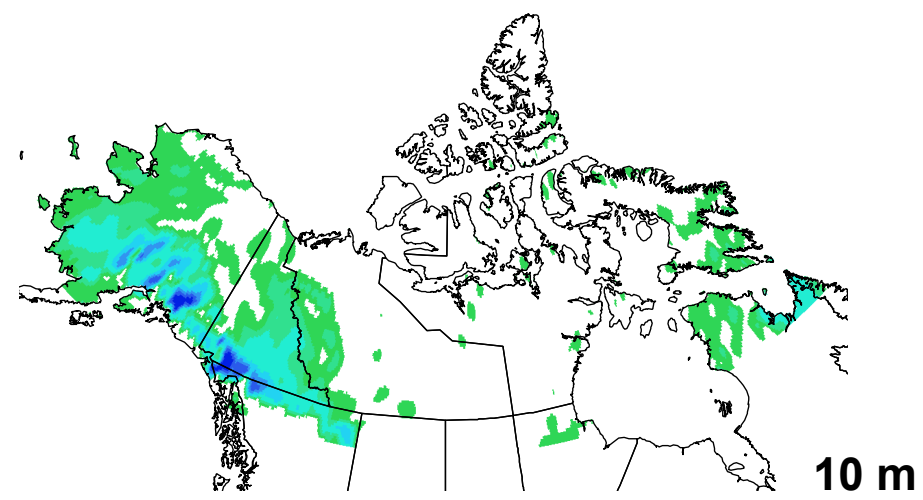
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








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**Ratio of snow ice thickness to total ice thickness**

 <1%	 20 - 30 %
 1 - 5 %	 30 - 40 %
 5 - 10 %	 40 - 50 %
 10 - 20 %	 >50 %

**Fig. 8.** Ratio of mean snow ice thickness to mean maximum ice thickness for 1961–1990.

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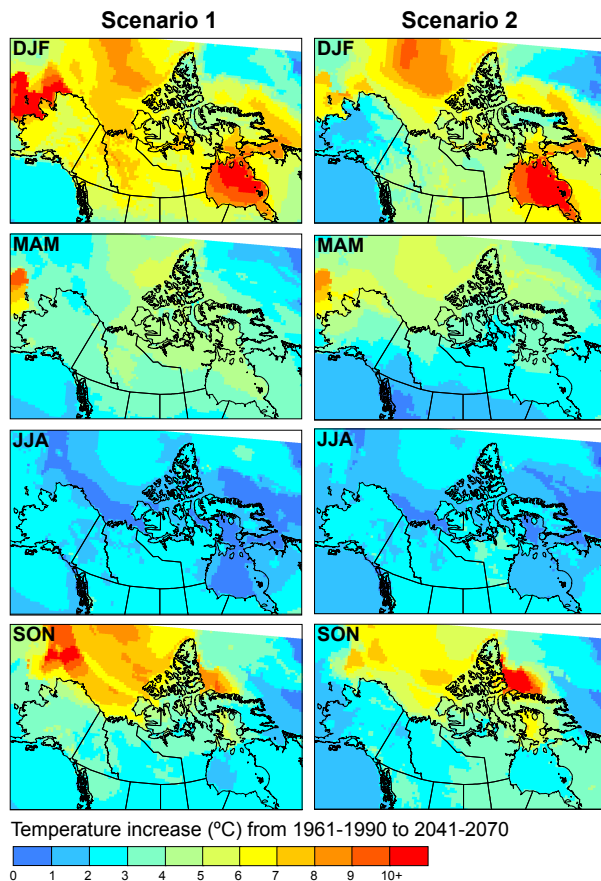
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**Fig. 9a.** Increase in air temperature from 1961–1990 mean to 2041–2070 mean from the CRCM data displayed by season winter (December–February), spring (March–May), summer (June–August) and fall (September–November).

