Simulation of Ice Phenology on a Large Lake in the Mackenzie River Basin (1960–2000)

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ABSTRACT: A one-dimensional thermodynamic lake ice model (the Canadian Lake Ice Model or CLIMo) is presented and validated against *in situ* observations from Back Bay on Great Slave Lake (GSL) in the Mackenzie River basin, N.W.T. CLIMo results are also compared with freeze-up and break-up dates derived from SSM/I 85 GHz passive microwave data over GSL. Simulations are carried out over a 41-year period (1960–2000). Meteorological variables used as input for model simulations consist of air temperature, relative humidity, wind speed, cloud cover and snow on the ground. In addition, snow density derived from snow course measurements is used whenever available. The model output contains several information, notably ice and snow thickness as well as freeze-up and break-up dates.

CLIMo reproduces lake ice phenology very well. Results show an excellent agreement between observed and simulated ice thickness and on-ice snow depth. The freeze-up and break-up dates are also well reproduced with a RMSE of 6 and 4 days, respectively. Undoubtedly, given the huge area of GSL, meteorological data from the Yellowknife airport weather station are probably representative of only a limited section of the lake. This is one of the reasons why a future investigation will focus on several weather stations around the lake.

RÉSUMÉ: Un modèle de glace lacustre thermodynamique unidimensionnel (Canadian Lake Ice Model ou CLIMo) est présenté et validé à l'aide d'observations *in situ* provenant de Back Bay (Grand lac des Esclaves) situé dans le bassin du fleuve Mackenzie, T.N.-O. De plus, les résultats sont comparés avec les dates de formation et de disparition du couvert glaciel dérivées à partir des données satellitaires en micro-ondes passives SSM/I 85GHz. Les simulations couvrent une période 41 années (1960–2000). Les données utilisées pour faire fonctionner le modèle sont : température de l'air, humidité relative, vitesse du vent, couverture nuageuse et la neige au sol. De plus, la densité de la neige calculée à partir des mesures d'équivalent en eau de la neige est utilisée lorsque disponible. Le modèle génère plusieurs informations, notamment l'épaisseur de glace et de neige, ainsi que les dates de formation et de disparition du couvert glaciel.

CLIMo a reproduit le cycle glaciologique lacustre avec une bonne précision. Les résultats montrent une excellente corrélation entre les épaisseurs de glace et de neige simulées et celles observées. Les dates de formation et de disparition du couvert de glace sont aussi bien reproduites avec un RMSE de 6 et de 4 jours respectivement. Évidemment, les données météorologiques provenant de la station de Yellowknife ne sont représentatives que d'une portion limitée du Grand Lac des Esclaves. Les travaux subséquents porteront sur la réalisation de simulations pour plusieurs stations situées sur le pourtour du lac.

Keywords: Modelling, lake ice, freeze-up, break-up, ice thickness, Great Slave Lake

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INTRODUCTION

Very large expenses 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 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 greatly enhance 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-early winter can be double those in spring-early autumn (Rouse, 2000). Information of 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 (Walsh *et al*. 1998; Launiainen and Cheng, 1998; Liston and Hall, 1995; Barry, 1984). A change of only a few degrees in air temperature is sufficient to shift freeze-up and break-up dates by several weeks (O'Neill *et al*., 2001; Liston and Hall, 1995).

The sensitivity of lake ice to climatic variability has promoted the development of lake ice models (e.g. Liston and Hall, 1995; Vavrus *et al*., 1996; Stefan and Fang, 1997). These models have been validated against 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, 1995; 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 the one-dimensional thermodynamic model CLIMo (Canadian Lake Ice Model) for the simulation of ice phenology on Great Slave Lake, NWT, for a period of 41 years (1960–2000). Model output such as ice thickness and snow depth on ice as well as freeze-up and break-up dates are compared to *in situ* and remote sensing observations.

MODEL DESCRIPTION AND DATA SET

Initially based on the one-dimensional sea ice model of Flato and Brown (1996), CLIMO has undergone several changes in order to simulate ice phenology on lakes of various sizes. A detailed description of the model (parameterizations and equations) can be found in Duguay *et al.* (submitted).

