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Simulation of ice phenology on Great Slave Lake, Northwest Territories, Canada

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Abstract:

A one-dimensional thermodynamic lake ice model (Canadian Lake Ice Model or CLIMo) is used to simulate ice phenology on Great Slave Lake (GSL) in the Mackenzie River basin, Northwest Territories, Canada. Model simulations are validated against freeze-up and break-up dates, as well as ice thickness and on-ice snow depth measurements made *in situ* at three sites on GSL (Back Bay near Yellowknife, 1960–91; Hay River, 1965–91; Charlton Bay near Fort Reliance, 1977–90). Freeze-up and break-up dates from the lake ice model are also compared with those derived from SSM/I 85 GHz passive microwave imagery over the entire lake surface (1988–99).

Results show a very good agreement between observed and simulated ice thickness and freeze-up/break-up dates over the 30–40 years of observations, particularly for the Back Bay and Hay River sites. CLIMo simulates the ice thickness and annual freeze-up/break-dates with a mean error of 7 cm and 4 days respectively. However, some limitations have been identified regarding the rather simplistic approach used to characterize the temporal evolution of snow cover on ice. Future model improvements will therefore focus on this particular aspect, through linkage or coupling to a snow model. Copyright © 2002 John Wiley & Sons, Ltd.

KEY WORDS modelling; lake ice; freeze-up; break-up; ice thickness; Great Slave Lake

INTRODUCTION

Very large expanses of land at northern latitudes are covered by lakes. Therefore, as a major component of the terrestrial landscape, lakes play a significant role in the energy and water balance of the cold regions of the globe. Lakes of all sizes exert time lags into energy and water exchange processes because of their ability to transmit solar radiation and to store heat. The determination of the length of the ice-free period is important, as global warming has the potential to enhance greatly the energy and moisture exchange role of lakes. For large, deep, lakes, in particular, the dates of freeze-up are more significant than break-up dates, as evaporation rates in autumn to early winter can be double those in spring to early summer (Rouse, 2000). Information on lake ice coverage is also interesting from a climatological standpoint, since freeze-up and break-up dates have been shown to be a good proxy indicator of climate variability and change (Barry, 1984; Liston and Hall, 1995a; Launiainen and Cheng, 1998; Walsh *et al.*, 1998). A change of only a few degrees in air temperature is sufficient to shift freeze-up and break-up dates by several weeks (Liston and Hall, 1995a; O'Neill *et al.*, 2001).

The sensitivity of lake ice to climatic variability has promoted the development of lake ice models (e.g. Liston and Hall, 1995b; Vavrus *et al.*, 1996; Stefan and Fang, 1997). These models have been validated against

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field observations in different regions of North America and, in some cases, have been used to examine the response of lake ice to climate change under various scenarios (Liston and Hall, 1995a,b; Vavrus *et al.*, 1996; Stefan and Fang, 1997; Fang and Stefan, 1998). However, to date, few studies have been conducted to simulate ice phenology of very large, deep, lakes and over long time periods.

In this paper, we present results obtained with a one-dimensional thermodynamic lake ice model, CLIMo (Canadian Lake Ice Model), for the simulation of ice phenology on Great Slave Lake (GSL), Northwest Territories, Canada. For this purpose, we used meteorological data from three climate stations located near the shore of GSL (Yellowknife, Hay River, and Fort Reliance). Results are compared with *in situ* observations and those derived from the passive microwave SSM/I (85 GHz) satellite imagery.

MODEL DESCRIPTION

Initially based on the one-dimensional sea ice model of Flato and Brown (1996), CLIMo has undergone some changes in order to simulate ice phenology on lakes of varying depths. A detailed description of the model (parameterizations and equations) and testing on shallow lakes can be found in Duguay *et al.* (submitted). Briefly, the model is based on the one-dimensional unsteady heat conduction equation, with penetrating solar radiation, of Maykut and Untersteiner (1971), i.e.

$$\rho C_{\mathrm{p}} \frac{\partial T}{\partial t} = \frac{\partial}{\partial z} k \frac{\partial T}{\partial z} + F_{\mathrm{sw}} I_{\mathrm{o}} (1 - \alpha) K \, \mathrm{e}^{-kz} \tag{1}$$

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

Then, the surface energy budget is computed from

$$F_{\mathrm{o}} = F_{\mathrm{lw}} - \varepsilon \sigma T^4(0, t) + (1 - \alpha)(1 - I_{\mathrm{o}}) F_{\mathrm{sw}} + F_{\mathrm{lat}} + F_{\mathrm{sens}} \tag{2}$$

where F_{o} (W m^{-2}) is the net downward heat flux absorbed at the surface, ε is the surface emissivity, σ is the Stefan–Boltzmann constant ($5{\cdot}67 \times 10^{-8}$ Wm^{-2} K^{-4}), F_{lw} (W m^{-2}) is the downwelling longwave radiative energy flux, F_{lat} (W m^{-2}) is the downward latent heat flux, and F_{sens} (W m^{-2}) is the downward sensible heat flux.

The model requires five meteorological variables and a few extra parameters to simulate lake ice phenology. The variables used as input consist of daily mean air temperature (°C), wind speed (m s^{-1}), relative humidity (%), cloud cover (tenths), and snow depth (m), measured at nearby meteorological stations. It should be noted that, in the current version of the model, snow cover is represented as a single slab and that snow redistribution and compaction are not simulated. Consequently, snow density is specified as a constant, typical, mid-winter value or, when available, allowed to vary when more frequent snow course measurements are available. The other parameters required are the number of layers in the ice cover for which temperatures are to be calculated (up to 99), the time step, the mixing depth, and the latitude of the site. The model output parameters generated by CLIMo include ice thickness (snow ice and black ice) and on-ice snow depth on a daily basis. The model also produces the annual freeze-up/break-up dates.

MODEL SIMULATIONS

Study area and input data

As the second largest lake of the Mackenzie River Basin, GSL covers an area of roughly 28 000 km^2. The lake can be subdivided into two distinctive sections: the main-lake section and the eastern arm section,

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where mean depths are 41 m and 249 m respectively. Maximum depths are approximately 163 m in the main, central, section and 614 m in the eastern arm section.

The lake ice model was forced with data obtained from three meteorological stations located near the shore of GSL and operated by Environment Canada: Yellowknife and Hay River (1960–2000), and Fort Reliance (1977–90) (Figure 1). The Hay River station is situated on the southwest shore of GSL (60·50 °N, 115·47 °W), at an altitude of 164 m a.s.l. It is located near the mouth of the river, within the taiga vegetation zone of the plains. The climate in this area is typified as a cold continental one, where the mean air temperature is −19·9 °C in January and is 20·9 °C in July. Total annual precipitation is 342 mm (158·5 cm of snow). The Fort Reliance climate station is located to the far-east side of GSL (62·43 °N, 109·10 °W), also at an elevation of 164 m a.s.l. Vegetation in this area is characterized by the taiga of the shield, and the regional climate is of the sub-arctic continental type. The mean air temperature for January is −24·3 °C and is 19·1 °C for the month of July, with 273 mm total annual precipitation (139·6 cm of snow). Finally, the Yellowknife Airport weather station is situated on the north shore of GSL (62·28 °N, 114·27 °W), at an altitude of 205 m a.s.l. The ecological and climatic conditions at this site are similar to those found at Fort Reliance.