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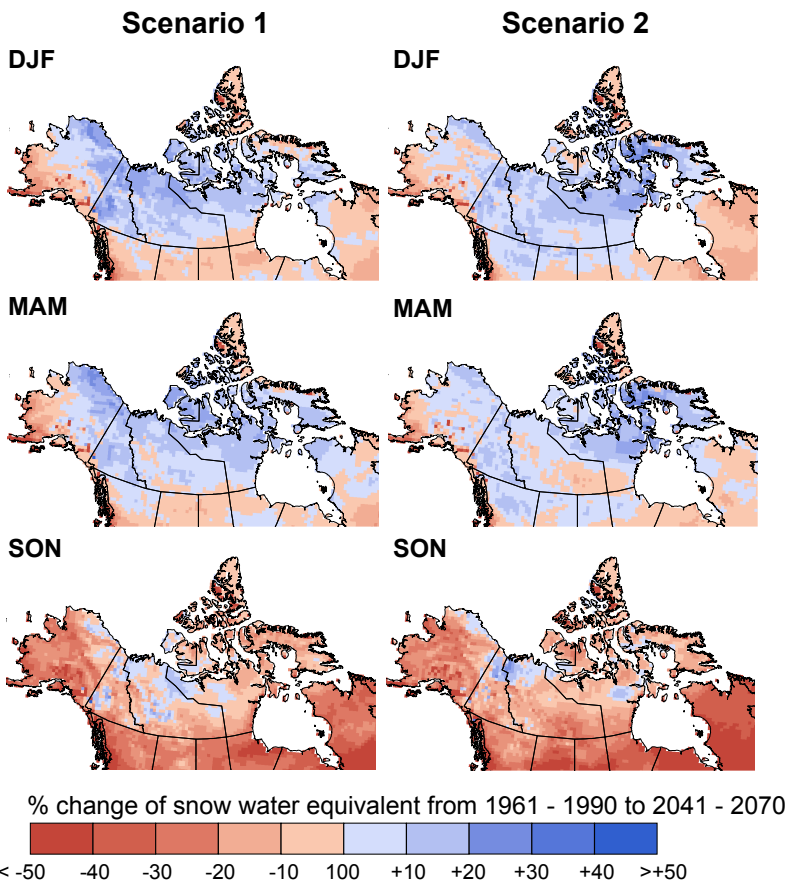
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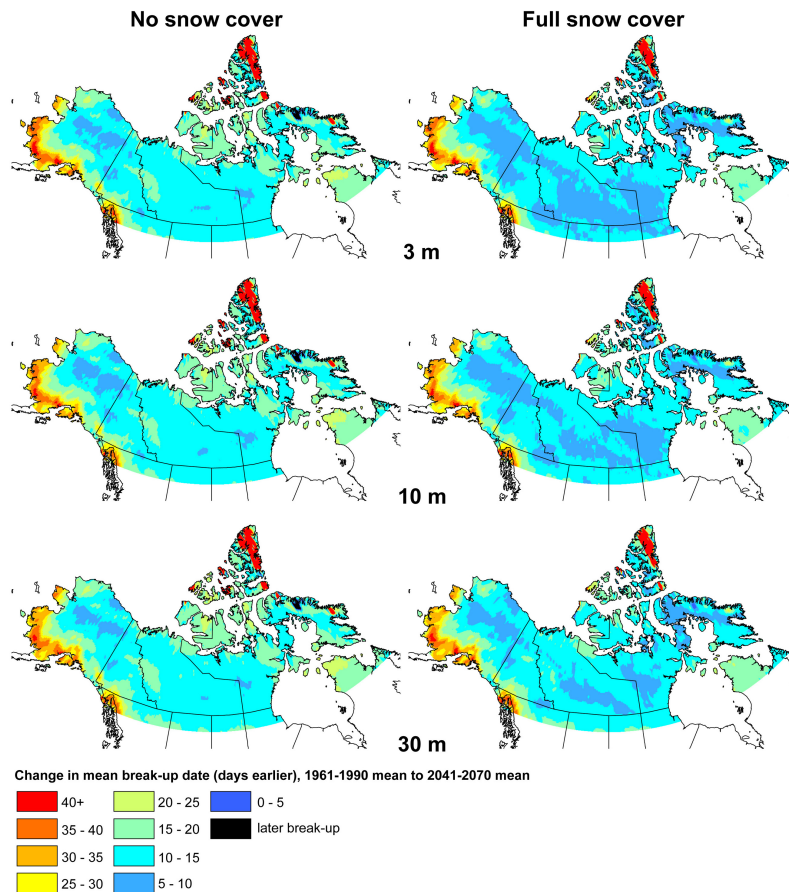


**Fig. 9b.** Change in snow water equivalent from 1961–1990 mean to 2041–2070 mean from the CRCM data displayed by season winter (December–February), spring (March–May) and fall (September–November).

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### a) Scenario 1



**Fig. 10.** Change in mean break-up date from 1961–1990 to 2041–2070 for **(a)** scenario 1; **(b)** scenario 2; **(c)** the difference between the scenarios for the 2041–2070 mean break-up dates.