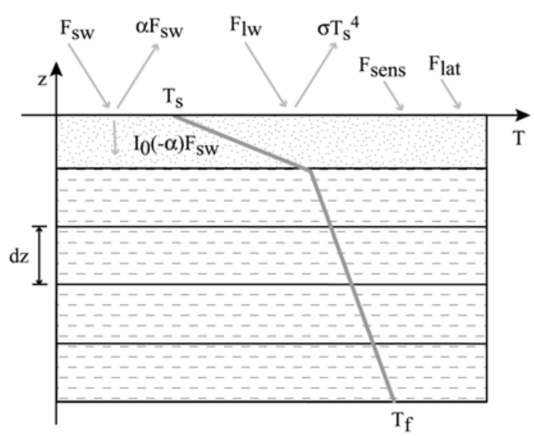

Figure 1. Schematic illustration of CLIMo under winter conditions.

A schematic illustration of the model under winter conditions is shown in Figure 1. The dotted layer represents snow cover and the layers with dashed lines the ice cover. The grey arrows above the surface represent the components of the surface heat budget used in the model. The heavy grey line passing through the snow and ice layers indicates the temperature profile. CLIMo solves this profile using the one-dimensional unsteady heat conduction equation, with penetrating solar radiation, presented by Maykut and Untersteiner (1971), i.e.,

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

where

ρ	density (kg m^{-3})
C_p	specific heat capacity (K kg^{-1} K^{-1})
T	temperature (°K)
t	time (s)
k	thermal conductivity (W m^{-1} K^{-1})
z	vertical coordinate, positive downward (m)
F_{sw}	downwelling shortwave radiative energy flux(W m^{-2})
I_o	fraction of shortwave radiation flux which penetrates the surface (W m^{-2})
α	surface albedo
K	bulk extinction coefficient for penetrating shortwave radiation

Then, the surface energy budget is computed from:

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

where

F_o	net downward heat flux absorbed at the surface (W m^{-2})
ε	surface emissivity
σ	Stefan–Boltzmann constant (5,67 x 10^{-8} Wm^{-2} K^{-4})
T	temperature (°K)
α	surface albedo
F_{lw}	downwelling longwave radiative energy flux(W m^{-2})
F_{sw}	downwelling shortwave radiative energy flux(W m^{-2})
F_{lat}	downward latent heat flux (W m^{-2})
F_{sens}	downward sensible heat flux (W m^{-2})
I_o	fraction of shortwave radiation flux which penetrates the surface (W m^{-2})

The model only requires 5 meteorological variables and a few extra parameters to simulate lake ice phenology. The meteorological variables used as input consist of daily mean air temperature (°C), wind speed (m/s), relative humidity (%), cloud cover (1/10), and snow depth (m). In addition, snow density derived from snow course measurements is used whenever available (Meteorological Service of Canada, 2000). The atmospheric forcings extend over a 41-year period (1960–2000). The other parameters required were the number of layers in the ice cover, the time step, the mixing depth and the latitude of the study area.

The model output parameters generated by CLIMo include ice thickness (snow ice and black ice) and snow depth on a daily basis. The annual freeze-up/break-up dates are also produced by the model. Lake ice, snow depth and freeze-up/break-up dates observations used to validate model results were extracted from Canadian Ice Database (CID) and extend over 30 years (1960–1991).

MODEL SIMULATION AND STATISTICAL MEASURES

Simulations were performed using meteorological data acquired at the Yellowknife Airport weather station (62.28 N 114.27W), which is located on the north shore of GSL (Figure 2). *In situ* observations used to validate model output are from Back Bay. As a major feature of the Mackenzie River Basin, GSL covers an area of over 28 000 km^2 , with a mean depth of 145 m and maximum depth of 614 m attained in the eastern section of the lake.