Simulations were carried out by setting the number of ice layers to ten and using different mixed-layer depths in order to account for variations in lake depth across the lake. The depth of the mixed layer represents the thickness of the water slab in which the heat is stored during the ice-free period. The greater the amount of energy stored in a lake during the summer months, the longer it takes for the ice cover to form in the fall to winter period. Lake depth has been shown to be an important parameter to consider for the determination of freeze-up dates (Barry and Maslanik, 1993; Vavrus *et al.*, 1996). The depth of GSL varies significantly between each observation sites (Hay River: <10 m; Charlton Bay (near Fort Reliance): >50 m; Back Bay (near Yellowknife): >10 m; Figure 2). Simulations were thus conducted by varying the depth of the mixed layer between 1 and 50 m.

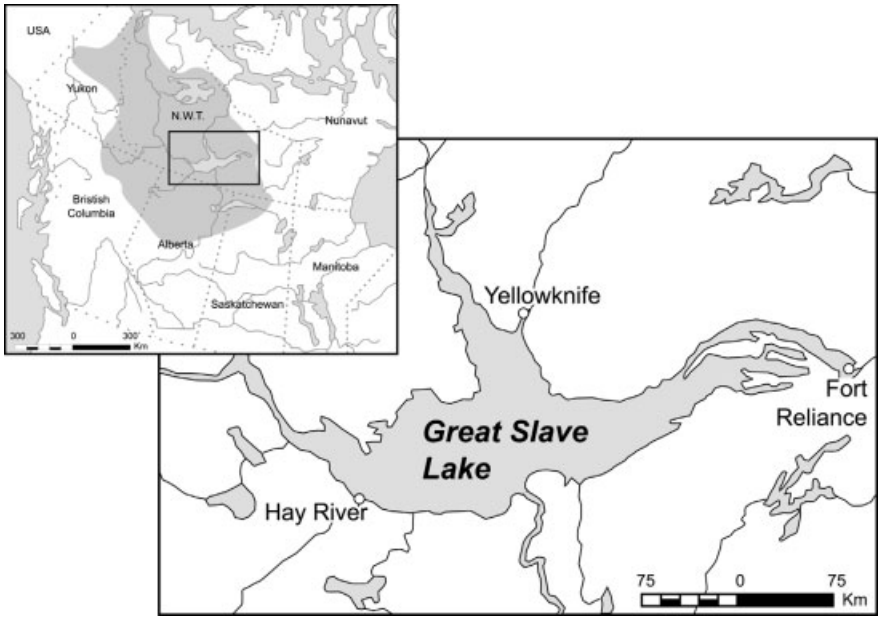

Figure 1. Maps showing the location of GSL within the Mackenzie River Basin and the locations of the three meteorological stations used for model simulations (Yellowknife, Hay River, and Fort Reliance). The ice observation sites (Back Bay, Hay River, and Charlton Bay) are located in the vicinity of the three meteorological stations

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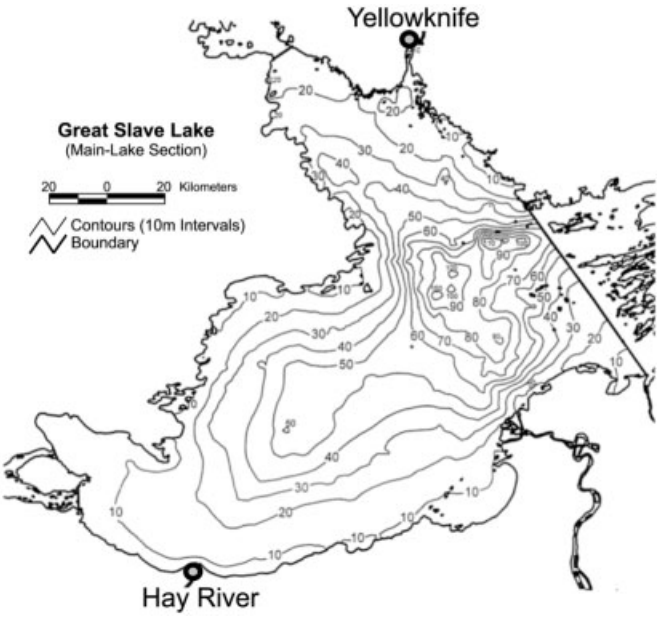

Figure 2. Bathymetry of the main section of GSL

In situ Data and statistical measures for model validation

Lake ice thickness, on-ice snow depth, and freeze-up/break-up dates, used to validate the model results, were extracted from Canadian Ice Database (CID) (Lenormand *et al.*, 2002) and extend over 30 years (1960–91) for the Back Bay and Hay River stations, and over 14 years (1977–90) for Charlton Bay. Ice thickness and on-ice snow depth measurements are taken about once a week (to the nearest centimetre), starting after freeze-up, when the ice is safe to walk on, and continuing until break-up, when the ice is unsafe (Atmospheric Environment Service, 1989). Freeze-up and break-up dates, as defined herein, correspond to complete freeze over (i.e. earliest date on which the lake is completely covered by ice) and water clear of ice (i.e. earliest date on which water is completely free of floating ice).

Three statistical indices were calculated to validate the lake ice model results: the relative index of agreement I_a, the root mean square error (RMSE), and the mean bias error (MBE). These indices have been shown to be robust statistical measures for validating model performance (e.g. Wilmott and Wicks, 1980; Hinzman *et al.*, 1998). The I_a is intended to be a descriptive measure, which is both a relative and bounded measure and can be widely applied to make cross-comparisons between models or between modelled and observed values. The I_a has values ranging from zero (worst performance) to one (best possible performance). The RMSE is a measure of non-systematic error, which gives a measure of the total error and does not distinguish between underprediction or overprediction, since the difference between the simulated and observed value is squared. Thus, an RMSE value of zero means that there is no deviation between the simulated and observed values. The MBE, on the other hand, provides a measure of systematic error. The MBE indicates whether a model underpredicts (negative value) or overpredicts (positive value) a variable throughout a simulation period. Both the RMSE and MBE are expressed in the same units as the variable under investigation. In the present study, RMSE and MBE values are reported in units of number of days for freeze-up and break-up dates, and centimetres for ice thickness and on-ice snow depth. According to Wilmott (1982), a good model's I_a should approach unity and the RMSE zero.