b) Scenario 2

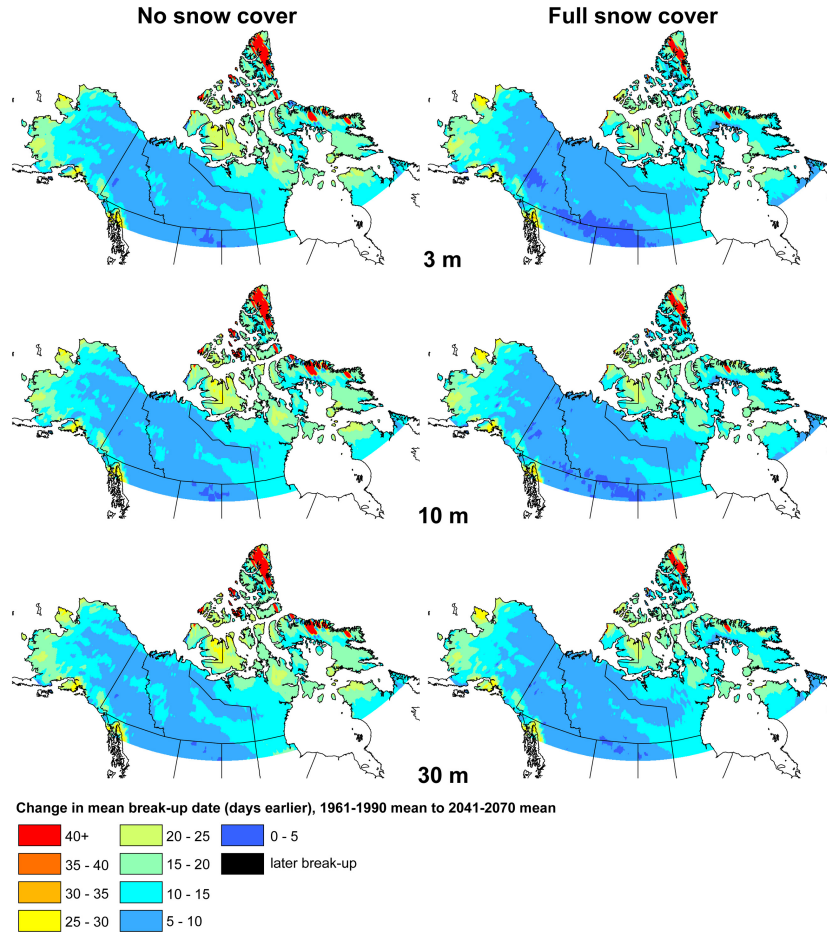


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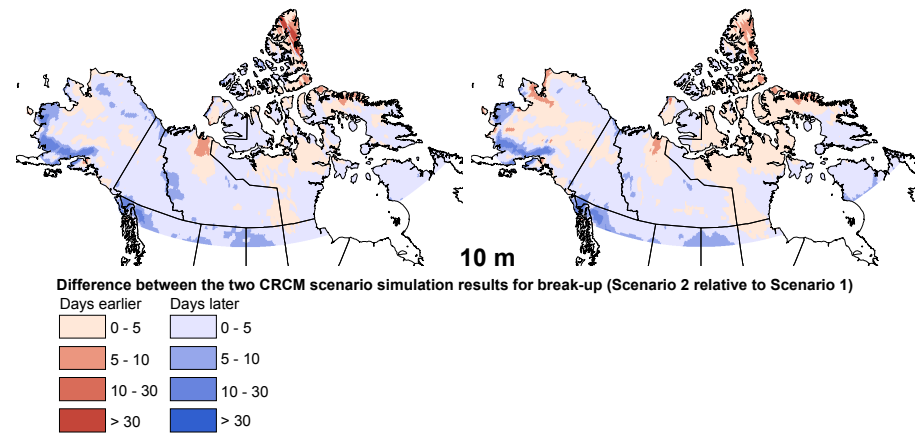


