Future Projections of Landfast Ice Thickness and Duration in the Canadian Arctic

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(Manuscript received 31 May 2005, in final form 2 December 2005)

ABSTRACT

Projections of future landfast ice thickness and duration were generated for nine sites in the Canadian Arctic and one site on the Labrador coast with a simple downscaling technique that used a one-dimensional sea ice model driven by observationally based forcing and superimposed projected future climate change from the Canadian Centre for Climate Modelling and Analysis global climate model (CGCM2). For the Canadian Arctic sites the downscaling approach indicated a decrease in maximum ice thickness of 30 and 50 cm and a reduction in ice cover duration of 1 and 2 months by 2041–60 and 2081–2100, respectively. In contrast, there is a slight increase in simulated landfast ice thickness and duration at Cartwright in the future due to its sensitivity to snow–ice formation with increased snowfall and to a projected slight cooling over this site (along the Labrador coast) by CGCM2. The magnitude of simulated changes in freeze-up and break-up date was largest for freeze up (e.g., 52 days later at Alert by 2081–2100), and freeze-up date changes exhibited much greater regional variability than break up, which was simulated to be 30 days earlier by 2081–2100 over the Canadian Arctic sites.

1. Introduction

Results from models participating in the Coupled Model Intercomparison Project show a change in ice thickness in the central Arctic of roughly 1 m as a consequence of transient doubling of CO₂, with an inter-model standard deviation of 0.5 m (Flato and Participating CMIP Modelling Groups 2004). Walsh and Timlin (2003) examined the projected sea ice extent change in several of these models and found that, although the model results suggest essentially ice-free summer conditions for much of the Arctic marginal seas, the Canadian Arctic Archipelago (CAA) and north coast of Greenland are expected to retain year-round ice cover through the twenty-first century. Although none of these coupled models resolves the CAA explicitly, there is some expectation (e.g., Brass 2002) that the Northwest Passage through the CAA will have a sufficiently long open water season as to be navigable by non-ice-breaking ships some time during this century. On the other hand, the presence of first-year ice is thought to control the amount of multiyear ice floes and icebergs that enter the archipelago (Corell et al. 2004; Jeffers et al. 2001). Therefore, longer melting seasons may lead to an increased amount of thick multiyear ice floes and icebergs moving into the archipelago from the Arctic basin.

A reduction in the duration of the ice could also have an impact on the marine mammals and subsistence lifestyle of the local residents. Local people have observed a reduction in the numbers of ringed seal pups, which is of concern as they are one of their main food sources. They attribute this reduction to less stable and reduced sea ice in recent decades (Corell et al. 2004). Reduced thickness and duration of the landfast ice also affects their access to hunting and fishing camps (Corell et al. 2004).
More accurate projections of future sea ice conditions in the CAA are therefore desirable, but are not possible with existing global climate models, which are unable to resolve the small islands and narrow waterways in the CAA. Here we use a detailed one-dimensional landfast ice model (Flato and Brown 1996) to simulate historical variations in landfast ice for several locations within the CAA where suitable meteorological data and sea ice observations are available. Further, we use this model to make projections of future landfast ice behavior by forcing the model with a future climate change scenario provided by the Canadian global climate model (Flato et al. 2000; Boer et al. 2000a,b; Flato and Boer 2001). This approach allows the fidelity of the landfast ice model to be evaluated using historical data, and allows for future projections of quantities (like landfast ice conditions) not explicitly included in the global climate model. This is, in essence, a type of regional climate “downscaling.”

2. Historical data and future climate

Ten stations were selected for this study that have relatively long periods of weekly ice thickness and on-ice snow depth measurements and corresponding synoptic or hourly meteorological observing programs. The stations are shown in Fig. 1 and include Alert, Eureka, Mould Bay, Resolute, Clyde, Cambridge Bay, Hall Beach, Iqaluit, Coral Harbour, and Carwright. These stations cover a wide range of landfast ice climates (Table 1) and have more or less continuous weekly fast ice thickness observations covering the 32-yr period from 1959 to 1990. Fast ice thickness along with derived quantities, such as break-up and freeze-up dates, are archived at the Canadian Ice Services. These observations have been made regularly (usually weekly) at a number of locations across Canada since the 1950s. The measurement program was terminated in 2000 for cost reasons, but a network of 10 sites was reopened in 2001/02. Further details of the dataset are provided by Brown and Cote (1992; and are available on the Canadian Ice Service Web site at http://iceglaces.ec.gc.ca, see Ice Archive).