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RESULTS AND DISCUSSION

Freeze-up/break-up dates

Yellowknife (Back Bay). The lake ice model reproduces freeze-up and break-up dates very well for the Back Bay site over the entire time series of observations (1960–91) (Figure 3). The effect of the mixed-layer depth on freeze-up dates is particularly noticeable. The greater the value, the longer it takes for the ice cover to form. The best agreement between observed and simulated dates is obtained with a mixed-layer depth of 10 m, which is representative of the mean depth of GSL observed in the area of Back Bay (see Figure 2). These results suggest a strong dependence of freeze-up dates on lake depth and, consequently, the depth of the mixed layer. Similar relations have been observed by other authors (e.g. Barry and Maslanik, 1993; Vavrus *et al.*, 1996). CLIMo predicts break-up dates with greater accuracy than freeze-up dates. The histogram of Figure 4 shows the absolute errors between simulated and observed freeze-up and break-up dates for Back Bay. A comparison between simulated and measured values is summarized in Table I. The statistics

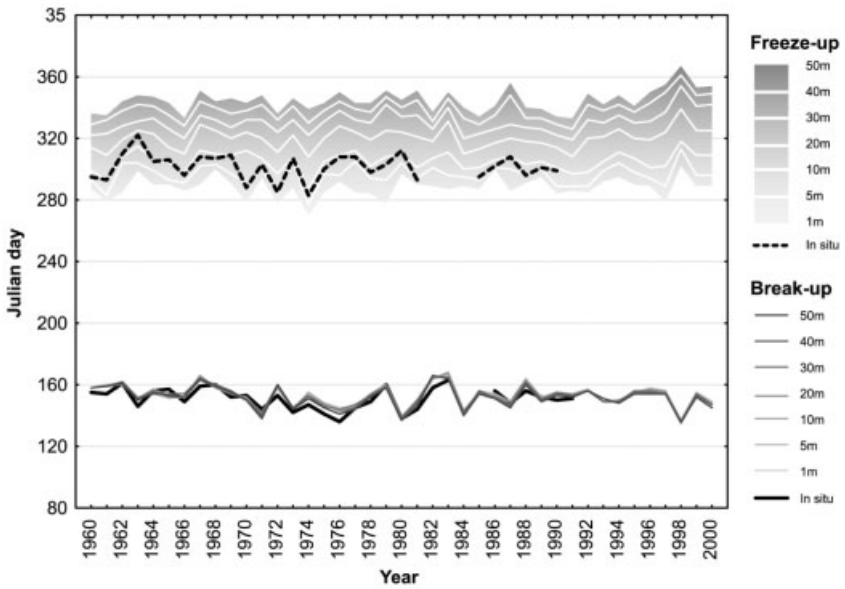

Figure 3. Comparison of observed and simulated freeze-up and break-up dates using different mixing depth values for Back Bay, near Yellowknife

Table I. Comparison of observed and simulated freeze-up/break-up dates for Yellowknife (Back Bay; 1960–91), Hay River (1960–91) and Fort Reliance (Charlton Bay; 1977–90) sites

	Yellowknife (10 m)[a]	Hay River (5 m)[a]	Fort Reliance (30 m)[a]
Freeze-up			
I_a	0·996	0·505	0·891
RMSE (days)	6	6	4
MBE (days)	6	5	3
Break-up			
I_a	0·901	0·999	0·998
RMSE (days)	4	6	11
MBE (days)	4	−4	−10

[a] Mixing depth.

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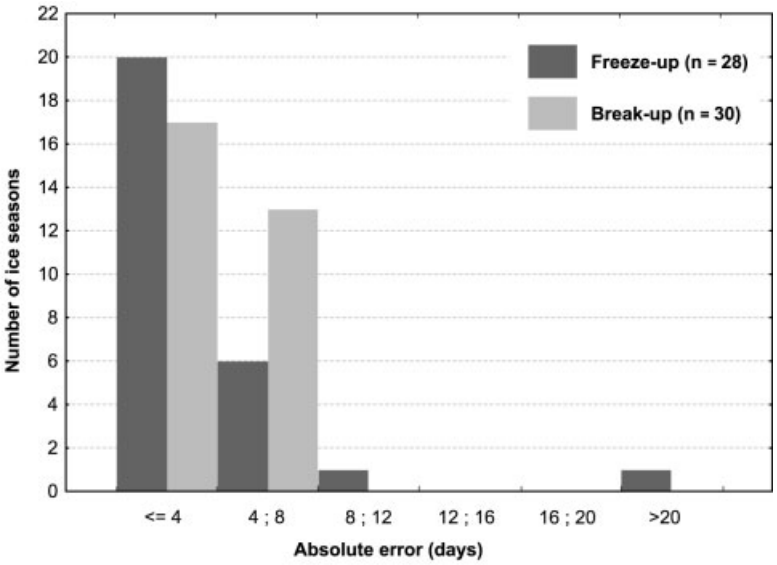

Figure 4. Histogram of the absolute errors in simulated freeze-up and break-up dates for Back Bay, near Yellowknife (mixing depth: 10 m)

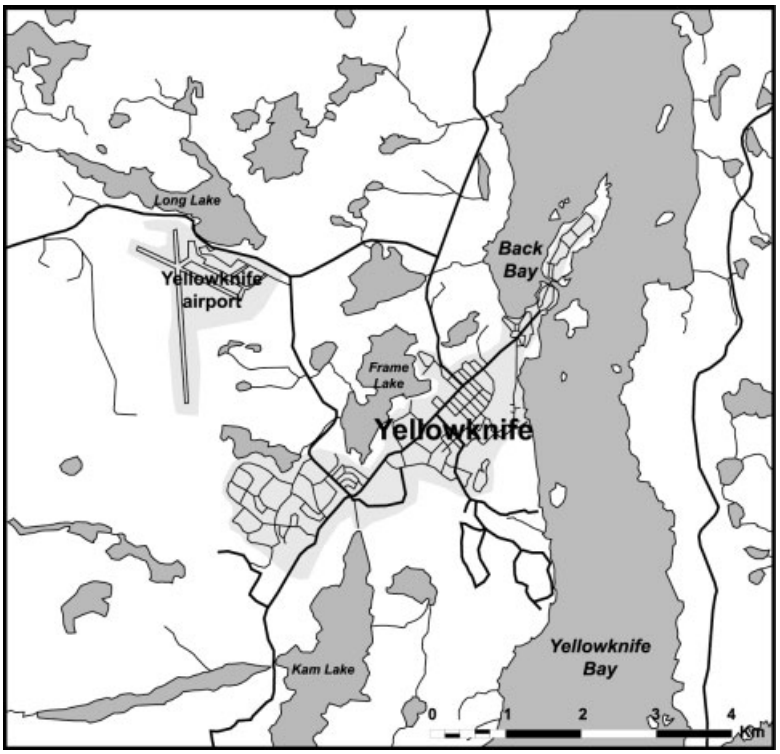

Figure 5. Map showing the location of the Yellowknife Airport weather station relative to Back Bay, Frame Lake, and Long Lake

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are presented for the mixed-layer depths at which the smallest MBE and RMSE were obtained. The RMSE is 6 days for freeze-up and only 4 days for break-up dates.