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**c) Scenario differences**

**No snow cover**



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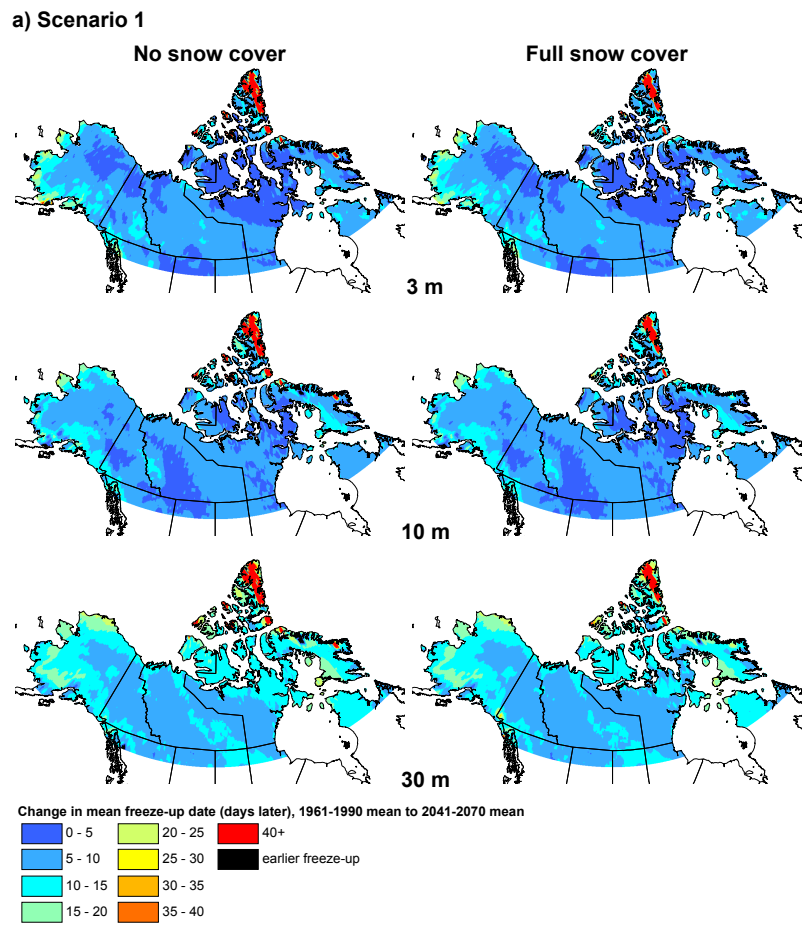
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**Fig. 11.** Change in mean freeze-up date from 1961–1990 to 2041–2070 for **(a)** scenario 1; **(b)** scenario 2; **(c)** the difference between the scenarios for the 2041–2070 mean freeze-up dates.