a. Historical runs and model description

The landfast ice model was driven with daily averaged values of surface air temperature (SAT), wind speed, cloud amount, relative humidity, and snowfall rate. Daily average values are sufficient to capture the seasonal and interannual variability in maximum fast ice thickness. Use of higher frequency (i.e., hourly) forcing data has been explored previously by Hanesiak et al. (1999), and the results indicate little difference in simulated ice thickness, some small changes in freeze-up and break-up dates, but no obvious overall improvement in the simulation results. Hourly and synoptic cli-
mate data were obtained from the Canadian Climate Archive of the Meteorological Service of Canada and daily averaged series of SAT, wind speed, cloud amount, and relative humidity assembled for the period from 1959 to 1990. Missing values were replaced with the corresponding daily mean value. The 20-yr period 1970–89 was selected for analysis to correspond to the definition of the “current climate” in the Canadian Centre for Climate Modelling and Analysis (CCCma) global climate model (CGCM2).

The provision of a snowfall rate to the model is not straightforward since the evolution of the on-ice snow cover is related more to wind redistribution of snow than snowfall events (Brown and Cote 1992). In addition, measuring snowfall and solid precipitation in high-latitude locations is complicated by wind-induced undercatch and frequent trace events (Goodison et al. 1998). The method used in this paper follows that of Flato and Brown (1996) where a mean daily snow depth accumulation rate (m day$^{-1}$) is derived from a linear fit to the observed on-ice weekly snow depth data during each snow accumulation season. A linear model was chosen as this was found to closely approximate the on-ice snow cover at most of the sites (see Fig. 2 for Alert as an example). The snow depth accumulation rate is converted to a mass flux in the model assuming a fixed density of 330 kg m$^{-3}$ when the snow layer temperature is below freezing and 450 kg m$^{-3}$ during the melting period (based on observations). This method is less successful at replicating the on-ice snow-pack at Cartwright where winter precipitation is more episodic and the snow accumulation season is shorter. We therefore use daily snowfall rates as forcing at Cartwright. We also use a lower snow density (200 kg m$^{-3}$), more appropriate to fresh snow, when the air temperature is below freezing. This Cartwright run will be referred to as Cartwright B. The former run, with similar snowfall forcing and snow density to all other stations, will be referred to as Cartwright A. It is included for comparison with Cartwright B.

The 1D sea ice model includes snow ice formation wherein surface ice growth occurs when there is enough snow to suppress the ice surface below water level. Although the model includes this process, snow-ice formation is relatively uncommon in the Arctic in comparison to the Antarctic (Jeffries et al. 2001; Massom et al. 2001; Powell et al. 2005). The surface albedo is computed at each time step and is dependant on the presence of surface snow, the surface temperature, and ice thickness. For surface temperatures below freezing, the snow albedo is set to 0.75, and the ice albedo ($\alpha$) is calculated according to Maykut (1982): $\alpha = (0.44H^{0.23}) + 0.08$, where $H$ is the ice thickness (m). A limit is set on the ice albedo so that it does not go below the value specified for open water (0.15). If the surface temperature is equal to or above freezing, the snow albedo is set.

### Table 1. Observed and simulated mean maximum ice thickness, standard deviation (σ), and correlation coefficient, $r$, at all stations over the period 1970–89. Bold correlations are significant at the 95% level. Stations are listed in order of decreasing latitude.