Results from the simulations also allow some comparison with lake ice observations made on two smaller lakes in the vicinity of the Yellowknife Airport weather station. The location of the two lakes, Long Lake and Frame Lake, in relation to Back Bay and the airport, is shown in Figure 5. In general, a strong temporal coherence (i.e. the degree to which different lakes in a region behave similarly over time) can be observed for both freeze-up and, in particular, break-up dates between these two lakes and Back Bay (Figure 6). The greater variability for freeze-up dates is likely due to the influence of lake morphometry (depth and area). As shown earlier, lake morphometry plays a significant role during the process of ice formation in fall. Back Bay freezes after Long Lake and Frame Lake mainly because this section of GSL covers a larger area and is likely of greater depth than these two smaller lakes. Finally, the fact that both simulated freeze-up and break-up dates follow the same temporal trajectories as those observed at the three lake sites indicates that meteorological data from the Yellowknife Airport weather station are suitable for modelling ice cover on lakes of all sizes in the region.

Hay River. The first set of simulations conducted for Hay River showed a relatively good match with *in situ* observations for the freeze-up period, but much less so for break-up, even though the cycles are well reproduced over the full simulation period (Figure 7a). Also noticeable is a difference of about 30 days between simulated and observed freeze-up dates in 1966. This large discrepancy is most likely due to an observational error or an error of entry into the database, especially given that the observed date largely deviates from the mean freeze-up date at this site, and that none of the other sites on GSL shows large deviations in 1966. Consequently, statistical measures used to compare simulated and observed freeze-up dates for Hay River were calculated by excluding this date.

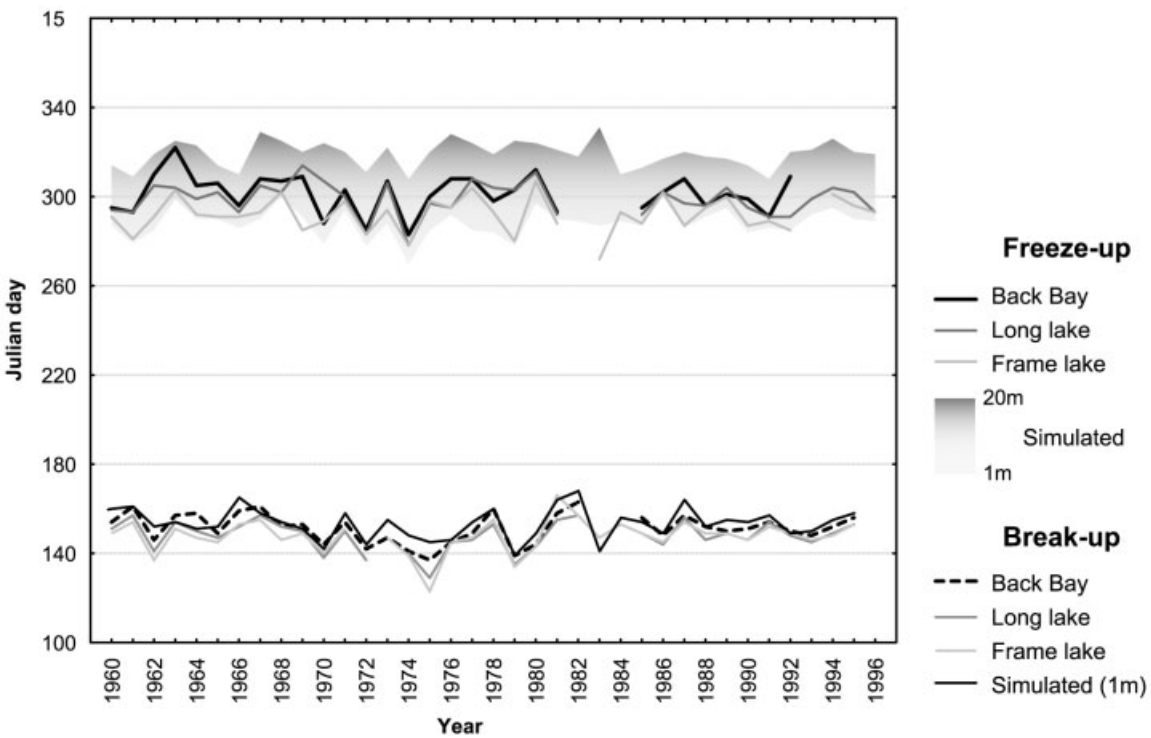

Figure 6. Comparison of observed and simulated freeze-up and break-up dates using different mixing depth values for Back Bay, Frame Lake, and Long Lake

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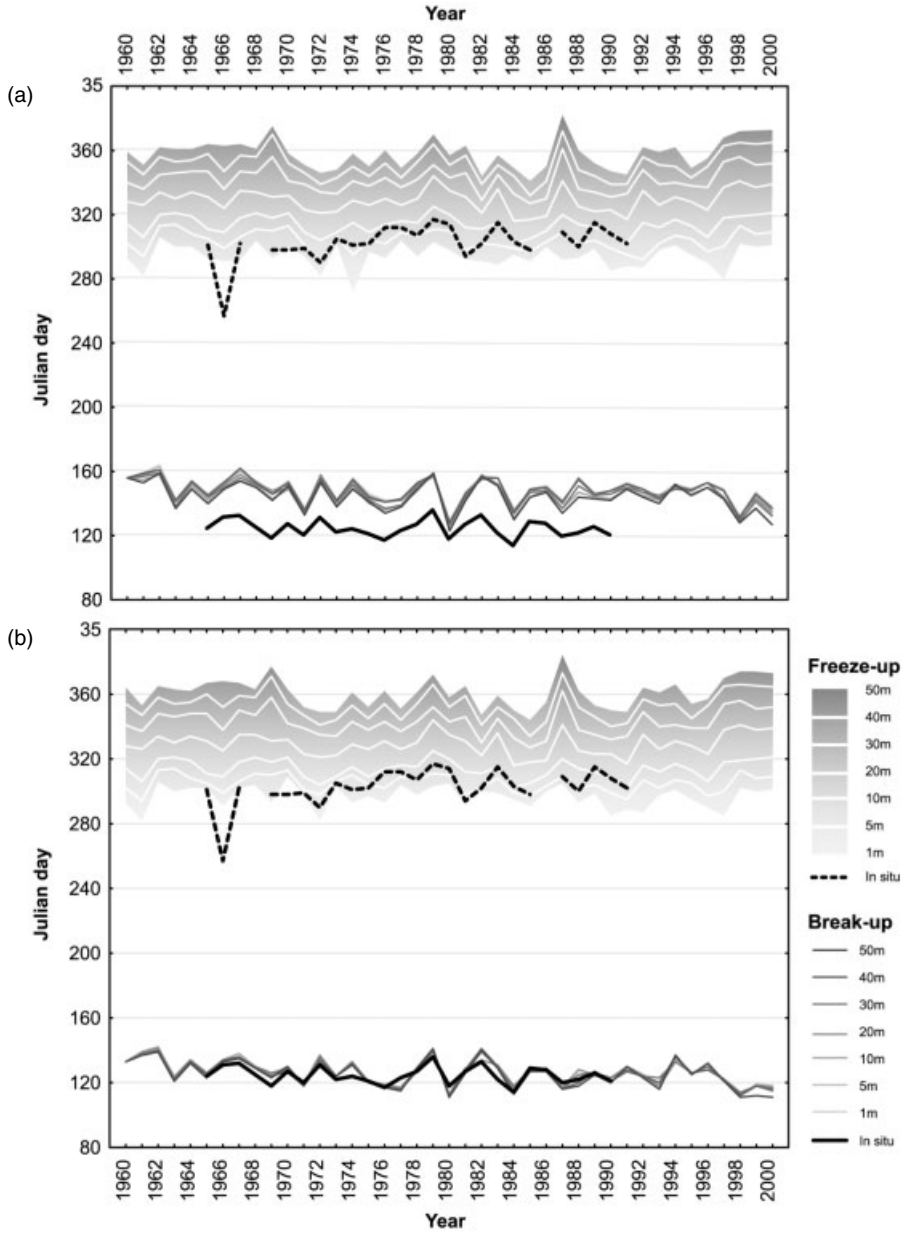