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b) Scenario 2

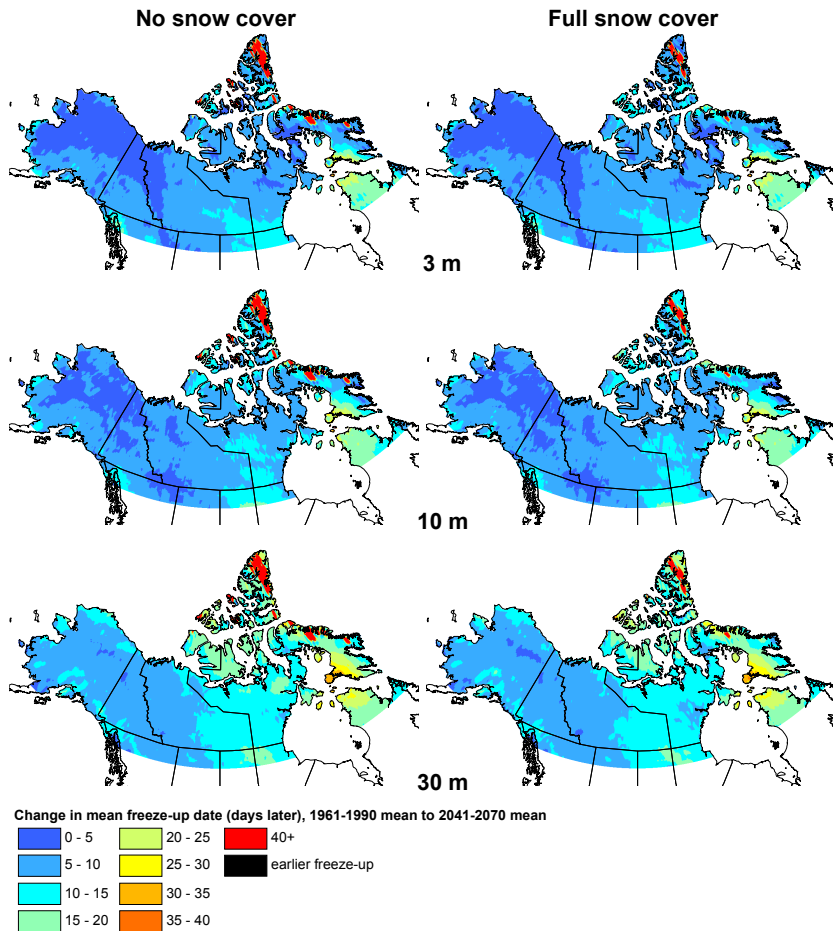


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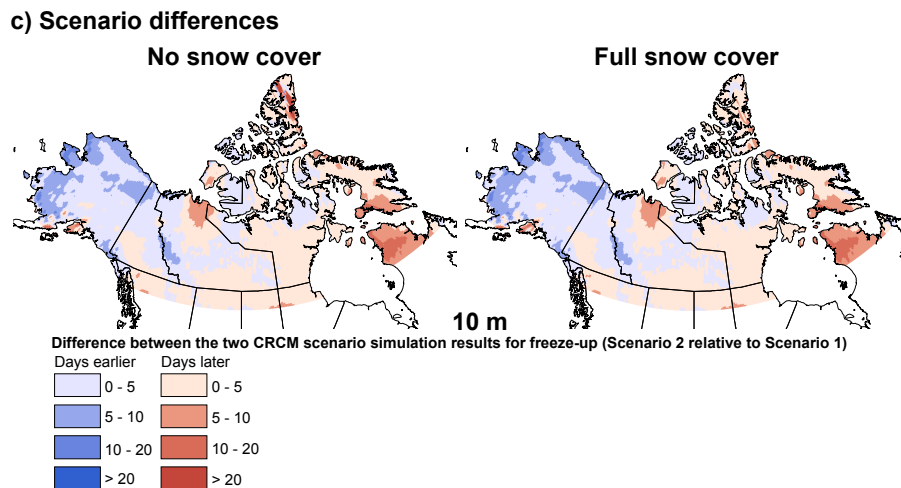
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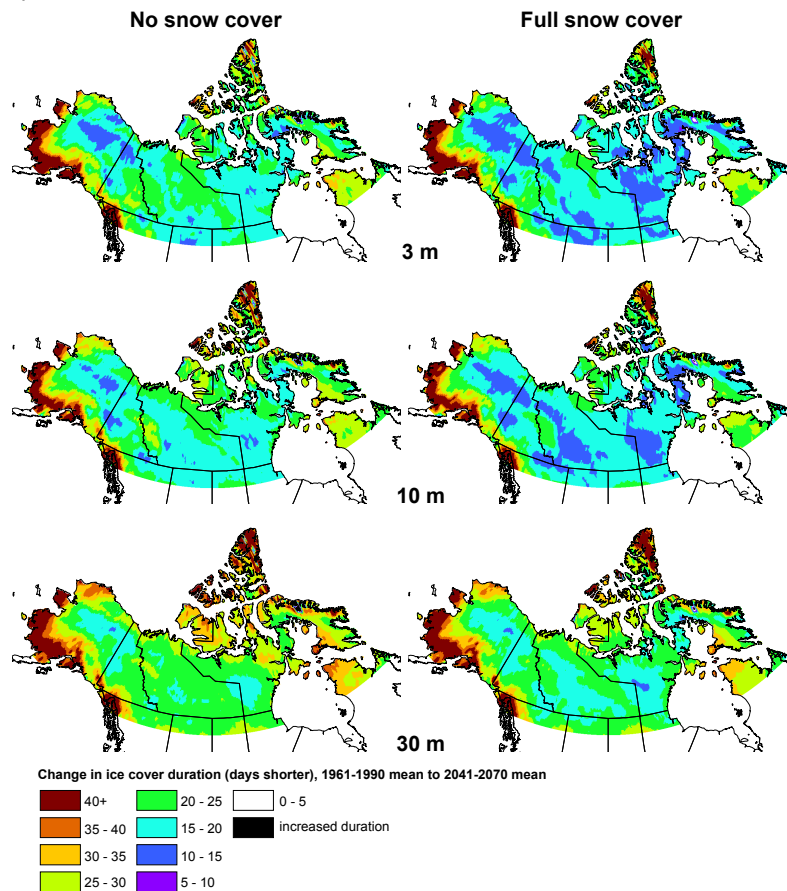
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### a) Scenario 1



**Fig. 12.** Change in mean ice cover duration from 1961–1990 to 2041–2070 for **(a)** scenario 1; **(b)** scenario 2; **(c)** the difference between the scenarios for the 2041–2070 mean ice cover duration.

