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Parameterization of lake thermodynamics in a high-resolution weather forecasting model

By PATRIK LJUNGEMYR*, NILS GUSTAFSSON and ANDERS OMSTEDT, *Swedish Meteorological and Hydrological Institute, S-601 76, Norrköping, Sweden*

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ABSTRACT

A model for the parameterization of lake temperatures and lake ice thicknesses in atmospheric models is presented. The model is verified independently, and it is also tested within the framework of the High Resolution Limited Area Model (HIRLAM), applied operationally for short range weather forecasting at the Swedish Meteorological and Hydrological Institute (SMHI). The lake model is a slab model based upon energy conservation and treats the lakes as well mixed boxes with depths represented by the mean depths. The model is forced by near surface fluxes calculated from total cloudiness, air temperature, air humidity and low-level winds. A data base, describing 92 000 Swedish lakes, provides the model with lake mean depths, areal sizes and locations. When the model is used for parameterization of lake effects in the atmospheric model, all the smaller lakes and the fractions of larger lakes within each horizontal grid square of the atmospheric model are parameterized by four model lakes, representing the lake size distribution. The verification of the lake model is done by comparing it with a more advanced, vertically resolved model, including parameterization of turbulent mixing processes, as well as by comparison with observations. A sensitivity test shows great interannual variations of the ice-covered season, which implies that lake models should be used instead of climate data. The results from an experiment with two-way coupling of the lake model to the atmospheric model are verified by comparing forecasted weather parameters with routine meteorological observations. These results show that the impact of lake effects can reach several °C in air temperatures close to the surface.

1. Introduction

High resolution weather forecasting models generally include sophisticated parameterization schemes for the calculation of heat, water and momentum fluxes between the surface of the earth and the atmosphere. With regard to land surfaces, the temporal development of the soil conditions is generally described by multi-layer models for the heat and water fluxes within the soil, and there may also be separate models for a vegetation layer between the soil and the atmosphere. Considering the time scales of the sea surface condition changes, sea water temperatures and sea ice coverage are generally treated as fixed during the time integration of the weather forecasting models, while the effects of surface waves on the fluxes between the sea surface and the atmosphere are taken care of by simple parameterization schemes. Initial conditions for the sea-surface conditions are generally obtained by objective analysis techniques, including the use of remote sensing data.

The effects of inland lakes have so far been neglected or treated very crudely in weather forecasting models. The Northern European area is of particular interest in this connection. Sweden has about 92 000 lakes, larger than 100^2 m^2, distributed over the whole country. These lakes cover

* Corresponding author

together 9% of the Swedish land area, and the conditions in Finland are similar to the conditions in Sweden. Most weather forecasting models, like the operational ECMWF model, permits the use of only one surface type within each computational grid square. Taking into account the applied horizontal resolution of these operational forecast models, most inland lakes simply disappear, since the lower boundary condition is treated as a pure land surface except over sea and over a few very large inland lakes. Other forecasting models like HIRLAM, see below, take lake effects into account by parameterization of surface sub-grid scale effects, but these effects are generally treated in a very crude way, e.g. by assuming a climatological variation of the lake temperature and ice conditions.

The treatment of the lake effects in weather forecasting models needs to be improved for two reasons. First, neglect of the lake effects will have a systematic and long term influence on the average model surface fluxes of latent and sensible heat. This will also influence other parts of the energy and water cycles, e.g., precipitation and low-level clouds. Then there is certainly also a direct effect on the local weather forecasts. Every duty forecaster, given the task to forecast the actual weather for the Northern Sweden inland areas, knows the importance of the ice conditions on the lakes in this area, in particular since the areas close to rivers and inland lakes are the most densely populated areas. A breaking up of the lake ice due to strong surface winds, for example, may completely alter the forecast for, e.g., visability due to the completely different evaporation characteristics from ice and water surfaces.

To improve the treatment of lake effects in weather forecasting models, we have the possibilities of trying to improve the lake climatology, of utilizing observations from e.g., satellites or, finally, of trying to introduce a parameterization based on lake models. In this paper we will show, that the climatology approach is not a very promising approach, since there is a significant interannual variablity of the lake conditions. Ideally, we would prefer to use a combination of lake modelling and observations of lake conditions. Lake models are needed in order to cope with the large spatial variations of lake conditions within an area to be represented by, e.g., a grid square and, in addition, if we want to consider also changing lake conditions within the forecast range. Available lake observations are today very sparsely distributed, but satellite observations are a potentially important data source. Lake observations will certainly be needed as a complement to the lake models in order to avoid a drift away from real lake conditions in the coupled lake-atmosphere forecasting system.

The main aim of this paper was to investigate whether the lake effects can be parameterized by a simple thermodynamic lake model. We have chosen to use the High Resolution Limited Area Model (HIRLAM) forecasting system for this investigation. HIRLAM has been developed within a research project among the weather services in the Nordic countries, the Netherlands and Ireland. HIRLAM is applied operationally by the Swedish Meteorological and Hydrological Institute.