<table>
<thead>
<tr>
<th>Stations</th>
<th>Observed</th>
<th>σ</th>
<th>Simulated</th>
<th>σ</th>
<th>$r$</th>
</tr>
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<tbody>
<tr>
<td>Alert*</td>
<td>1.90</td>
<td>0.20</td>
<td>2.13</td>
<td>0.16</td>
<td>0.74</td>
</tr>
<tr>
<td>Eureka</td>
<td>2.28</td>
<td>0.18</td>
<td>2.42</td>
<td>0.17</td>
<td>0.53</td>
</tr>
<tr>
<td>Mould Bay</td>
<td>2.00</td>
<td>0.19</td>
<td>2.03</td>
<td>0.19</td>
<td>0.63</td>
</tr>
<tr>
<td>Resolute</td>
<td>1.99</td>
<td>0.25</td>
<td>2.09</td>
<td>0.25</td>
<td>0.60</td>
</tr>
<tr>
<td>Clyde</td>
<td>1.71</td>
<td>0.24</td>
<td>1.96</td>
<td>0.24</td>
<td>0.82</td>
</tr>
<tr>
<td>Cambridge Bay</td>
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<td>0.20</td>
<td>2.33</td>
<td>0.10</td>
<td>0.62</td>
</tr>
<tr>
<td>Hall Beach</td>
<td>2.12</td>
<td>0.26</td>
<td>2.13</td>
<td>0.16</td>
<td>0.24</td>
</tr>
<tr>
<td>Iqaluit</td>
<td>1.72</td>
<td>0.22</td>
<td>1.79</td>
<td>0.18</td>
<td>0.86</td>
</tr>
<tr>
<td>Coral Harbour</td>
<td>1.83</td>
<td>0.15</td>
<td>1.97</td>
<td>0.14</td>
<td>0.78</td>
</tr>
<tr>
<td>Cartwright A</td>
<td>1.12</td>
<td>0.21</td>
<td>0.88</td>
<td>0.10</td>
<td>0.21</td>
</tr>
<tr>
<td>Cartwright B</td>
<td>1.12</td>
<td>0.21</td>
<td>1.08</td>
<td>0.23</td>
<td>0.32</td>
</tr>
</tbody>
</table>

* Data missing for the 1988 season.
to 0.65, and the ice albedo is calculated according to Heron and Woo (1994), $\alpha = 0.075H^2 + 0.15$, with an upper limit of 0.55. This approximates the process of melt-pond formation as the melt season progresses.

Incoming solar radiation was estimated using the method of Shine (1984) and incoming longwave radiation from Maykut and Church (1973). Oceanic heat flux was assumed to be zero as the measurement sites are typically located in shallow waters in bays and inlets. The depth of the mixed layer was chosen at each station to reproduce most closely the average historical ice freeze-up date (cf. Flato and Brown 1996).

b. 2041–60 and 2081–2100 projections

To make projections of the future seasonality and ice thickness in the CAA we make use of future climate change scenarios produced by the CCCma coupled global climate model. The original version of this model and its climatology were described by Flato et al. (2000). Its projection of historical and future climate change, assuming a particular scenario of increasing greenhouse gas and aerosol forcing, are documented in Boer et al. (2000a,b). Here we use the results of an updated version of the CCCma model, CGCM2, which is described briefly in Flato and Boer (2001). These data are available from the CCCma Web site (online at http://www.cccma.bc.ec.gc.ca). Because CGCM2 does not explicitly resolve the detailed geography of the CAA, its simulated climate necessarily has local biases. To account for this, we apply a conventional climate downscaling technique (e.g., Hulme et al. 1999) in which the change in a particular quantity, projected by CGCM2, is combined with the observed historical climatology. Methods like this have previously been used with CGCM2 data (e.g., Saenko et al. 2001) and are described in more detail below.

For surface air temperature we use

$$X_2(t) = X_1(t) + (\overline{C}_2 - \overline{C}_1),$$

where $t$ is time in days, $\overline{C}$ is the climatological daily mean obtained from a 20-yr segment of the CGCM2 climate simulation, and subscripts 1 and 2 represent contemporary (1970–89) and future (either 2041–60 or 2081–2100) time periods, respectively. For all other meteorological variables we use a ratio, rather than adding the change, to avoid negative values:

$$X_2(t) = (\overline{C}_2/\overline{C}_1)X_1(t).$$

In both equations, $X$ is the meteorological quantity being modified and, without an overbar, it is a time series of daily values (except in the case of snowfall where it is the annual snowfall rate). For snow accumulation rate $C_2$ and $C_1$ are the mean precipitation for the ice growth season only (September–May), as opposed to the climatological daily means; $X_1$ is the observed time series, while $X_2$ is the future scenario. Further criteria are set for cloud amount and relative humidity so that they do not exceed 1 and 100%, respectively. Experiments using this forcing will be referred to as “scenario 1” hereafter.

The above method produces a “future” time series of meteorological forcing that has the same daily variability that was inherent in the historical observations. There is no particular reason to expect that variability in the future climate will be the same as in the past; however, it is not obvious how best to impose a prescribed change in climate variability. To get a hint of the potential sensitivity to changes in variability, we construct a second forcing scenario (scenario 2) in which the historical variability is replaced by the variability projected by the climate model for the future. In this case we construct the forcing as follows:

$$X_2(t) = \overline{X}_1 + (\overline{C}_2 - \overline{C}_1) + (C_2(t) - \overline{C}_2).$$

Equation (3) can be simplified as $X_2(t) = C_2(t) + \overline{X}_1 - \overline{C}_1$. Then

$$X_2(t) = (\overline{C}_2/\overline{C}_1)X_1 + (C_2(t) - \overline{C}_2).$$

In this case, $C_2(t)$ is the daily time series of the meteorological quantity produced by the climate model for the future period. As before, $X_2$ is constrained so that negative values are not produced.