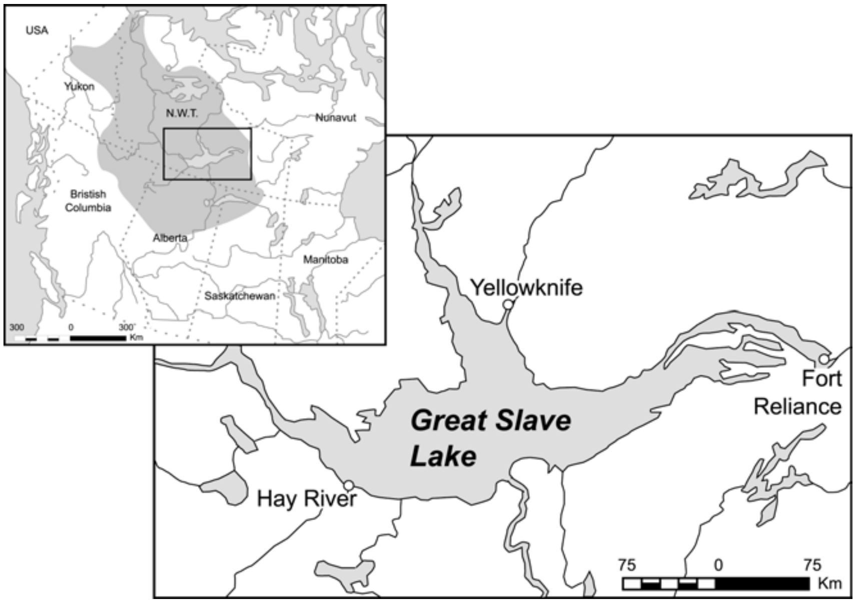

Figure 2. Location of study area.

Yellowknife is located at an altitude of 200 m a.s.l. in a region characterized by a vegetation cover typical of the taiga shield. The regional climate is of the sub-arctic continental type with a mean temperature of –28 C for the month of January and 16.5 C in July. Total annual precipitation rarely exceeds 267 mm, of which less than half falls in solid form. Since the model does not use lake depth as an input variable, the depth of the mixed layer is used instead. More specifically, 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 is

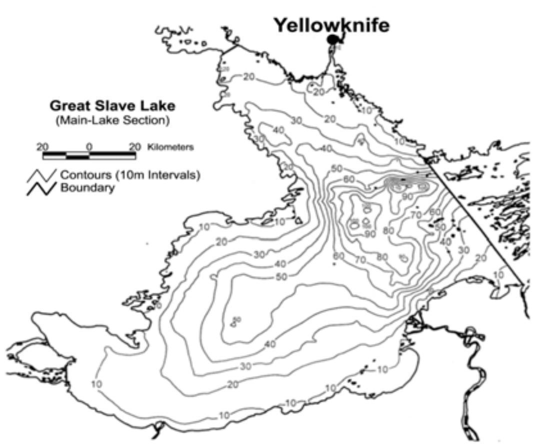

Figure 3. Bathymetry of Great Slave Lake (Schertzer *et al*., 2000).

therefore an important parameter in the determination of freeze-up dates (Vavrus *et al*., 1996 ; Barry & Maslanik, 1993). The mean depth of Back Bay, where the in situ lake ice observations were made, is approximately 10 m (Figure 3). Simulations were thus conducted by varying the depth of the mixed layer between 1 and 50 m.

Three statistical indices were calculated to validate the lake ice model results: the relative index of agreement, the root mean square error, and the mean bias error. These indices have shown to be robust statistical measures for validating model performance (e.g. Wilmott and Wicks, 1980; Hinzman *et al*., 1998). The relative index of agreement (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 modeled and observed values. I_a has values ranging from 0 (worst performance) to 1 (best possible performance). The root mean square error (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 a RMSE value of zero means that there is no deviation between the simulated and observed values. The mean bias error (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 cm 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.