Several models have been developed for lake studies. Vertically resolved models are generally used for thermodynamic studies, and different aspects of the energy exchange have been studied (Svensson, 1978; Sahlberg, 1988; Omstedt, 1984; Elo, 1994). In these studies, single individual lakes were simulated with vertically resolved and time-dependent models and with the turbulent exchange calculated from a two-equation model of turbulence. In general, these studies demonstrate that the lake surface temperature can be well simulated on the basis of meteorological forcing from standard station data and the fact that lake ice is important to consider during the winter season. In the present paper, we use these lake studies as a guidance for the parameterization of lakes in atmospheric models. We will simplify the model approach and consider the lakes from an atmospheric point of view. Thus the effects of lakes will be treated as a large number of sources or sinks for heat and moisture to the atmosphere. These sources and sinks will be distributed according to the real lake area distribution. Some statistics on the distribution of lakes in Sweden are given in Section 2. Then, in Section 3, the lake model is outlined with details of calculations presented in Section 4. In Section 5, some different results from application of the lake model are given. Firstly, we compare the model with results from a vertically resolved model. Secondly, we compare calculated and observed data from some lakes for the period 1985–1993. Thirdly we examine the model sensitivity to changes in lake depth. The lake model is finally applied to all lakes in Sweden and coupled to the atmospheric model HIRLAM. The results from some coupled model runs are given in Section 6. Finally, a summary with some conclusions is given in Section 7.

2. The lakes of Sweden: areal sizes and depths

The total lake area in Sweden is 41 463 km^2, which corresponds to 9.3% of the land area (Table 1). The ten largest lakes of Sweden cover 27% of the lake area (Table 2). The largest lake is Vänern with an area of 5 648 km^2. The deepest lake is Hornavan with a maximum depth of 222 m. All lakes that are larger than 100^2 m^2 are included in the Swedish data base SVAR. The total number of lakes is 92 409 and the data base gives information about the lake areas, the mean depths and, for the larger lakes, also the shore lines and the positions of the lakes.

The SVAR archive information has been adapted to the HIRLAM grid. All the lakes are divided into 4 groups. The large lakes have, when necessary, been divided into more than one grid square. These large lakes are about 4 000. The other three lake groups have been given constant areas and constant depths. The data base gives the number of lakes in each of these three groups for each grid cell. Grid squares of size (0.05°)^2 are used, as it will be possible to use this resolution for the HIRLAM model in the future. Today the (0.05°)^2 squares are summed up to the larger HIRLAM grid squares. The total fraction of lake area in the HIRLAM (0.5°)^2 grid squares is illustrated in Fig. 1.

The ice on the lakes in Sweden is normally formed between 15 October and 1 January, and the ice breaks up between 15 March and 15 June. The longest ice periods are in the north of Sweden and the shortest in the south. The length of the

Table 1. *The lake area distribution in Sweden*

Size (km^2)	Number of lakes	Lake area (km^2)	Lake area (%)
>1000	3	8 662	21
100–1000	21	4 594	11
10–100	371	9 317	22.5
1–10	3 533	9 735	23.5
0.1–1	20 277	6 854	16.5
0.01–0.1	68 254	2 301	5.5
Total	92 409	41 463	100

Table 2. *The 10 largest lakes in Sweden*

	Lake name	Area (km^2)	Mean depth (m)
1	Vänern	5 648	27.0
2	Vättern	1 912	40.8
3	Mälaren	1 140	12.5
4	Hjälmaren	484	6.2
5	Storsjön	464	17.3
6	Torneträsk	330	51.8
7	Siljan	290	27.8
8	Uddjaure	252	25.0
9	Hornavan	250	47.7
10	Akkajaure	242	25.0

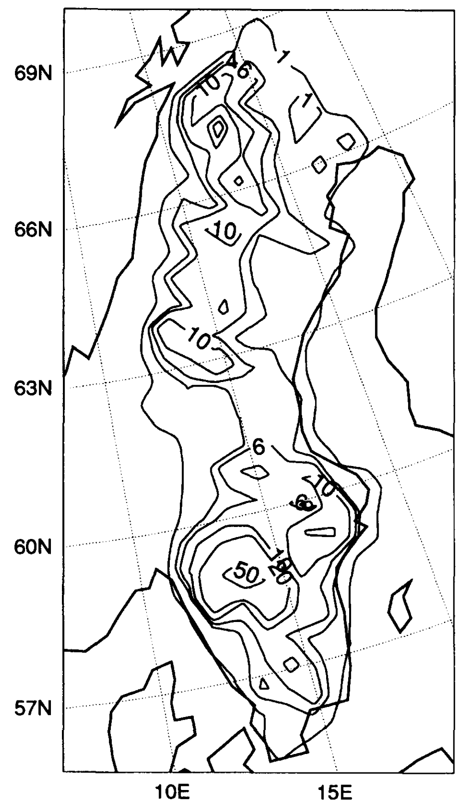

Fig. 1. Fraction of lake area (%) in 0.5° HIRLAM grid-squares.

ice period also depends on the size and depth of the lake. On deeper lakes the ice forms later because their heat content is larger compared to shallow lakes, and they therefore cools with a lower rate. The lakes that are near the coast have ice formed later due to the milder coastal climate. Lakes in the mountain regions are influenced by mild westerly winds from the Atlantic Ocean.

Within the HIRLAM computational area there are, except for Sweden, also Finland and the western part of Russia that have considerable land areas covered with lakes. Finland has about 10% of the land area covered with lakes and Lake Ladoga and Lake Onega, east of St. Petersburg, are two large lakes that probably are important enough to include in the simulations.