Figure 7. Comparison of observed and simulated freeze-up and break-up dates using different mixing depth values for Hay River: (a) without and (b) with consideration of water inflow from the river

Simulated break-up dates show an almost constant difference from *in situ* observations (Figure 7a). This indicates that an external factor not well captured by the lake ice model, influences break-up dates at the Hay River site. The consistency of the difference points to the fact that the factor is relatively constant from year to year. A plausible explanation is that the ice observation site is located at the mouth of Hay River. Indeed, a river flowing into a lake may increase the heat flux, which can lead to accelerated ice melt during spring thaw (Bengtsson, 1986).

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In order to verify whether the specific conditions found at the Hay River site were responsible for the difference, a further simulation was carried out, in which a constant heat flux of 25 W m^{-2} was added in order to account for the inflow of warmer water into GSL. The result of this simulation is shown in Figure 7b. It can be seen that the consideration of the additional heat flux results in a very good match for freeze-up dates, but even more so for break-up dates. The RMSE are similar to the Back Bay site, with values of 6 days and 4 days for freeze-up dates and break-up dates respectively (Figure 8). Unfortunately, no ice thickness measurements are available for the Hay River site for the simulation period. This would have provided a further verification of the effect of modifying the heat flux on ice thickness. Nonetheless, the results indicate that the influence of warmer water inflow on lake ice conditions near the mouth of a river can be effectively simulated with CLIMo.

Fort Reliance (Charlton Bay). The freeze-up dates simulated for Fort Reliance are generally in good agreement with those observed *in situ* (Figure 9). However, although both the simulated and observed break-up dates vary in phase, the MBE is −10 days. The absolute errors in freeze-up and break-up dates are shown in Figure 10. Contrary to the situations observed at the Back Bay and Hay River sites, CLIMo tends to simulate earlier thaw dates. Therefore, there must be a factor (climatological, geographical or other) not accounted for in the lake ice model that influences ice cover conditions at Fort Reliance.

The *in situ* observations used to validate the model runs were acquired in Charlton Bay. This site is connected to the east arm of GSL only by a very narrow channel that protects the bay from ice rifting, which, during spring thaw, accelerates the disintegration and melt of ice (Woo and Heron, 1989). The topography that surrounds Charlton Bay is relatively steep and may create a local environment favourable to the preservation of an ice cover for a longer period in spring. This factor alone may provide a partial explanation for the 10 day difference between simulated and observed break-up dates.

Comparison with freeze-up and break-up dates derived from SSM/I. A comparison of break-up dates at the three observation sites illustrates the spatial dynamics of ice melt on GSL (Figure 11). It can be noted that the site located on the southern shore of GSL, Hay River, experiences earlier melt, followed by Back Bay in the north central section of the lake, and Charlton Bay located in the east arm section. With respect to

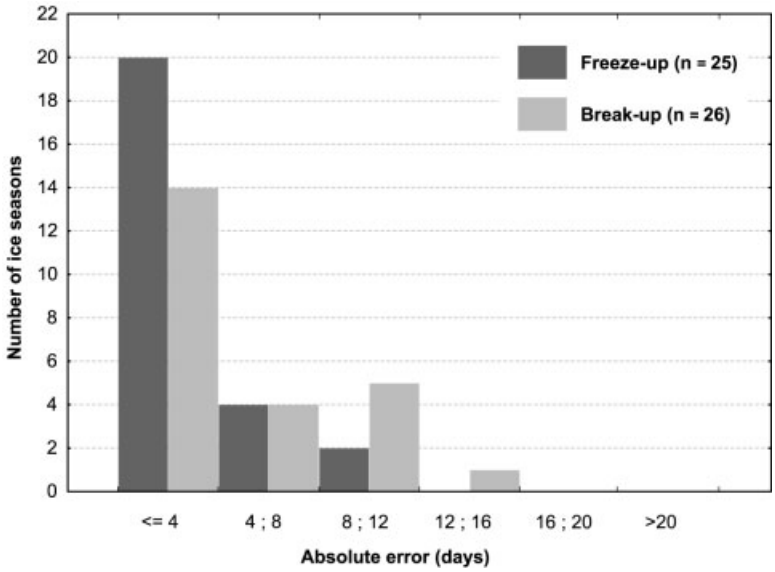

Figure 8. Histogram of absolute errors in simulated freeze-up and break-up dates for Hay River (mixing depth: 5 m)

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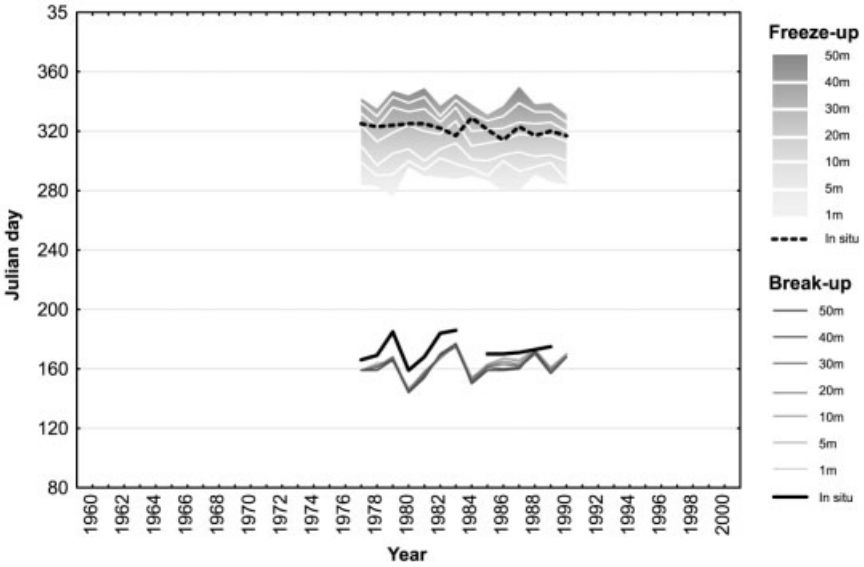