3. Current climate simulations and future projections of landfast ice

In the following, we focus on the annual maximum ice thickness and the ice cover duration as indicators of landfast ice conditions. Ice duration is calculated as the time between the freeze-up and break-up dates. To provide results from the model that are reasonably consistent with practical considerations, the ice freeze-up date is defined as the day when the ice thickness increases to 30 cm, when ice might be considered safe to walk on; whereas, the ice break-up is defined as the day the ice thickness decreases to 50 cm, reflecting the notion that once the ice has decreased to 50 cm, dynamic effects become important for the final stages of deterioration.

a. Current climate

Although the snowfall forcing is derived from snow depth observations, we specify a constant annual snowfall rate rather than representing each precipitation
event. As discussed in section 2, this method is successful at all stations except for Cartwright A (Fig. 3) owing to very episodic precipitation at this station. We therefore use the run with daily snowfall rate (Cartwright B) for the rest of this study.

The simulated annual cycle of snow and ice are in good agreement with the observations. The interannual variability in ice thickness also agrees quite well overall, although there are some years when the simulations deviate noticeably from the observations (Fig. 4).
Fig. 4. Modeled and observed (weekly) ice thickness and on-ice snow depth at the 10 stations from 1979 to 1989.
some cases (e.g., Hall Beach in 1983, 1984, and 1987) the differences are due to measurements not being made consistently on the same area of first-year ice. At Cartwright B there are a few years when the simulated ice is too thin (e.g., 1975, 1979, 1987) and one year when the ice is too thick (1974).

Table 1 shows the mean observed and simulated maximum ice thickness, standard deviations, and correlation coefficients at all stations. The simulations seem to slightly overestimate the ice thickness, except at Cartwright B, where it is slightly underestimated. The reduced snow density in this run allows more snow to accumulate on the ice before surface submergence occurs. Because of the insulating effect of snow, the ice growth is delayed. Surface growth, through snow-ice formation, is important at Cartwright B, whereas it does not occur in significant amounts at any of the other stations. Cartwright, our most southerly station, has thinner ice and significantly thicker snow than the other stations (as shown in Fig. 4). It receives an average of 440 cm of snowfall per year (1951–80 average), which is about a factor of 4 higher than stations in the CAA. It therefore seems reasonable that snow-ice formation would be relevant only at Cartwright B, owing to the greater snow/ice ratio.

The correlations between observations and simulations are significant at all stations with the exception of Hall Beach and Cartwright. The Hall Beach result is not surprising in light of the previously mentioned problem with the thickness observations. The difficulties simulating interannual variability in maximum ice thickness at Cartwright are related to a shorter ice season, thinner ice, and a higher and more variable snowfall regime than the more northern sites.

Observed and simulated ice duration means, standard deviations, and correlation coefficients are shown in Table 2. Only six of the stations have significant correlations, which is a reflection of the greater noise in subjective visual reports of ice-on and ice-off dates, as well as the assumptions and simplifications related to freeze-up and break-up processes in the model. The spatial pattern of modeled maximum ice thickness and duration is shown in Fig. 5. The thickest ice is found near Eureka, the coldest station in all seasons but summer; this is followed by Hall Beach and Cambridge Bay. As expected, the most northerly stations have the longest ice duration, a consequence of shorter sunlight duration, lower solar elevation angle, and lower mean temperatures.

\section*{b. Future scenarios}

When the landfast ice model is driven by future scenario forcing (scenario 1) there is, as expected, a general decline in ice thickness and a reduction in ice cover duration (i.e., longer open water season) as the climate warms. Figure 6 compares the annual cycle of ice thickness for the periods of 1970–89, 2041–60, and 2081–2100. Cartwright is the exception to this general pattern in that the ice thickens slightly and persists longer in both periods (2041–60 and 2081–2100). This region exhibits a cooling trend in the early twenty-first century in the CGCM2 projection as a consequence of reduced deep ocean convection (e.g., Flato and Boer 2001; Cubasch et al. 2001), which is reminiscent of observed changes in Baffin Bay in the later part of the twentieth century (e.g., Jones and Moberg 2003). Moreover, due to its relatively thinner ice, this region is sensitive to snow-ice formation. With the predicted future increase in snowfall, more surface submergence occurs, which thickens the ice. It is interesting that in the run at Cartwright with higher snow density and annual snowfall rate (Cartwright A), the ice thickness increase in 2041–60 and then decreases by 2081–2100. Our confidence in the future simulation at this site is limited since the landfast ice model was unable to skillfully reproduce the historical ice thickness. Still, we have shown that this more southerly site could behave differently under the future climate scenarios studied here.