3. Theoretical considerations

The main physical processes relevant for the conditions in lakes are illustrated in Fig. 2. The amount of surface lake areas and lake surface properties as temperature and ice are the main issues of interest when dealing with the coupling between the lakes and the atmosphere. Lakes in mid latitudes exhibit a characteristic annual thermal cycle with two convective overturns, one during spring and one during autumn, when the lakes are mixed from top to bottom. In the summer season a well mixed warm surface layer (eplimnion) is formed on top of the colder deep water masses. Several physical processes are active in the lakes, see for example Ashton (1986). In the present approach (slab model) we will only consider the vertical exchange at the lake/atmosphere interface, and thus neglect horizontal effects as thermal bars and river and groundwater inflows of different temperatures. The vertical stratification is thus neglected, but as will be shown in the paper, the mean lake depth represents a good approximation for the active surface layer thickness when calculating the lake surface temperature. Based upon heat conservation principles, the lake temperature can be modelled according to:

$$\frac{\partial T_{\mathrm{w}}}{\partial t} = -\frac{1}{(\rho C_{\mathrm{P}} D)} [F_{\mathrm{h}} + F_{\mathrm{e}} + F_{\mathrm{lu}} + F_{\mathrm{ld}} + F_{\mathrm{s}}], \qquad (1)$$

where T_{w} is the water temperature, ρ the water density, C_{p} the specific heat of water (at constant pressure), D the mean depth. The heat fluxes are: F_{h}, the sensible heat flux, F_{e}, the latent heat flux, $F_{\mathrm{lu}} + F_{\mathrm{ld}}$, the net long-wave radiation, F_{s} the short wave radiation. All fluxes are defined to be positive from the surface towards the atmosphere.

After the autumn overturn, re-stratification starts, and lighter colder water is formed on top of denser water, and may freeze during late autumn

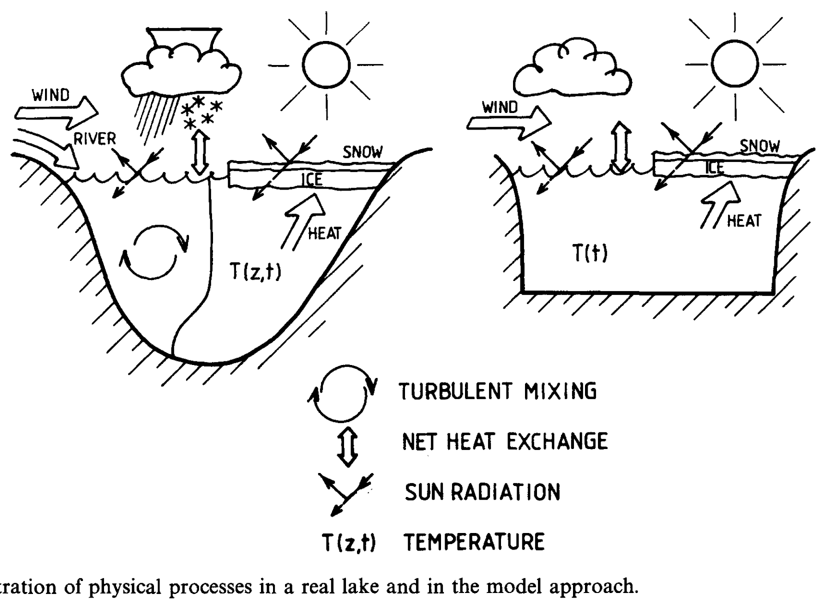

Fig. 2. Illustration of physical processes in a real lake and in the model approach.

and form ice during the winter season. Different ice types can form, and the growth is sensitive to snow, Leppäranta (1983). The classical modelling approach is to treat the ice growth as a one-dimensional heat conduction problem. We will follow this approach but assume that the initial ice growth is due to frazil ice. This implies that the initial ice grows linearly with time. As soon as the frazil ice has grown above a 5-cm thick layer, we assume that the ice grows as columnar ice, proportional to the square root of time. The equation for the frazil ice (Omstedt and Svensson, 1984) reads:

$$\frac{\partial H_\mathrm{f}}{\partial t}=\frac{F_\mathrm{NP}}{(L_\mathrm{i}\rho_\mathrm{i})} \quad \text{with} \quad F_\mathrm{NP}=\begin{cases} F_\mathrm{N} & F_\mathrm{N}>0 \\ 0 & F_\mathrm{N}\leqslant 0 \end{cases}, \tag{2}$$

where H_f is the frazil ice thickness, F_N the net heat flux (except short wave radiation) from the water surface, L_i the latent heat of ice and ρ_i the density of ice. The short-wave radiation (from the sun) is thus ignored in the frazil ice equation, as it is almost zero during autumn and early winter.The equation for the growth of columnar ice (Maykut, 1986) reads:

$$\frac{\partial H_\mathrm{c}}{\partial t}=(T_\mathrm{F}-T_\mathrm{A})\frac{k_\mathrm{s}k_\mathrm{i}}{(k_\mathrm{i}H_\mathrm{s}+k_\mathrm{s}H_\mathrm{i})L_\mathrm{i}\rho_\mathrm{i}}, \tag{3}$$

where H_c is the columnar ice thickness, H_i the total ice thickness ($H_\mathrm{f}+H_\mathrm{c}$), T_F the freezing temperature of the water, T_A the air temperature, k_s and k_i are the thermal conductivities of snow and ice and H_s is the snow thickness. The equation describes the heat conduction through the ice and snow layers. From the equation we notice that it can not be applied to the growth of the initial ice (when H_s and H_i both are equal to zero). This is another reason why we need to treat the initial ice growth separately.