Figure 9. Comparison of observed and simulated freeze-up and break-up dates using different mixing depth values for Charlton Bay, near Fort Reliance

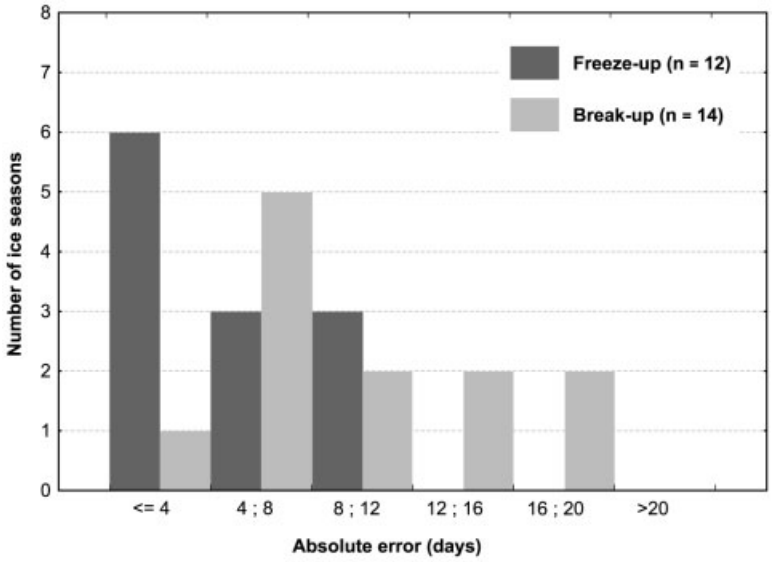

Figure 10. Histogram of absolute errors in simulated freeze-up and break-up dates for Charlton Bay, near Fort Reliance (mixing depth: 30 m)

freeze-up dates, the pattern is less consistent between the sites. That is, the dates observed at the sites do not always show a constant deviation between them. The site located near Fort Reliance is the one where one can observe later freeze-up, whereas the two other sites show similar ice-in conditions. Therefore, based on the analysis of the three sites, GSL seems to present more variability in freeze-up than break-up dates.

Since *in situ* observations used to validate the lake ice model were no longer acquired after 1990, passive microwave imagery acquired by the SSM/I sensor at a frequency of 85·5 GHz, and pixel size of 12·5 km,

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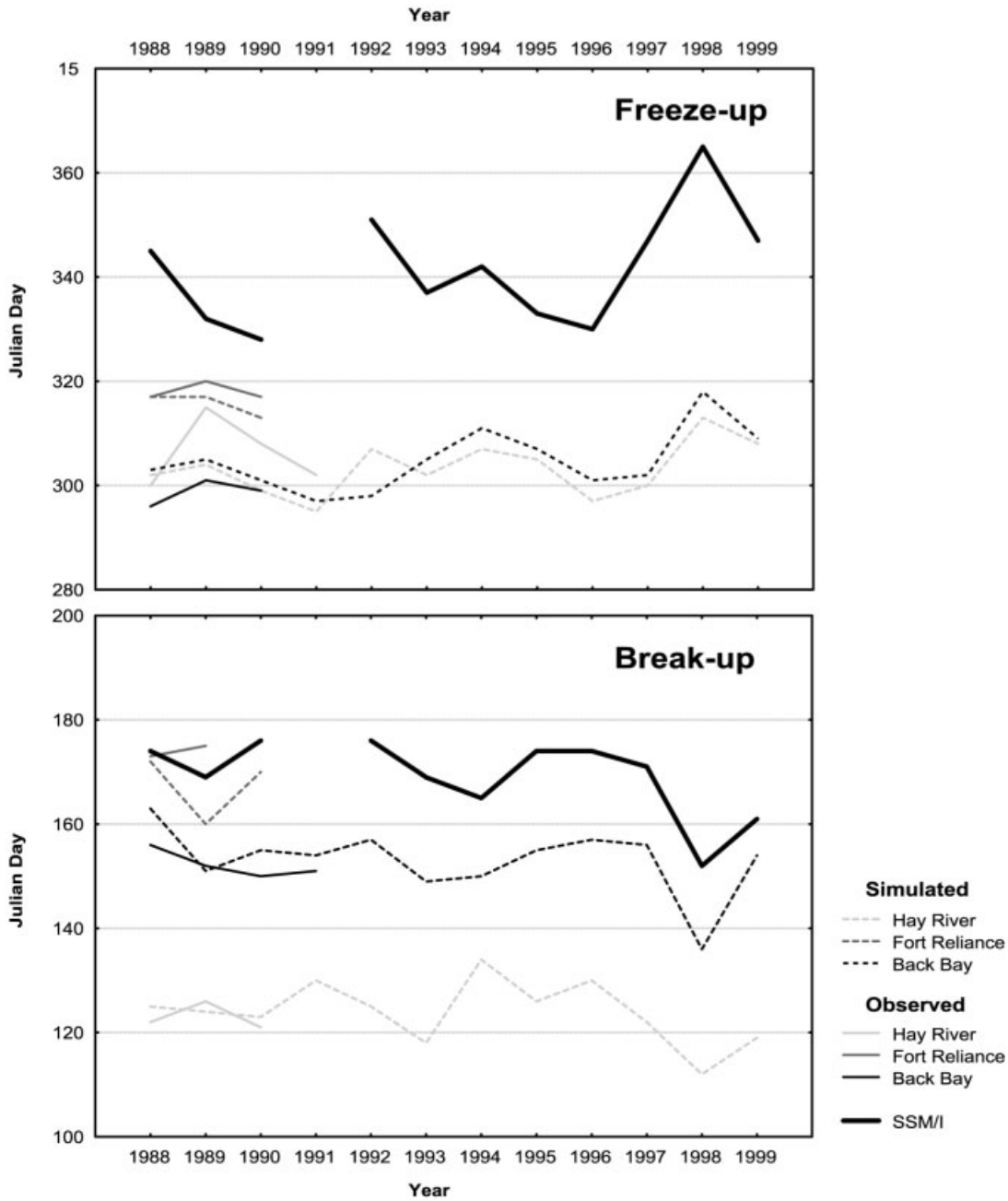

Figure 11. Comparison of the best freeze-up/break-up simulation results from Back Bay, Hay River, and Fort Reliance (Charlton Bay) with dates obtained from SSM/I 85 GHz data over the entire area of GSL

were used for comparison. Details on the method for determining freeze-up and break-up dates on GSL with this type of imagery are given in Walker and Davey (1993). Unlike *in situ* observations, satellite sensors such as SSM/I provide a spatial coverage, which permits the monitoring of ice formation and decay over the complete lake surface in an objective, timely fashion.