The changes are summarized in Table 3. Excluding Cartwright, the mean maximum ice thickness decreases by roughly 30 cm from 1970–89 to 2041–60, and by roughly 55 cm from 1970–89 to 2081–2100. Overall, the ice duration decreases (or equivalently, the open water season increases) by roughly one month in the 2041–60 simulation and by roughly 2 months in 2081–2100. The changes in mean ice thickness and duration are significant at the 95% level at all stations, except for the 2041–60 ice thickness at Cartwright. Changes in interannual thickness variability are small.

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|c|}
\hline
\textbf{Stations} & \textbf{N} & \textbf{Observed} & \textbf{Simulated} & \textbf{r} \\
\hline
Alert & 7 & 328 & 17 & 303 & 0.87 \\
Eureka & 13 & 318 & 18 & 297 & 0.72 \\
Mould Bay & 4 & 318 & 25 & 290 & 0.36 \\
Resolute & 12 & 306 & 16 & 279 & 0.37 \\
Clyde & 15 & 268 & 24 & 242 & 0.66 \\
Cambridge Bay & 20 & 285 & 15 & 266 & 0.23 \\
Hall Beach & 9 & 248 & 23 & 250 & -0.01 \\
Iqaluit & 18 & 245 & 12 & 216 & 0.51 \\
Coral Harbour & 15 & 252 & 16 & 236 & 0.68 \\
Cartwright A & 16 & 168 & 13 & 134 & 0.62 \\
Cartwright B & 16 & 168 & 13 & 142 & 0.72 \\
\hline
\end{tabular}
\caption{Mean observed and simulated ice duration, standard deviations (\(\sigma\)), and correlation coefficient, \(r\), at all stations over the 1970–89 period. Bold values are significant at the 95% level. The first column (\(N\)) refers to the number of years ice duration observations were available.}
\end{table}
compared to the changes in duration and are of mixed signs. This is not unexpected since the variability in the forcing remains the same in the future forcing scenarios (a limitation that will be explored further in section 4a). The differences that do arise result from changes in the onset of ice freeze up and melt. Table 4 gives the values for regional changes in break-up and freeze-up dates for each time period. The overall picture is similar in the two future time periods. The delayed freeze-up dates have greater regional variation and the maxima
Fig. 6. Modeled climatological ice thickness at the 10 stations for the periods of 1970–89, 2041–60, and 2081–2100.
are larger than for changes in break-up dates. The greatest delays in freeze-up date occur at Alert, Hall Beach, and Mould Bay. This may explain why the largest changes in ice duration (shown in Table 3) are found at Alert and Hall Beach, followed closely by Mould Bay. Although the maxima are largest for freeze-up dates, there are three stations that consistently have lower changes in freeze-up dates than break-up dates; they are Eureka, Cambridge Bay, and Coral Harbour. Cartwright’s change in break-up date is delayed rather than advanced in both future simulations. The larger maxima in delay of freeze-up dates can be attributed to a longer open water season, which allows more heat to be stored in the ocean; this heat must first be used up before freeze up can begin (a positive feedback). Moreover, the seasonal cycle of surface air temperature is not symmetric. The cooling in the fall is slower than the spring warm up. Therefore, it makes sense that an overall increase in air temperature delays the date that the temperature drops to below freezing in the fall more than it advances the date that the temperature increases above the freezing temperature in the spring. The reasons for the large variability in simulated freeze-up date change are not clear, although it may reflect the fact that the freeze-up process is dependent on more variables than melt, which is mainly driven by net radiation.