The wind influences the ice by forming rafted and ridged ice. This is important to consider in large lakes but has been neglected in the present study. The snow ice growth must include correct precipitation values, this has, however, also not been considered.

The ice melt is a complex process, for example when the sun melts the ice and the albedo of the ice changes. In general, the thickness of the ice does not decrease much when it melts, but the ice becomes porous and then it melts rather rapidly during the break up. This is modelled by considering the net radiation balance between the short-wave radiation, that reaches the ice surface (F_ST) and the short wave radiation that penetrates the ice and goes into the water (F_SB). The equation reads:

$$\frac{\partial H_\mathrm{i}}{\partial t}=\frac{F_\mathrm{ST}-F_\mathrm{SB}}{L_\mathrm{i}\rho_\mathrm{i}}. \tag{4}$$

Thus, the ice thickness decreases linearly with time, since the difference in short wave radiation always is negative (positive flux upwards). The linear decay is in good accordance with field observations, Billelo (1980). For the calculation of the heat fluxes in eqs. (1) and (4) we at present follow Omstedt (1990). A more consistent approach would be to use the HIRLAM fluxes. This will be considered as the next step.

4. Details of the calculations

4.1. *The Lake model*

We have treated the lakes in a simplified way and neglected several processes as those related to horizontal and vertical gradients, in- and outflows, variations in ice albedo, ice ridging etc. However, we consider the basic thermodynamic balance, and the results in Section 5 give confidence in the approach. The basic simplifications are thus that the lakes are treated as well mixed (slab model) boxes and that ice ridging is neglected.

In each HIRLAM grid cell, the lakesize distribution is modelled by four lake models with different surface areas and depths according to the lake data base. The time step of the lake model is one hour, and the model is forced with meteorological data from every third hour. The following meteorological parameters are used: air temperature, relative humidity, total cloudiness and wind velocity. The temperature and humidity are taken from a height of 2 m and the wind from 10 m.

Some empirical limits are applied in the lake model. The lower limit for the water temperature is set to -0.01°C due to ice formation. Ice growth is only permitted when the water is colder than $+0.01$ degrees. The frazil ice is permitted to grow up to 10 cm. The columnar ice starts to grow when the ice thickness reaches 5 cm. For the simulation of wind and waves that may break up thin ice, the following condition is applied: If the wind is stronger than 6 m/s and the ice is thinner than 10 cm, the ice will break up and disappear. This rule of thumb was introduced by Sahlberg (1988).

During spring, the sun makes the ice porous and it may break up more easily. This is simulated through conditions on the ice thickness and season. During spring, the short wave radiation may penetrate the ice/snow cover if the ice is thin enough. This heats the water, and when it reaches 2°C above zero, the ice is assumed to break up. The snow cover is set to 2 cm if the ice thickness exceeds 10 cm, otherwise there is no snow cover in the model.

4.2. The High Resolution Limited Area Model (HIRLAM) forecasting system

A detailed description of the HIRLAM forecast model is given by Kållberg (1989). Here only a brief overview of the model formulation together with literature references and some details of relevance for the coupling to the lake model are given. The particular model set-up used for the experiments reported on in this paper is described in Section 6.

The HIRLAM model is based on the primitive equations with horizontal velocity components, temperature and surface pressure as prognostic variables. In addition, specific humidity is advected in the three spatial dimensions by the explicit Eulerian method, while cloud water is handled by an upstream advection scheme. The vertical co-ordinate is the terrain-following hybrid co-ordinate with sigma levels at the surface and pressure levels at the top (Simmons and Burridge, 1981). The horizontal grid is a spherical rotated co-ordinate system with the equator going through the centre of the integration area. The model is written on the Arakawa C-grid with second order spatial accuracy (Arakawa, 1966; Sadourny, 1975), and the time scheme is a three-time level semi-implicit scheme (Simmons and Burridge, 1981). Horizontal diffusion is carried out by a linear fourth order scheme. The model is initialized by an implicit non-linear normal mode initialization scheme similar to the scheme developed by Temperton (1988) adjusted for limited area initialization. The horizontal resolution is 55 km.

4.2.1. Parameterization of physical processes in HIRLAM. The vertical diffusion affects the horizontal wind components, dry static energy and specific humidity. The vertical diffusion scheme is based on first order turbulence closure, and it follows closely the scheme described by Louis (1979). Surface fluxes affect the prognostic values in the lowest model layer. They are determined by means of a drag coefficient formulation, using Monin-Obukhov (1954) similarity theory for the atmospheric surface layer. The drag coefficients are functions of a surface Richardson number, and a roughness length, For each grid point a fraction of land and a fraction of sea are defined. The roughness length over the fraction of the grid area covered by open sea is computed by Charnock's formula. The roughness length over land is given as a combination of a contribution from the vegetation and a contribution from the sub-grid scale variation of orography. For each grid point the surface fluxes are computed separately over land (including the ice-covered part of the sea) and over open sea including lakes. The calculation of fluxes above the lowest model level is based on a mixing length formulation, using exchange coefficients, which depend on static stability and windshear, described by means of a Richardson number. The analytic formulae describing the dependency of drag/exchange-coefficients on static stability are those proposed by Louis (1979). The effect of shallow convection is included by defining a modified Richardson number as proposed by Geleyn (1987).