RESULTS AND DISCUSSION

Freeze-up/Break-up dates

The lake ice model reproduces freeze-up and break-up dates very well for the Yellowknife (Back Bay) site over the entire time series of observations, between 1960 and 1991 (Figure 4). The effect of the mixed-layer depth on freeze-up dates is particularly noticeable. The greater the value,

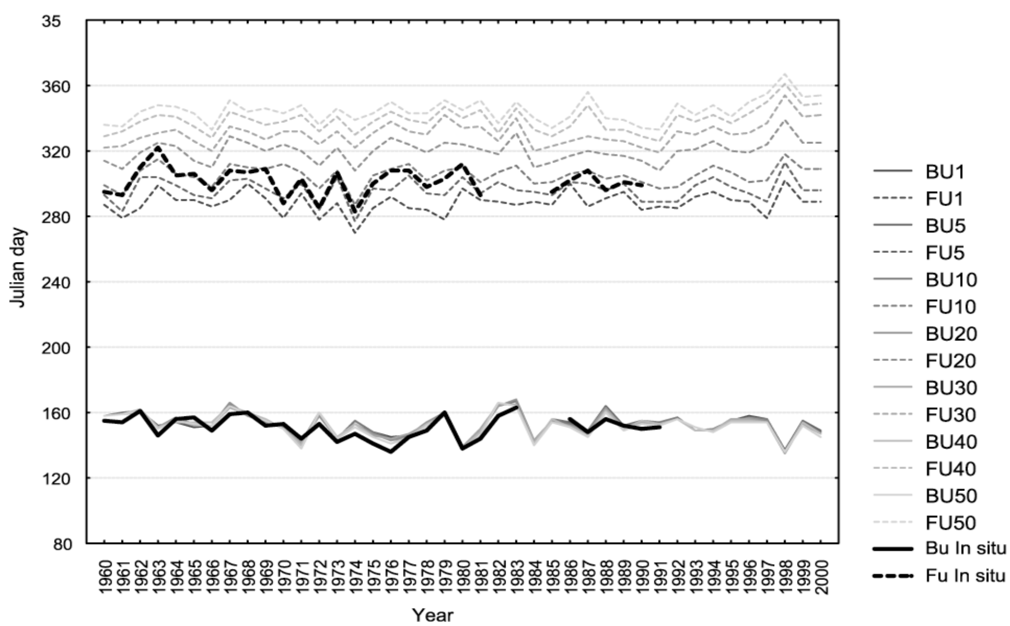

Figure 4. Freeze-up/break-up dates simulated and observed using different mixing depth values, Back Bay, 1960–2000.

the longer it takes for the ice cover to form. The best results are 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 3).

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

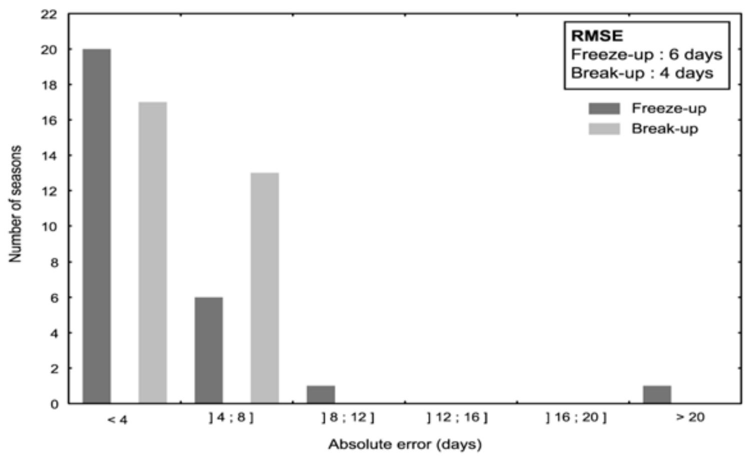

Figure 5. Histogram of absolute errors in simulated and observed freeze-up/break-up dates, Back Bay, 1960-2000 (mixing depth : 10m).

freeze-up dates. The histogram of Figure 5 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 root mean square error (RMSE) is 6 days for freeze-up and only 4 days for break-up dates.

Table I. Comparison of observed and simulated freeze-up/break-up dates, ice thickness and snow depth, Yellowknife (Back Bay) 1960–2000.

Statistical measures	Freeze-up	Break-up	Ice thickness (cm)	Snow depth (cm)
I_a	0.996	0.901	0.943	0.817
RMSE	6	4	9	5
MBE	6	4	6	–4
I_a : relative index of agreement, RMSE : root mean square error (days or cm), MBE : mean bias error (days or cm)				

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 were used for comparison. The potential of this type of imagery for the determination of freeze-up and break-up dates on GSL has been shown in a previous study by Walker and Davey (1993). Unlike in situ observations, satellite sensors such as SSM/I provide a spatial coverage which permits to monitor ice formation and decay over the complete lake surface in an objective, timely, fashion. In order to better compare lake-wide SSM/I-derived dates with simulated dates for Back Bay, we plotted the freeze-up and break-up dates obtained with mixed layer depths of 30, 40 and 50 m (Figure 6).