With climate warming we may expect more mixed precipitation and/or rain on snow, which could increase the snow’s density. In the present-day simulation the model’s snow density is set to 330 kg m\(^{-3}\) when the snow temperature is less than freezing, and 450 kg m\(^{-3}\) during melt. Since the humidity tends to be higher with a warmer climate and snow tends to have greater water content, we anticipate that the snow density could be greater with a warmer climate. To see how an increase in density with climate warming could affect the ice thickness, a sensitivity experiment was conducted by increasing the cold snow density from 330 to 350 and 380 kg m\(^{-3}\). As expected, the resulting simulated ice is somewhat thicker. The spatial mean decrease in ice thickness from 1970–89 to 2041–60 is of 0.27 and 0.22 m, respectively, for the cold snow density in the future would act to offset slightly the projected change in ice thickness.

### Table 3. Mean changes in mean maximum simulated ice thickness and ice duration, as well as changes in standard deviations (\(\sigma\)) for 2041–60 and 2081–2100 with respect to 1970–89.

<table>
<thead>
<tr>
<th>Station</th>
<th>Thickness (m)</th>
<th>(\sigma)</th>
<th>Duration (days)</th>
<th>(\sigma)</th>
<th>Thickness (m)</th>
<th>(\sigma)</th>
<th>Duration (days)</th>
<th>(\sigma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alert</td>
<td>–0.41</td>
<td>–0.01</td>
<td>–49</td>
<td>0</td>
<td>–0.64</td>
<td>–0.04</td>
<td>–84</td>
<td>8</td>
</tr>
<tr>
<td>Eureka</td>
<td>–0.36</td>
<td>0.00</td>
<td>–28</td>
<td>–5</td>
<td>–0.38</td>
<td>–0.02</td>
<td>–39</td>
<td>0</td>
</tr>
<tr>
<td>Mould Bay</td>
<td>–0.38</td>
<td>–0.04</td>
<td>–45</td>
<td>0</td>
<td>–0.65</td>
<td>–0.10</td>
<td>–64</td>
<td>10</td>
</tr>
<tr>
<td>Resolute</td>
<td>–0.23</td>
<td>–0.06</td>
<td>–39</td>
<td>–3</td>
<td>–0.49</td>
<td>–0.06</td>
<td>–53</td>
<td>–3</td>
</tr>
<tr>
<td>Clyde</td>
<td>–0.27</td>
<td>–0.04</td>
<td>–41</td>
<td>–2</td>
<td>–0.51</td>
<td>–0.04</td>
<td>–60</td>
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<tr>
<td>Cambridge Bay</td>
<td>–0.26</td>
<td>0.01</td>
<td>–24</td>
<td>–2</td>
<td>–0.44</td>
<td>0.00</td>
<td>–37</td>
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<tr>
<td>Hall Beach</td>
<td>–0.31</td>
<td>–0.02</td>
<td>–50</td>
<td>0</td>
<td>–0.61</td>
<td>–0.03</td>
<td>–80</td>
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<tr>
<td>Iqaluit</td>
<td>–0.26</td>
<td>–0.01</td>
<td>–31</td>
<td>3</td>
<td>–0.56</td>
<td>0.04</td>
<td>–50</td>
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<tr>
<td>Coral Harbour</td>
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<td>–0.64</td>
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<td>Cartwright B</td>
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<td>2</td>
<td>0.17</td>
<td>0.00</td>
<td>13</td>
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### Table 4. Mean present day break-up (BU) and freeze-up (FU) dates (Julian day), and mean future changes for 2041–60 and 2081–2100 with respect to 1970–89.

<table>
<thead>
<tr>
<th>Station</th>
<th>1970–89</th>
<th>2041–2060</th>
<th>2081–2100</th>
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</thead>
<tbody>
<tr>
<td>BU</td>
<td>FU</td>
<td>BU</td>
<td>FU</td>
</tr>
<tr>
<td>Alert</td>
<td>207</td>
<td>270</td>
<td>20</td>
</tr>
<tr>
<td>Eureka</td>
<td>204</td>
<td>273</td>
<td>21</td>
</tr>
<tr>
<td>Mould Bay</td>
<td>202</td>
<td>278</td>
<td>19</td>
</tr>
<tr>
<td>Resolute</td>
<td>200</td>
<td>286</td>
<td>18</td>
</tr>
<tr>
<td>Clyde</td>
<td>193</td>
<td>316</td>
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</tr>
<tr>
<td>Cambridge Bay</td>
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<td>294</td>
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<tr>
<td>Hall Beach</td>
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</tr>
<tr>
<td>Iqaluit</td>
<td>176</td>
<td>327</td>
<td>17</td>
</tr>
<tr>
<td>Coral Harbour</td>
<td>185</td>
<td>316</td>
<td>18</td>
</tr>
<tr>
<td>Cartwright B</td>
<td>134</td>
<td>357</td>
<td>–16</td>
</tr>
</tbody>
</table>