The SMHI version of HIRLAM includes a scheme for parameterization of condensation, cloud and precipitation processes based on an explicit treatment of cloud water as a prognostic variable (Sundqvist et al. 1989, Sundqvist 1993). The surface parameterization scheme used is in essence the earlier ECMWF scheme with three soil layers (Sommeria, 1985), but modified with special attention paid to the treatment of snow and sea ice. The physical parameterization package also includes a radiation scheme (Savijärvi 1990; Sass et al., 1994).

4.2.2. Data assimilation. Initial atmospheric data for the HIRLAM forecast model integrations are obtained by forward intermittent data assimilation with a 6-h data assimilation cycle. The analysis of mass-, wind- and humidity-fields is based on 3-dimensional statistical interpolation of forecast errors (Lorenc, 1981). The analysis of the wind field and the mass field is multivariate and near geostrophic in analysis increments, while the analysis of the humidity field is univariate. The surface fields are influenced by the atmospheric data assimilation only via the subsequent adjustment processes during the forecast model integrations. The initial fields of snow depth, sea-surface temperature and sea-ice coverage are obtained from observed data by the aid of a simple 2-dimensional statistical interpolation scheme. One exception to this is the sea-ice coverage in the Baltic Sea, that is obtained from a short range forecast by a model describing sea ice drift as well as sea ice and sea water thermodynamics, see Omstedt et al. (1994) and Omstedt and Nyberg (1995). No data assimilation for soil parameters is presently included in the HIRLAM forecasting system. To prevent the state of soil to drift away without control, the deepest soil layer is prescribed by climatology.

4.3. *Coupling between the lake model and HIRLAM*

As a first simple approach, the coupling between the lake model and HIRLAM has been linked with the 6 hourly data assimilation and forecast cycles of HIRLAM. The lake conditions are kept constant in time during each such data assimilation and forecast cycle. The HIRLAM +3 h and +6 h forecasts are then used to force the lake model in order to obtain the lake conditions for the next HIRLAM data assimilation and forecast cycle.

It was mentioned above, that the surface fluxes of latent and sensible heat are calculated separately over land/ice and sea/lake water surfaces in HIRLAM. This calculation of surface fluxes has been integrated into the HIRLAM parameterization of vertical diffusion, where the lower boundary conditions are given by the grid areal fraction of land/ice, a sea/lake surface temperature, a land surface temperature and a surface air moisture parameter over land/ice. For the coupling of the lake model to HIRLAM, we simply calculate the grid areal fraction of land/ice and a representative lake surface temperature by averaging over all the lakes within each grid square. It would, because of the nonlinear relation between the fluxes and the temperatures, be better to average the fluxes instead of the temperatures, but the operational HIRLAM at SMHI (that calculates the fluxes when the lake model is coupled to HIRLAM) cannot deal with more than one lake/sea temperature per grid square.

5. Results from uncoupled lake simulations

The lake model has been tested by two methods. First, we have compared it with a well known and well tested lake model (Sahlberg, 1988) and then, we have validated it against measured and observed lake conditions. Of course, the latter method is the best one, but there are quite few measured data sequences for complete years from lakes available. Measurements from some ten lakes are taken twice a year in Sweden. The exception is lake Vänern for which surface temperature and ice cover are analysed twice a week by the Marine Forecast Office at SMHI. There are regular data on ice formation and ice break-up dates for about 500 lakes in Sweden and measurements of the ice thickness from about 20 lakes. The lack of day by day lake information clearly illustrates the need for lake models.

5.1. *Comparison with a vertically resolved lake model*

The vertically resolved model, (Sahlberg, 1988), for the lake of Helgasjön was developed on request from the Växjö municipality in Sweden. It was tested against measurements from several places in the lake during several years. The model is a multi-layer model which takes care of vertical mixing, heat from both surface processes and bottom sediment, ice growth and melting, but it does not take notice of horizontal processes, as it is a one-dimensional model. It uses the same subroutine as in the present study for calculating the heat fluxes through water and ice surfaces.

Our well mixed model has been tested against the vertically resolved model during 1983/1984 (see Figs. 3 and 4) assuming that the lake depth in our model could be represented by the mean depth. The results are illustrated by the figures and they are most satisfactory. The maximum model difference is 3.4°C during a hot period of the summer and the average absolute model difference is 0.7°C. The model results for ice do not agree with Sahlberg's model as well as the temperature results. The ice formation date is well caught, but the main ice period is about three weeks too long. The results indicate that further work is needed in the development of an improved ice model.

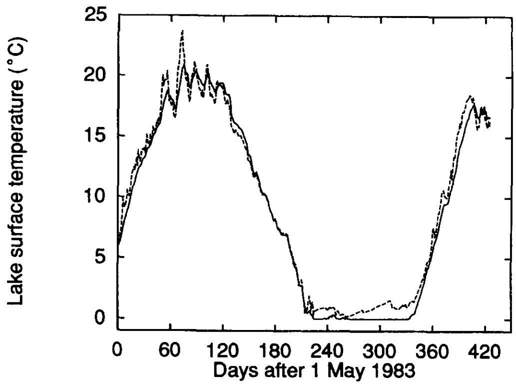

Fig. 3. Temperature comparison between the well-mixed model (full line) and the vertically resolved model (dashed line).