The mixed layer depth at a site near the mid section of GSL on September 10, 1998 was determined to be around 50 m (Schertzer, pers. comm., 2000). An excellent correspondence is achieved for the freeze-up dates over the 11 years of simulation. The MBE is –8, 0, and 6 days for mixing depths of 30, 40 and 50 m, respectively. The deviation between simulated and observed break-up dates is, as expected, more important.

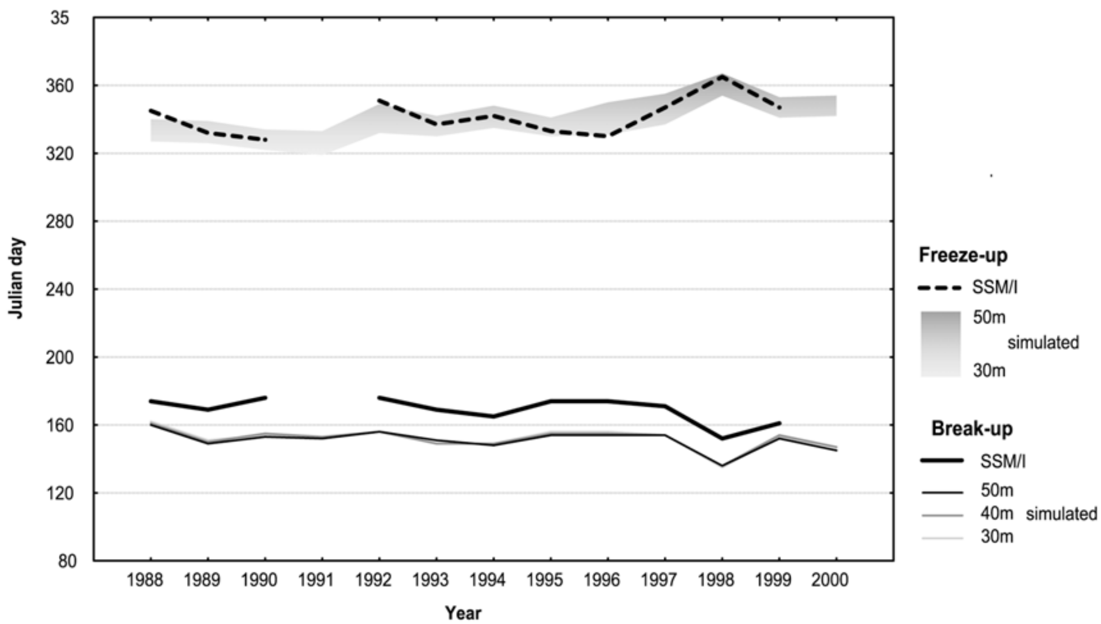

Figure 6. Comparison of freeze-up/break-up simulation results obtained using mixed layer depths of 30, 40, and 50 m, and dates obtained from SSMI/I 85 GHz data over the entire area of GSL.

Ice thickness and snow depth

The model reproduces quite well the evolution of ice thickness and on-ice snow depth for the Yellowknife (Back Bay) site (Figure 7). 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 (Table I). The ice thickness is overestimated with a MBE of 6 cm and a RMSE of 9 cm. On-ice snow depth, on the other hand, is underestimated by 4 cm (MBE of –4 cm). Therefore, given the snow depth and ice thickness values observed, 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 to improve the results with regards 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.