4. Comparison with ice simulated by the CGCM2

As mentioned earlier, the global climate model, CGCM2, is unable to resolve the detailed geography of the CAA. However, it does provide estimates of sea ice change at sites along its resolved coastline. In this case, 4 of the 10 stations discussed above can be plausibly collocated with grid points in the global model. By way of illustrating the global model’s rendition of sea ice change at these sites (without any downscaling), we...
examine the “raw” CGCM2 output for the grid points containing Alert, Mould Bay, Coral Harbour, and Cartwright. Figure 7 compares the climatological annual cycle of raw CGCM2 ice thickness (for the 1970–89 period) to ice thickness observations and the simulation obtained by the landfast ice model driven by observationally based meteorological forcing. Although simulated as perennial ice, Mould Bay is the only station with a reasonably close match between the CGCM2 ice thickness simulation and the landfast ice model’s simulation (and what is observed). At the other stations, the global model produces ice that is either much too thin or much too thick. It should be noted that there is no attempt made in the formulation of CGCM2 to represent immobile landfast ice. Rather, the model includes a representation of sea ice dynamics (Flato and Boer 2001), so it is really intended to represent the mobile pack ice. As a result, the simulated mean thickness and its variability are a consequence of both thermodynamic and dynamic processes.

Figure 8 shows the annual cycle of ice thickness produced by the global model for the future time periods compared to the historical period. The ice thickness at Cartwright produced by the global model increases in 2041–60 and then decreases in 2081–2100, owing to cooler air temperature in this region in the earlier part of the century. This result is similar to the future scenario in the landfast ice model’s run A at this site. At Alert and Mould Bay, the ice thickness changes from multiyear ice during 1970–89 to seasonal ice by 2041–60 and thins substantially. Changes in ice thickness and variability produced by CGCM2 for 2041–60 and 2081–2100 are shown in Table 5.

**Future variability**

Table 3 summarized the changes in maximum ice thickness and duration as well as the standard deviations. These results were obtained using scenario 1 in which the temporal variability in the future forcing was determined by the observed historical variability. As a result, the year-to-year variability in ice thickness essentially coincides in the three different time periods (shown in Fig. 9). The differences that exist are due to nonlinearities in the landfast ice model. These nonlinearities mean that changes in the variability in the model forcing can alter the projected changes in mean thickness and seasonality. In the following paragraph, we describe a simple experiment to examine the potential importance of this nonlinear effect.

The CGCM2 simulation, results shown in Fig. 8, pro-
vides an opportunity to explore the sensitivity of the future landfast ice projections to changes in variability. To do this, we use the forcing from scenario 2, described in section 2a, in which the future variability is that produced by CGCM2. Time series of ice thickness anomaly for four selected sites are shown in Fig. 10. Table 6 shows the resulting mean maximum ice thickness and duration and compares these to the results obtained using present-day interannual variability (scenario 1). The results are very similar. A statistical test comparing means was performed. Only for 1 out of 10 stations can we reject the hypothesis that the means are equal with 95% confidence. The case where the means are not equal is for ice thickness at Mould Bay. There are of course small changes in projected thickness, duration, and variability (interannual standard deviation), but there are no large, systematic differences. The implication is that changes in forcing variability are not likely to have a significant, nonlinear effect on the projected change in mean landfast ice climate.

5. Conclusions

We used a detailed one-dimensional landfast ice model driven by both observationally based forcing of

![Fig. 8. CGCM2 modeled climatological ice thickness for the periods of 1970–89, 2041–60, and 2081–2100. Note that the y axis for Cartwright is different due to very thin ice.](image)
Fig. 9. Comparing the variability (anomaly in m) in ice thickness for 1970–89, 2041–60, and 2081–2100, using scenario 1 forcing in the 1D model.