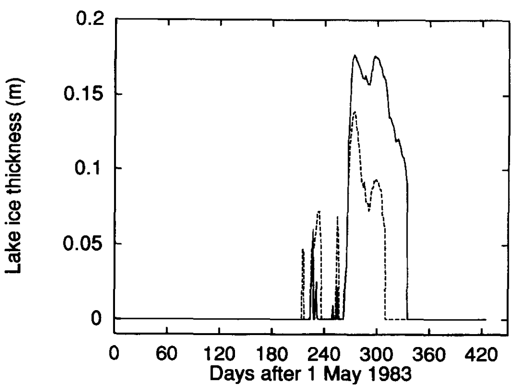

Fig. 4. Ice thickness comparison between the well-mixed model (full line) and the vertically resolved model (dashed line).

5.2. *Comparison with observed lake temperatures and lake ice*

For a further test of the lake model, we extracted the temperature measurements and the ice formation/break-up dates from eight different lakes, chosen to be representative of the various lake conditions of Sweden (Fig. 5, and Table 3). The lake model was forced with standard meteorological data for the period 1 January 1984–31 March 1994. This period includes cold as well as warm years. The model results are presented in Figs. 6–8, and in Table 4.

The ice verification results from 1984 to 1992 are given in Table 5. The mean error for ice formation/break-up of 1–10 days can be regarded

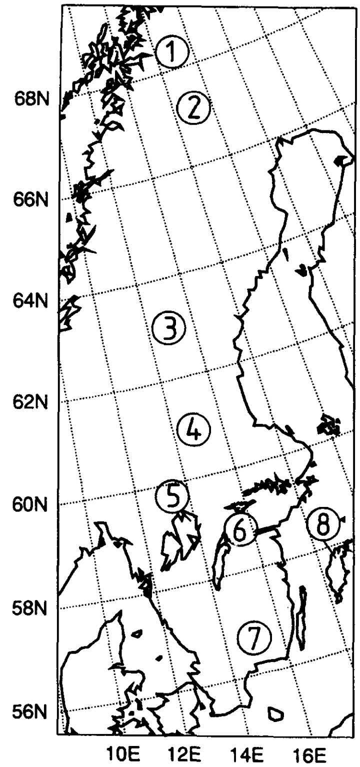

Fig. 5. Map of Sweden with the location of the 8 lakes used in the verification study.

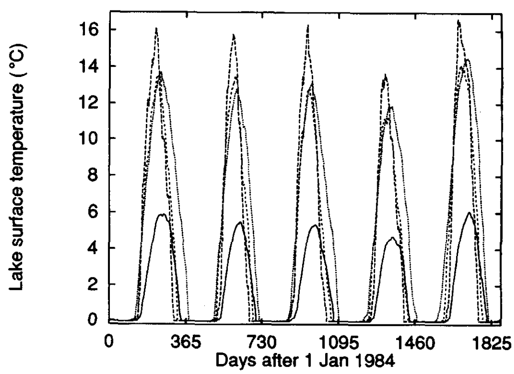

Fig. 6. Simulated temperatures for lake 1 (full line), lake 2 (dashed line), lake 3 (dotted line) and lake 4 (dashed-dotted line) 1984–1988.

as a good result, if one considers the fact that the observations are made at one place in the lake and that the criteria of ice formation and ice break up are not so easily defined. The Root Mean

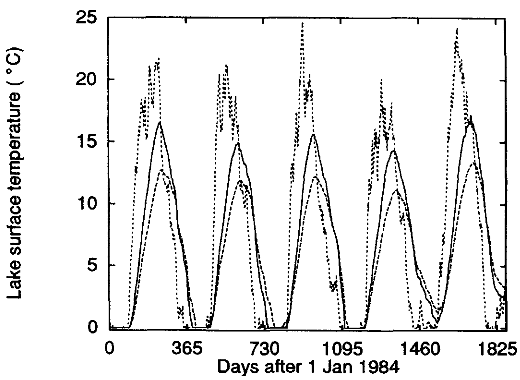

Fig. 7. Simulated temperatures for lake 5 (full line), lake 6 (dashed line) and lake 7 (dotted line) 1984–1988.

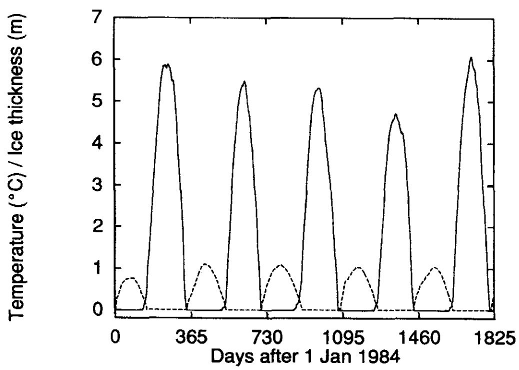

Fig. 8. Simulated temperature (full line) and ice thickness (dashed line) for lake 1, 1984–1988

Table 3. *The 8 lakes used for verification studies*

	Name	Mean depth (m)
1	Torneträsk	51.8
2	Stora Lulevatten	9.3
3	Storsjön	17.3
4	Siljan	27.8
5	Vänern	27.0
6	Vättern	40.8
7	Åsnen	3.1
8	Tingstäde träsk	1.6

Square (RMS) error is between 7 and 11 days, except for the ice formation of Lake 3 and Lake 5, each of which have one occasion with a very delayed simulated ice formation.

The test against surface water maps of Lake Vänern (Fig. 9) between 29 May 1986 and 16 May 1989 showed a good agreement between model results and observations. The mean error for the studied period was 1.7°C, the maximum error was 6.6°C and the maximum ice thickness error was 36 cm (not shown in figure). This large ice thickness error is due to ridging and melting processes that need more advanced ice modelling. The most important task of our work is, however, to catch the ice formation/break-up dates properly, and that is achieved with an error of 7 and 9 days, respectively.