b) Scenario 2

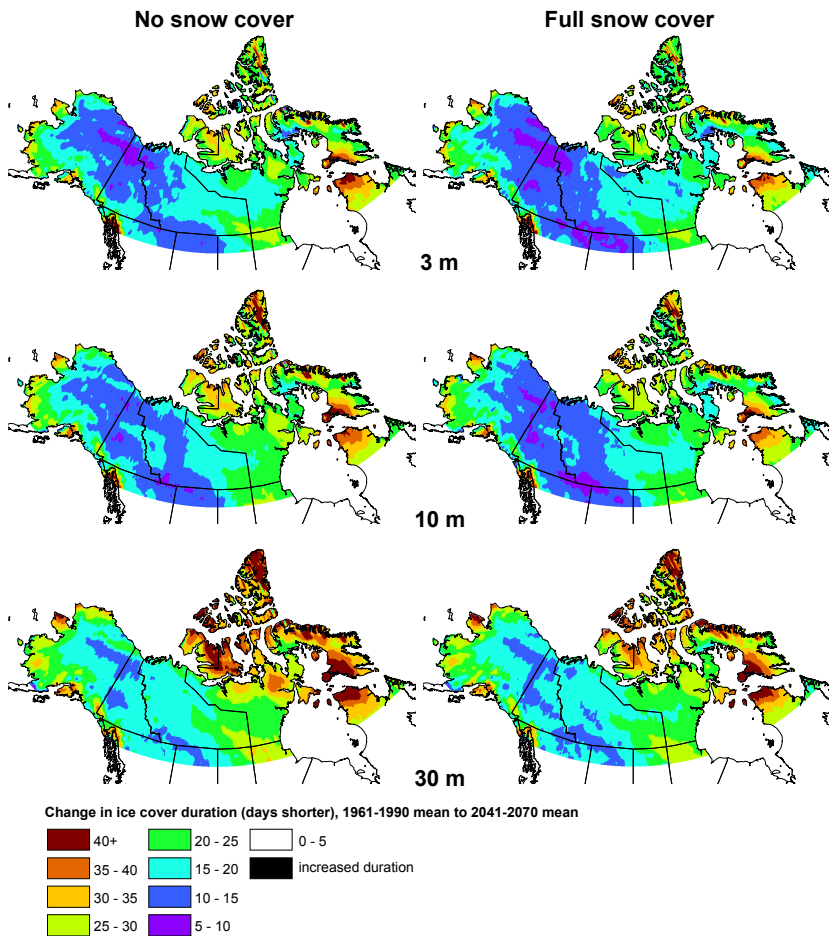


Fig. 12. Continued.

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### c) Scenario differences

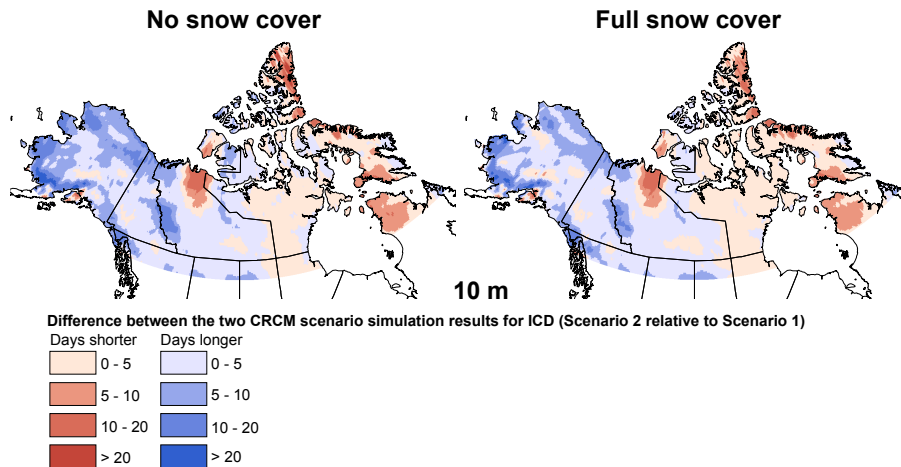


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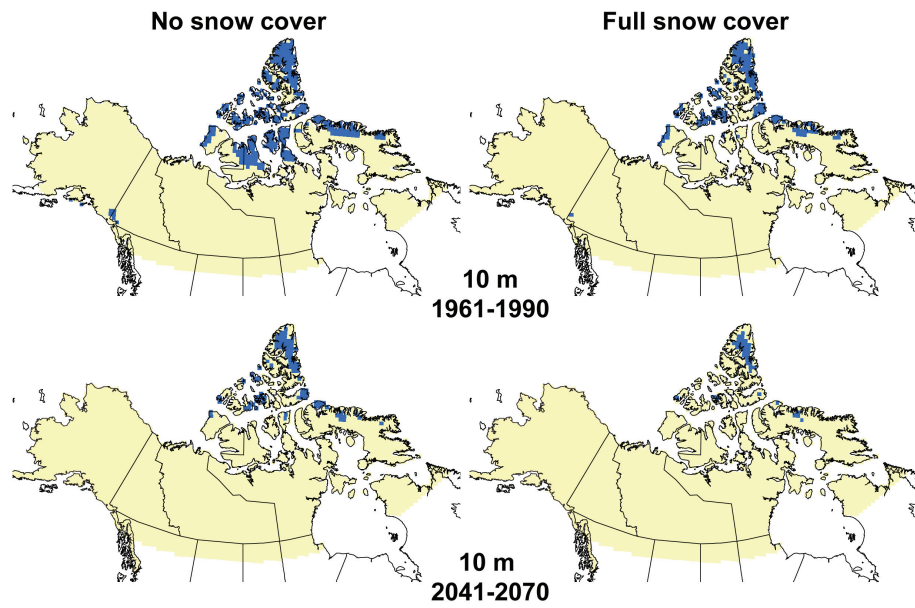
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**Fig. 13.** Area of occasional summer ice (including perennial ice cover) and the change from 1961–1990 to 2041–2070. Scenario 1, 10 m lakes shown.