Fig. 10. Comparing the resulting 2041–60 ice thickness variability (anomaly in m) when using scenario 1 and scenario 2 forcing in the 1D model. The CGCM2 ice thickness for this period is also shown.
the late twentieth century and projected future climate change from the Canadian Centre for Climate Modeling and Analysis global climate model to produce projections of future landfast ice thickness and duration at nine sites in the CAA and Hudson Bay, and one much more southerly site on the coast of the Labrador Sea. The landfast ice model is able to reproduce the observed ice thickness seasonal cycle and interannual variability at northern sites reasonably well based on comparisons to available observations. These historical simulations show, not surprisingly, that the landfast ice is thicker and lasts longer at the more northerly sites. Although the bias in maximum ice thickness was reduced and all of the correlations increased, the simulation at the most southerly site (Cartwright) still did not correlate significantly with the observations when the snowfall forcing and snow density was changed. Because the ice is much thinner in this region, it is likely that other processes, not considered here (e.g., variations in heat transport by the Labrador Current), influence its ice thickness.

When the landfast ice model is driven by projected changes in climate, we find a decrease of 30 and 50 cm in maximum ice thickness and 1 and 2 months ice duration by the years 2041–60 and 2081–2100, respectively. The changes in freeze-up dates vary more regionally and the maximum change is greater than for break-up dates. This is most likely due to the longer open water season allowing more heat to be stored in the ocean and also to the asymmetric seasonal surface air temperature.

The ice thickness decrease is only slightly less if we assume higher snow density with climate warming. There is no obvious spatial pattern to the projected changes in either thickness or duration (although the Labrador Sea coastal station, Cartwright, is anomalous in that it exhibits a small increase in ice thickness and duration owing to a localized cooling in the Labrador Sea and increased snow ice formation). These results are essentially unchanged if projected future meteorological variability is used rather than the observed, historical variability.

The raw global model results are only similar at one of the four stations at which a comparison could be made, although the global model suffers from rather large biases in both thickness and seasonality, due in part to the limitations in resolving the local geography and in part to the fact that immobile, landfast ice processes are not explicitly treated in the global model. The landfast ice model, along with the simple downscaling technique applied here, provides a means of developing more physically based, location specific scenarios of future landfast ice conditions in the Canadian Arctic. Although it is not possible to directly evaluate the skill of these projections at this point, it is hoped that they will serve as additional information for use in impacts and adaptations research and as an aid in planning and decision making.

Acknowledgments. The authors acknowledge the important contribution of the Canadian weekly ice thickness observing program to this paper and the Canadian Ice Service for maintaining these data online (http://iceglaces.ec.gc.ca/ Ice Archive, Ice Thickness). We also thank Diane Lavoie and Oleg Saenko for helpful comments on a draft version of the manuscript. This research was funded under Project 4.1 of the integrated natural/medical/social study of the changing coastal Canadian Arctic (ArcticNet) NCE.

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| Table 6. Projected mean change in maximum ice thickness (m) $\Delta Z_{\text{max}}$, ice duration (days), and their interannual standard deviations (\(\sigma\)) from 1970–89 to 2041–60. Results identified by Pres$\Delta$ and Fut$\Delta$ refer to projections made using observed and model-projected variability (i.e., scenario 1 and scenario 2, respectively). |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Station         | Pres$\Delta$ $\Delta Z_{\text{max}}$ $\sigma$ | Fut$\Delta$ $\Delta Z_{\text{max}}$ $\sigma$ | Pres$\Delta$ Duration $\sigma$ | Fut$\Delta$ Duration $\sigma$ |
| Alert           | −0.41           | 0.00            | −0.47           | 0.00            | −49             | 0.00            | −48             | 0.00            |
| Eureka          | −0.36           | 0.00            | −0.35           | 0.00            | −28             | 0.00            | −26             | 0.00            |
| Mould Bay       | −0.38           | 0.00            | −0.49           | 0.00            | −45             | 0.00            | −48             | 0.00            |
| Resolute        | −0.23           | 0.00            | −0.21           | 0.00            | −39             | 0.00            | −36             | 0.00            |
| Clyde           | −0.27           | 0.00            | −0.24           | 0.00            | −41             | 0.00            | −40             | 0.00            |
| Cambridge Bay   | −0.26           | 0.00            | −0.27           | 0.00            | −24             | 0.00            | −22             | 0.00            |
| Hall Beach      | −0.31           | 0.00            | −0.32           | 0.00            | −50             | 0.00            | −49             | 0.00            |
| Iqaluit         | −0.26           | 0.00            | −0.27           | 0.00            | −31             | 0.00            | −32             | 0.00            |
| Coral Harbour   | −0.32           | 0.00            | −0.36           | 0.00            | −22             | 0.00            | −22             | 0.00            |
| Cartwright B    | +0.11           | 0.00            | +0.06           | 0.00            | +9              | 0.00            | +9              | 0.00            |

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