The model temperature and ice thickness compared with the measurements twice a year in lake Siljan and lake Vättern are given in Table 6. The deep lakes are difficult to simulate during the summer when the water is stratified until strong winds mix the water. This explains the low model temperatures during the summer for lake Siljan (mean depth 27.8 m) and lake Vättern (mean depth 40.8 m). The model ice thickness differs much from the observed ice thickness, but the ice break up date is better simulated. If we compare with some measurements done in March each year (at this time the ice thickness in many lakes is at the maximum), the ice thickness is relatively well predicted (Table 7).

5.3 Sensitivity to lake depth

The sensitivity of the length of the ice-covered period to the lake depth is also interesting to analyse. In order to find out how much the depth influence the ice formation and the ice break up dates we run the model for eight lakes, with different depths (0.5, 1.0, 2.3, 4.5, 10, 14, 30 and 50 m), forced with identical weather. The results are illustrated in Fig. 10.

From the figure, we can first notice the large differences between the length of the ice periods for the different winters, illustrating large interannual variations. This strongly supports the use of a lake model instead of applying lake climate data. Secondly, we can notice that if there are lakes with different depths in a HIRLAM grid square, there is a need for more than one model to simulate the temperatures correctly.

The lakes with the smallest depths have in general shorter ice periods, since short wave radiation penetrates the ice during the spring and rapidly warms up the underlying water. The water

Table 4. *Model compared with observed ice formation and break up dates (mean value in the parenthesis is without the observation that is denoted by *): a negative value means that the model formed the ice to early compared to observations*

Lake number	Observed formation date	Model error (days)	Observed break up date	Model error (days)
1	Dec 20	−1	Jun 30	−13
2	Nov 5	+5	Jun 17	0
3	Dec 21	+10	May 23	+2
4	Jan 1	−1	May 7	+10
5	Jan 7	+7	Apr 26	−9
6	Jan 18	+27*	Apr 23	−8
7	Dec 23	+8	Apr 17	+7
8	Dec 24	−1	Apr 16	+4
absolute mean error		7.6 (4.7)		6.6

Table 5. *Model mean error (ME) and root mean square error (RMS) for the eight lakes during 8 year; units in days*

Lake number	Ice formation ME	Ice formation RMS	Ice break up ME	Ice break up RMS
1	−5.1	8.3	−1.3	9.3
2	4.9	7.1	4.5	7.4
3	10.4	28.4	1.4	11.3
4	4.8	8.5	2.8	11.1
5	6.5	18.5	−5.6	7.3
6	4.4	10.0	−4.1	8.3
7	−3.6	9.7	−1.8	8.9
8	1.9	10.3	−1.9	7.7

The ice formation date 1991 was for lake 3, 78 days too late (without this value: ME = 0.7 and RMS = 7.3), The ice formation date 1985 was for lake 5, 42 days too late (without this value: ME = 1.4 and RMS = 11.1).

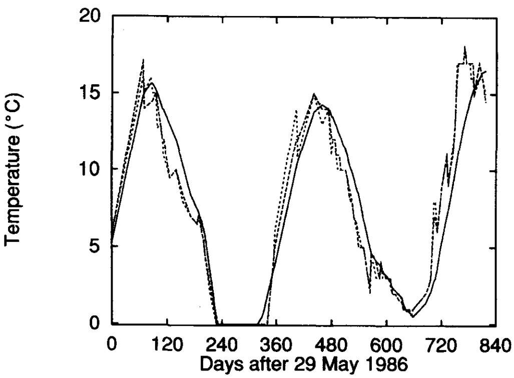

Fig. 9. The well mixed model (full line), and measurements from the two sub-basins, Lake Dalbo (dotted line) and Lake Värmland (dashed line.), of Lake Vänern, 29 May 1986–22 August 1988.

then melts the ice from below. This is due to the applied condition that the ice is assumed to break up when the water reaches +2°C. The deep lakes also have shorter ice periods because they reach 0°C later than the shallower lakes.

6. Results from experiments with coupled atmosphere and lake models

Before coupling the lake model to HIRLAM it was necessary to initialize the lake temperature and lake ice thickness fields. This was achieved by calculating the heat contents in all lakes during a spin up period of one and a half year, during which the lake model was forced by meteorological data in a way similar to that in the earlier tests (Subsection 5.2). The model lakes run until 2 May 1994 uncoupled with the HIRLAM model.

From 2 May 1994, the experiment with the coupling of the lake model to HIRLAM was carried out for a two week period until 16 May 1994. The coupling between HIRLAM and the lake model was included in the 6 hourly data assimilation cycles of HIRLAM. The lake model was forced by +3 h and +6 h HIRLAM forecasts to derive +6 h lake condition forecasts. Initial lake conditions for the HIRLAM forecasts were taken as these +6 h lake forecasts, valid at the initial time of the HIRLAM forecasts. Lake conditions were kept constant during the HIRLAM forecast runs. HIRLAM forecasts up to +48 h

Table 6. *The measurements from lakes Vättern and Siljan compared with the model*