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A comparison between observed and SSM/I-derived freeze-up and break-up dates is shown in Figure 11. The best correspondence for break-up dates is with Charlton Bay near Fort Reliance, although only three ice seasons are available for comparison. The input data used for model simulations at this particular site end in 1990 and the SSM/I data acquisitions only begin in 1988. Nonetheless, the temporal patterns, which exhibit relatively constant deviations between the SSM/I-derived and simulated freeze-up and break-up dates for Back Bay and Hay River, provide validation, to some extent, of the simulation results for the 1990s.

In order to compare lake-wide SSM/I-derived dates with simulated dates better, we plotted the freeze-up and break-up dates obtained with mixed-layer depths of 30, 40 and 50 m, and forced with meteorological data from the Yellowknife weather station (Figure 12). The mixed layer depth at a site near the mid section of GSL on 10 September 1998 was determined to be around 50 m (Schertzer, personal communication, 2000). An excellent correspondence is achieved for the freeze-up dates over the 11 years of simulation. The MBE is −8 days, 0 days, and 6 days for mixing depths of 30 m, 40 m, and 50 m respectively. The difference between simulated and observed break-up dates is, as expected, more important. However, in this case, the analysis of Landsat Thematic Mapper (TM) images and *in situ* observations reveal the latest break-up dates on GSL are consistently observed year after year in the east arm of GSL, near Charlton Bay. This is about 20–30 days later than in Back Bay (see Figures 3 and 9 for comparison), which is a difference of the same order of magnitude as the one shown in Figure 12 between model simulations and observations in Back Bay near Yellowknife. The similar temporal trajectories observed for break-up dates from SSM/I and those obtained with CLIMo are further evidence that this model reproduces very well the ice phenology on GSL.

Ice thickness and on-ice snow depth

The model reproduces quite well the evolution of ice thickness and on-ice snow depth for the Yellowknife (Back Bay) and Fort Reliance (Charlton Bay) sites (Figure 13). Unfortunately, as indicated earlier, no *in situ* measurements were available for validating the model performance with regards to these two variables for the Hay River site.

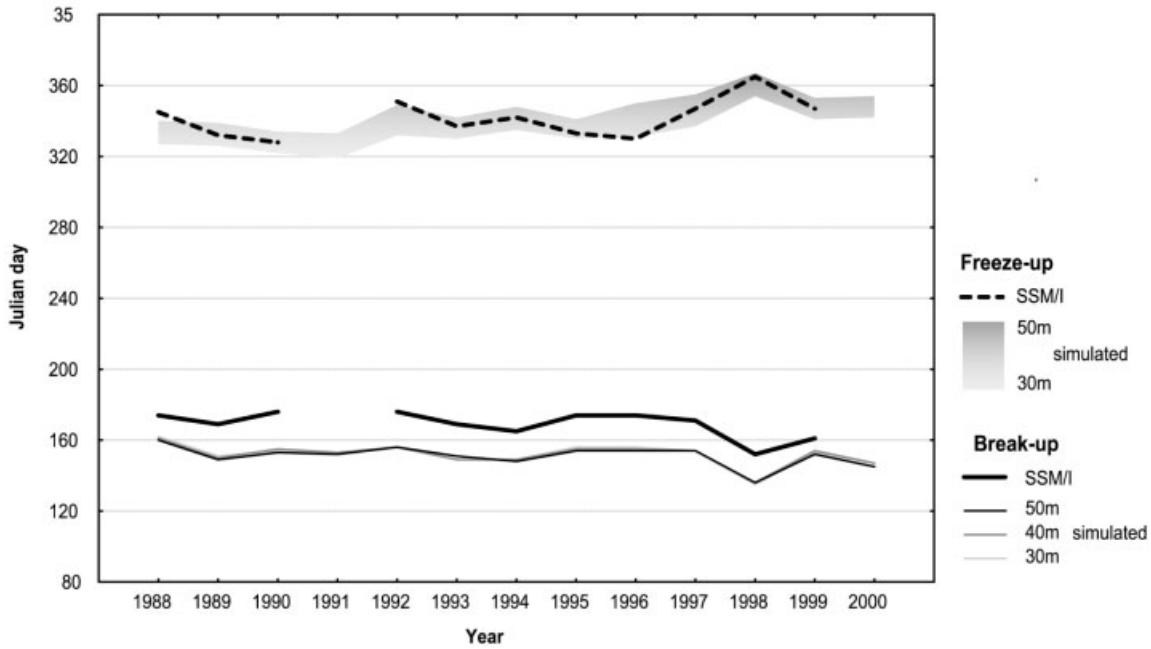

Figure 12. Comparison of freeze-up/break-up simulation results obtained using Yellowknife Airport meteorological data with mixed layer depths of 30, 40, and 50 m, and freeze-up/break-up dates obtained from SSM/I 85 GHz data over the entire GSL area

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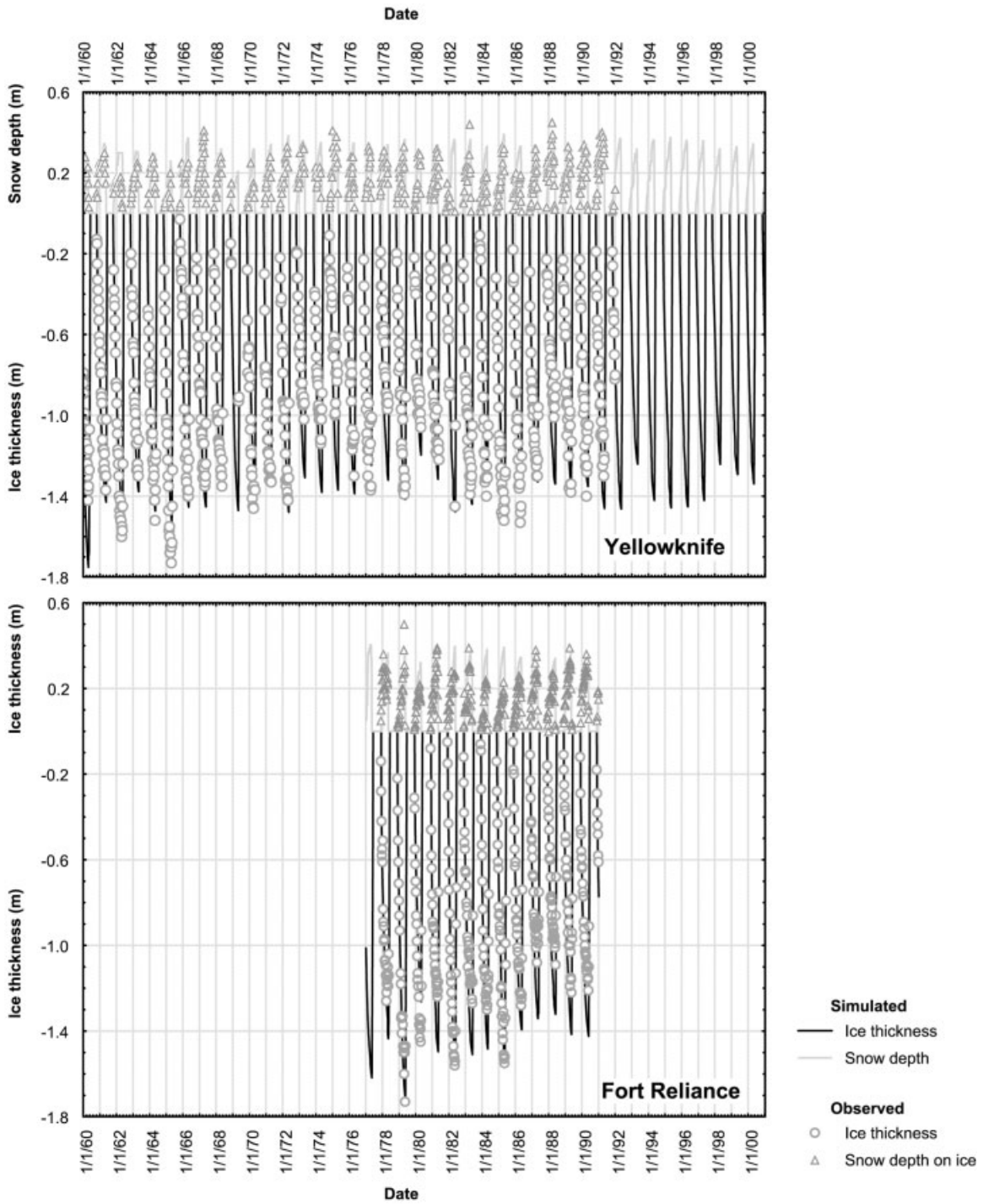