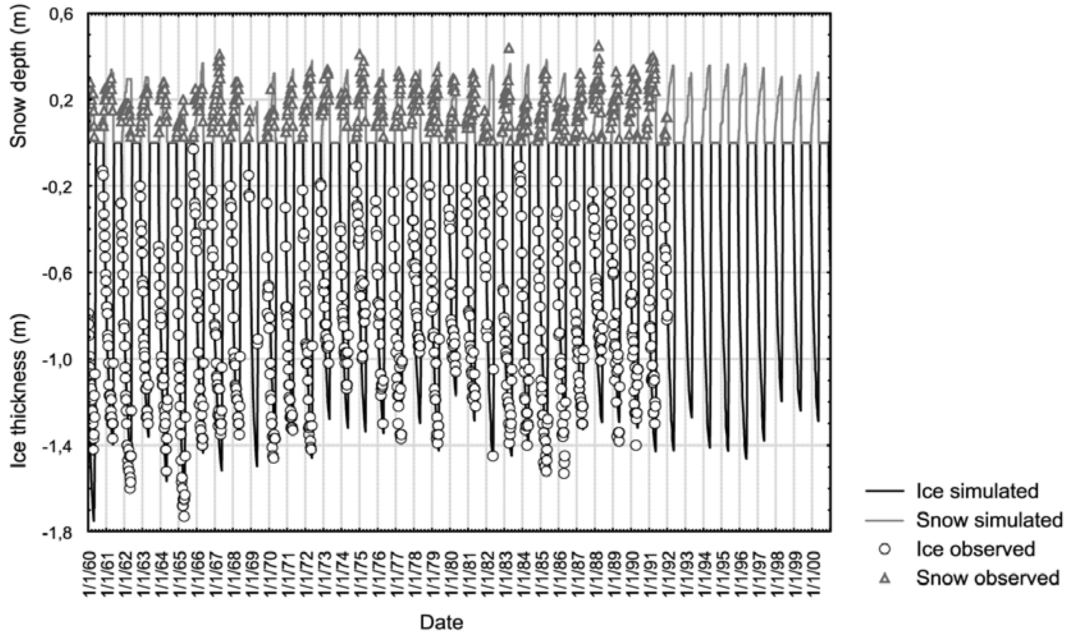

Figure 7. Simulated and observed ice thickness and snow depth, Back Bay, 1960–2000 (mixing depth 10 m).

CONCLUSION

A one-dimensional thermodynamic lake ice model (CLIMo) has been used to simulate ice phenology on Great Slave Lake (N.W.T.). The simulations conducted over several years 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. Freeze-up dates were off by 6 days when compared to shore-based observations. The simulation results have shown that lake depth is a determinant of freeze-up dates and that CLIMo is able to 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.

There are several avenues worth pursuing with regards 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 to be further investigated. Other aspects of interest related to the validation of outputs from CLIMo include: 1) the comparison between modeled albedos and those obtained in situ and derived from satellite sensors such as NOAA AVHRR, and 2) the effect of using hourly instead of mean daily values of meteorological input data on, for example, break-up dates. Radiation and energy balance instrumentation installed at three different-sized lakes in the Yellowknife area in 2001 will permit to look into these in the near future. 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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REFERENCES

Adams, W.P., Roulet, N.T., 1980. Illustration of the roles of snow in the evolution of the winter ice of a lake. *Artic*, vol. 33, 100–116.

Barry, R.G., Maslanik, J.A., 1993. Monitoring lake freeze-up/break-up as a climatic index. World Data Center for Glaciology. 66–77.

Bengtsson, L., 1986. Spatial variability of lake ice covers. *Geografiska Annaler*, vol. 68A, 113–121.

Brown, R.L., Satyawali, P.K., Lehning, M., Bartelt, P., 2001. Modeling the changes in microstructure of snow during metamorphism. *Cold Regions Science And Technology*, vol. 33, no. 2-3, 91-101.

Brun, E., Martin, E., Simon, V., Gendre, C., Coleou, C., 1989. An energy and mass model of snow cover suitable for operational avalanche forecasting. Journal of Glaciology, vol. 35, 333–342.

Duguay, C.R., Flato, G.M., Jeffries, M.O., Ménard, P., Morris, K., Rouse, W.R., 2001. Ice cover variability on shallow lakes at high latitudes: model simulation and observations. *Hydrological Processes*, in press.

Fang, X., Stefan, H.G., 1998. Potential climate warming effects on ice covers of small lakes in the contiguous U.S. Cold Regions Science and Technology, vol. 27, 119–140.