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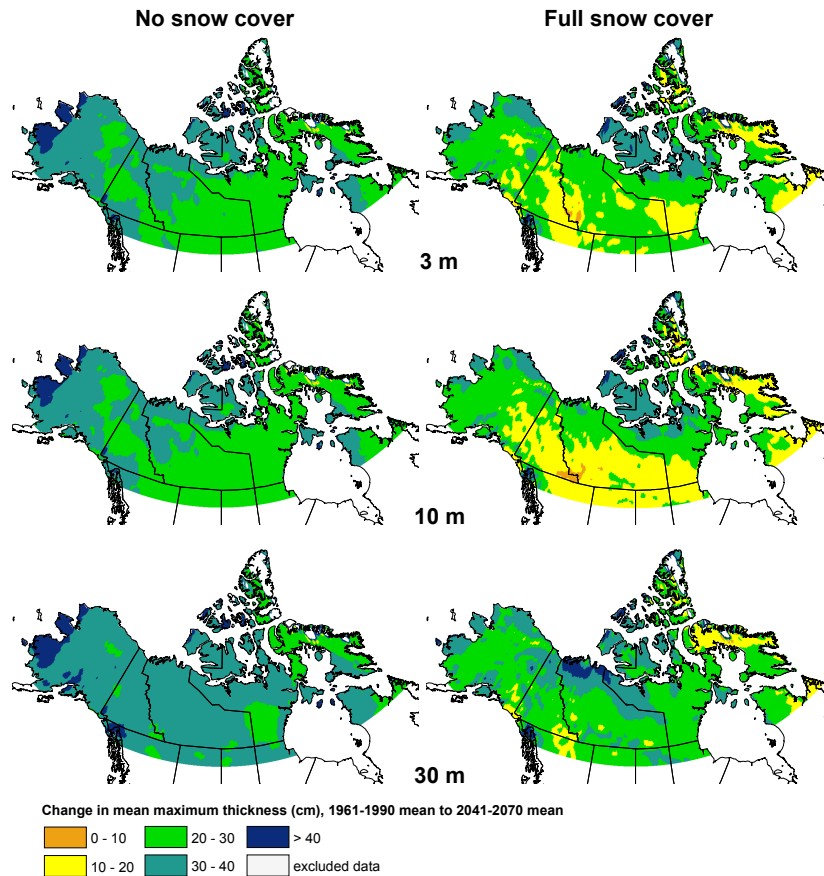




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### a) Scenario 1



**Fig. 14.** Change in mean maximum thickness 1961–1990 to 2041–2070 for **(a)** scenario 1; **(b)** scenario 2; **(c)** the difference between the scenarios for the 2041–2070 mean maximum thickness.