Figure 13. Comparison of measured and simulated ice thickness and on-ice snow depth for Back Bay (Yellowknife) and Charlton Bay (Fort Reliance)

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Table II. Comparison of measured and simulated ice thickness and on-ice snow depth at Yellowknife (Back Bay; 1960–91) and Fort Reliance (Charlton Bay; 1977–90) sites

	Yellowknife (10 m)[a]	Fort Reliance (30 m)[a]
Ice thickness		
I_a	0·943	0·992
RMSE (cm)	9	18
MBE (cm)	6	8
Snow depth		
I_a	0·817	0·939
RMSE (cm)	5	9
MBE (cm)	−4	−4

[a] Mixing depth.

Simulated and measured ice thickness and snow depth values are compared in Table II. The index of agreement I_a indicates that the model does very well at reproducing the seasonal evolution and interannual variations of ice thickness in Charlton Bay ($I_a = 0{\cdot}992$) and Back Bay ($I_a = 0{\cdot}943$), and slightly less so for snow depth ($I_a = 0{\cdot}939$ and 0·817 respectively for the same two sites). Figure 13 shows that the model tends to overestimate ice thickness for several years of the simulation. The MBE and RMSE permit a better appreciation of the differences between simulated and observed values. For Charlton Bay, the MBE is 8 cm and RMSE 18 cm, which are a bit higher than those calculated for Back Bay (6 cm and 9 cm respectively). On-ice snow depth, on the other hand, is underestimated by 4 cm (MBE of −4 cm) at both sites. Therefore, given the snow depth and ice thickness observed at the two sites, the proportion of error is greater for snow depth. The overestimation of ice thickness in these model runs is likely due to the fact that snow depth is underestimated. Indeed, for an equivalent snow density, a shallower snow cover will favour the development of a thicker ice cover. However, it should also be noted that snow densities derived from snow courses on land and used in the simulations may also account for some level of error.

These results suggest that the model needs to be improved upon regarding its handling of snow cover. Through its role as a thermal insulator and as a contributing factor to the formation of snow ice, snow cover plays a significant role in the evolution of lake ice covers (Adams and Roulet, 1980; Bengtsson, 1986). The use of more frequent snow density observations by the model, on a daily basis for example, could permit one to improve the results with regard to the evolution of snow cover on the lake ice surface. In fact, snow water equivalent and depth measurements from snow courses used to calculate snow density in the model were only made very sporadically during the winter months. Linking or coupling CLIMo to a snow model, such as SNTHERM (Jordan *et al.*, 1999), CROCUS (Brun *et al.*, 1989) or SNOWPACK (Brown *et al.*, 2001), could improve the ice cover simulations.

SUMMARY AND CONCLUSION

A one-dimensional thermodynamic lake ice model (CLIMo) has been used to simulate ice phenology on GSL. Input data from three weather stations (Yellowknife, Hay River and Fort Reliance) were used for model simulations, and *in situ* ice observation sites on GSL, located near the weather stations, were utilized to validate model results. The simulations conducted for a several-years period have shown that the model is capable of reproducing the seasonal and interannual evolution of ice thickness and on-ice snow depth, as well as the interannual variations in freeze-up and break-up dates.

Simulated freeze-up dates showed differences of 3 to 6 days compared with shore-based observations. The simulation results have revealed that lake depth is a determinant of freeze-up dates and that CLIMo is able to

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simulate ice cover for lake sites of various depths. Freeze-up dates derived from SSM/I passive microwave imagery over GSL presented an excellent match with simulation results obtained with mixed-layer depths (30, 40, 50 m) close to those observed in the main-lake section before fall freeze-up. Break-up dates were also generally in good agreement with shore-based observations, within 4 days, with the exception of the Charlton Bay site (10 days). External factors (e.g. topography surrounding the bay or other environmental factors) not captured by the model could explain, at least in part, the discrepancies between simulated and observed break-up dates. Simulated ice thicknesses presented a close correspondence to measurements made in Back Bay and Charlton Bay over several years. Some of these deviations could be explained by errors in simulated snow depths.

There are several avenues worth pursuing with regard to future improvements and simulations with CLIMo. One is the handling of the seasonal evolution of snow cover. In its current version, the model does not handle snow metamorphism, nor does it take into account the redistribution of snow by wind on the lake ice surface. The possible improvement of on-ice snow depth and density estimates with a snow model clearly merits further investigation. Other aspects of interest related to the validation of outputs from CLIMo include: (1) the comparison between modelled albedos and those obtained *in situ* and derived from satellite sensors such as NOAA AVHRR; (2) the effect of using hourly instead of mean daily values of meteorological input data on, for example, break-up dates; and (3) a more in-depth comparison of the freeze-up and break-up dates derived from SSM/I (and eventually SMMR) with those obtained with CLIMo. With regard to the first two points, radiation and energy balance instrumentation installed at three different-sized lakes in the Yellowknife area in 2001 will permit us to look into these in the near future. In relation to the third point, comparison of simulation results is envisaged using input data from single stations and groupings of stations around GSL, as well as gridded data products (e.g. National Centers for Environmental Prediction–National Center for Atmospheric Research reanalysis, European Center for Medium-range Weather Forecasts). Lastly, the impact of climate change on ice cover duration on GSL, and smaller lakes in its vicinity, is another logical next step to the research described herein.

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