Flato, G.M., Brown, R., 1996. Variability and climate sensitivity of landfast artic sea ice. *Journal of geophysical research-ocean*, vol. 101, C10, 25767–25777.

Heron, R., Woo, M.-K., 1994. Decay of a high Arctic lake-ice cover: observations and modeling. *Journal of Glaciology*, vol. 40, 283–292.

Hostetler, S.W., Bartlein, P.J., 1990. Simulation of lake evaporation with application to modeling lake level variations of Harney-Malheur Lake, Oregon. *Water resources Research*, vol. 26, no. 10, 2603–2612.

Hinzman, L.D., Goering, D.J., and Kane, D.L., 1998. A distributed thermal model for calculating soil temperature profiles and depth of thaw in permafrost regions. *Journal of Geophysical Research*, vol. 103, no. D22, 28,975–28,991.

Jordan, R.E., Andreas, E.L., Makshtas, A.P. 1999. Heat budget of snow-covered sea ice at North Pole 4. *Journal of Geophysical Research* vol. 104 (C4), 7785–7806.

Liston, G.E., Hall, D.K., 1995. Sensitivity of lake freeze-up and break-up to climate change: a physically based modeling study. *Annals of Glaciology*, vol. 21, 387–393.

Liston, G.E., Hall, D.K., 1995. An energy-balance model of lake-ice evolution. *Journal of Glaciology*, vol. 41, no.138, 373–382.

Maykut, G.A., Untersteiner, N., 1971. Some results from a time-dependent thermodynamic model of sea ice. *Journal of Geophysical Research*, vol. 76, 1550–1575.

MSC. 2000. *Canadian snow data CD-ROM*. CRYSYS Project, Climate Processes and Earth Observation Division, Meteorological Service of Canada, Downsview, Ontario, January, 2000.

O'Neill, D., Brown, R., Agnew, T., Burgess, M., Cogley, G., Demuth, M., Duguay, C., Flato, G., Goodison, B., Koerner, R., Melling, H., Prowse, T., Ramsay, B., Sharp, M., Smith, S. and Walker, A. 2001. *The Canadian GCOS Plan—Cryosphere*, Meteorological Service of Canada, 70 pp.

Rouse, W.R., 2000. Progress in hydrological research in the Mackenzie GEWEX Study. *Hydrological Processes*, vol. 14, 1667–1685.

Schertzer, W.M., Rouse, W., Blanken, P., 2000. Cross-lake variation of physical limnological and climatological processes of Great Slave lake. *Physical Geography*, vol. 21, no. 5, 385–406.

Stefan, H.G. Fang, X., 1997. Simulated climate change effects on ice and snow covers on lakes in temperate region. *Cold Regions Science and Technology*, vol. 25, 137–152.

Stefan, H.G., Fang, X., Hondzo, M., 1998. Simulated climate change effects on year-round water temperature in temperate zone lakes. *Climatic Change*, vol. 40, 547–576.

Vavrus, S.J., Wynne, R.H., Foley, J.A., 1996. Measuring the sensitivity of southern Wisconsin lake ice to climate variations and lake depth using a numerical model. *Limnology and Oceanography*, vol. 41 no. 5, 822–831.

Walker, A. E., Davey, M. R., 1993. Observation of Great Slave Lake ice freeze-up and break-up processes using passive microwave satellite data. *Proceedings of the 16th Canadian Remote Sensing Symposium*, 7–10 June, Sherbrooke, Quebec, Canada, 233–238.

Walsh, S.E., Vavrus, S.J., Foley, J.A., Fisher, V.A., Wynne, R.H., Lenters, J.D., 1998. Global pattern of lake ice phenology and climate :Model simulation and observations. *Journal of Geophysical Research-Atmosphere*, vol. 103, D22, 28825–28837.

Wilmott, C.J., 1982. Some comments on the evaluation of model performance. *Bulletin of the American Meteorological Society*, vol. 63, 1309–1313.

Wilmott, C.J. and Wicks, D.E., 1980. An empirical method for the spatial interpolation of monthly precipitation within California. *Physical Geography*, 1, 59–73.