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b) Scenario 2

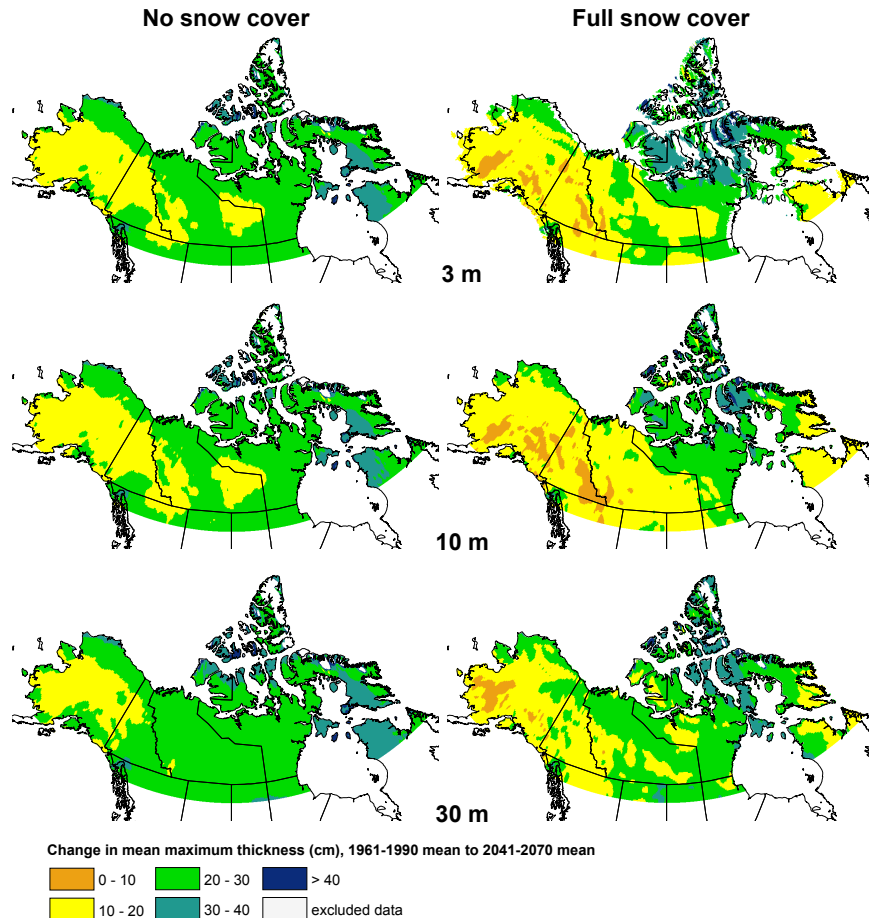


Fig. 14. Continued.

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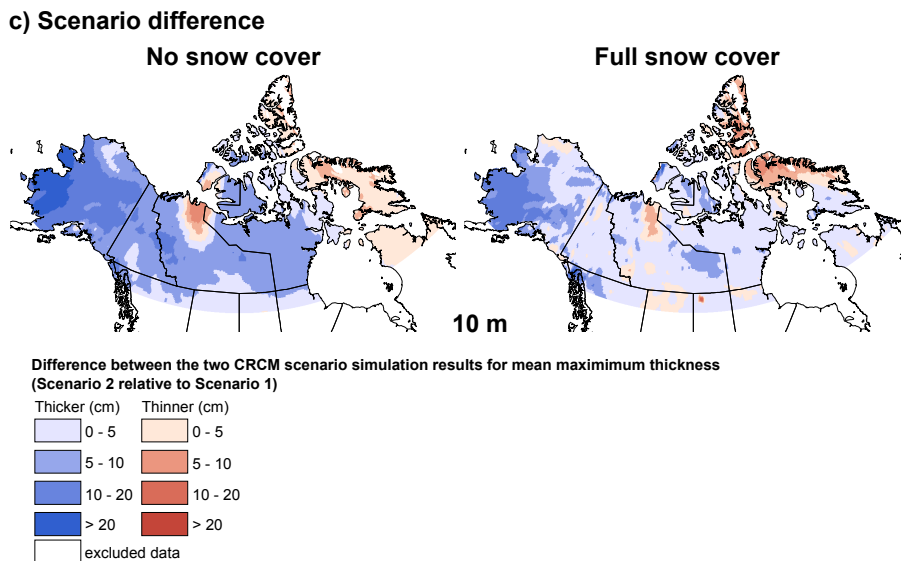
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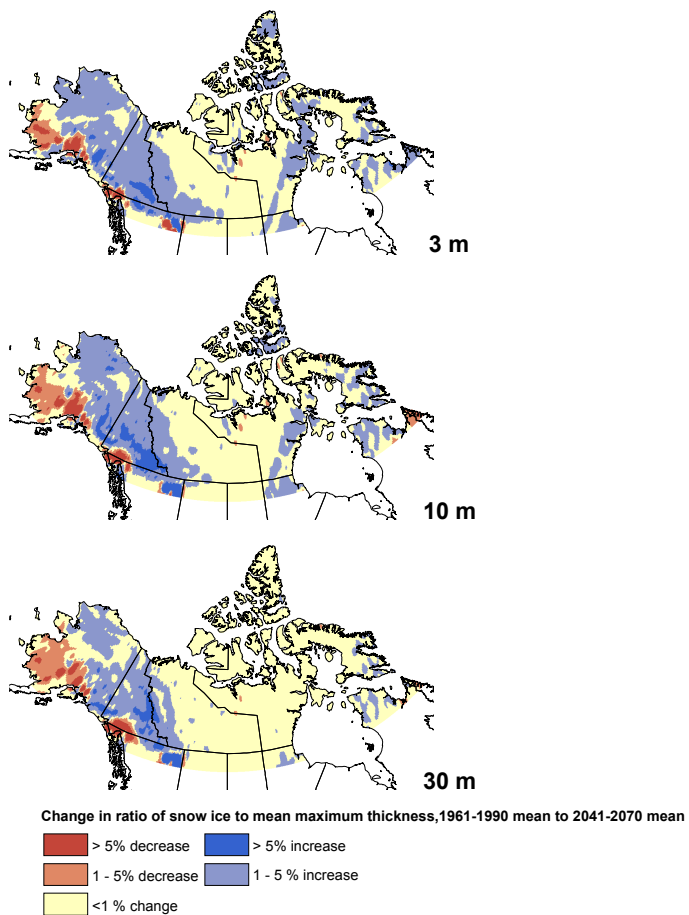
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**Fig. 15.** Change in snow ice thickness to total ice thickness from 1961–1990 to 2041–2070 mean.

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