Lake	Siljan	Vättern	Siljan	Vättern	Siljan	Vättern
date	5 Aug 1986	6 Aug 1986	5 Mar 1987	25 Feb 1987	27 Jul 1987	29 Jul 1987
temp (°C)	17.0	13.0	0.10	0.55	13.3	13.1
ice (cm)	–	–	52 cm	50 cm	–	–
model	12.5°C	11.4°C	69 cm	15 cm	10.3°C	9.3°C
difference	−4.5°C	−1.6°C	+17 cm	−35 cm	−3.0°C	−3.8°C

Table 7. *Calculated ice thickness (cm) compared with observed values (once a year) for lake 1, 4, 5 and 6 (see Table 3)*

Date	Lake 1 obs.	Lake 1 model	Lake 4 obs.	Lake 4 model	Lake 5 obs.	Lake 5 model	Lake 6 obs.	Lake 6 model
21 Mar 1985	74	108	60	58	39	23	44	15
26 Mar 1986	102	102	60	56	30	17	24	0
26 Mar 1987	102	103	63	63	50	29	50	27
31 Mar 1988	80	98	33	13	0	0	0	0
17 Mar 1989	56	71	26	11	0	0	0	0
25 Jan 1990	58	62	42	0	0	0	0	0
21 Mar 1991	74	77	40	32	10	0	0	0
19 Mar 1992	52	52	13	17	0	0	0	0
absolute mean error		10 cm		12 cm		7.5 cm		10 cm

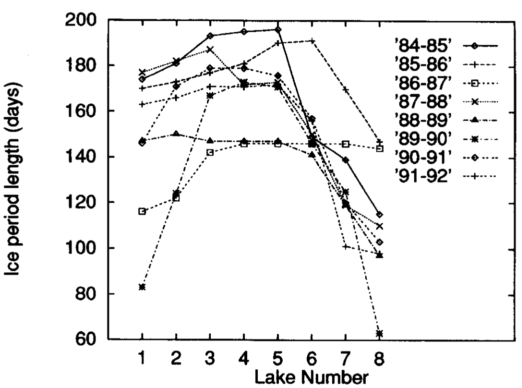

Fig. 10. Sensitivity analysis of 8 different depths forced with meteorological data from 8 years (1984–1992).

were carried out twice a day, for 00 UTC and 12 UTC initial data. In order to have reference forecasts to compare with, the HIRLAM data assimilation and forecast experiment was repeated for the period 2–16 May 1994, with lake conditions in Sweden according to the (crude) climate lake conditions.

The most significant impact on the atmospheric forecasts of using the coupled lake model instead of climatological lake conditions is a general cooling of low-level air temperatures. This result is consistent with the differences between the climatological and model simulated lake conditions. According to the available lake climatology used in the HIRLAM system, which in fact is a global sea surface temperature climatology horizontally extrapolated to the lakes, all Swedish lakes are ice-free in May. Differences between 2-m air temperature forecasts not using the coupled lake model and using the coupled lake model are presented in Fig. 11a for 3 May 1994, 18 UTC +6 h and in Fig. 11b for 13 May 1994, 18 UTC +6 h. Local temperature differences up to 3°C can be noticed, with the temperature forecasts based on utilisation of the lake model consistently being cooler. Also notice the northwestward shift of the area with temperature differences over the period 3–13 May, 1994, corresponding to the northwestward shift of the ice melting period as simulated by the lake model. This simulation of the northwestward shift of the lake ice melting period also verifies with available observations.

The comparison of 2-m temperature forecasts from the experiments with and without the coupled lake model indicates a definite impact from the application of the lake model in the form

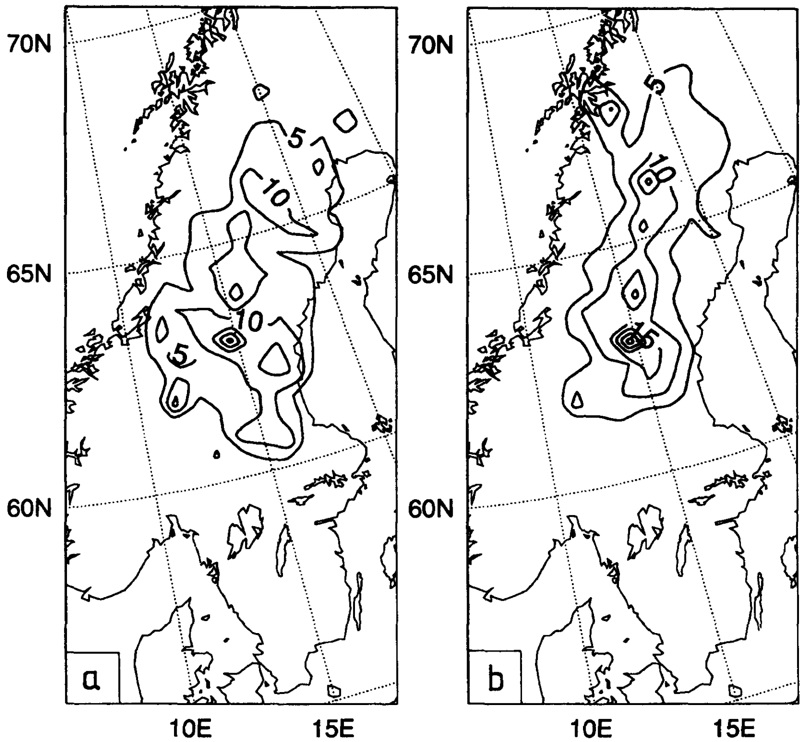

Fig. 11. Difference between forecasted air temperature (tenths of °C) without and with the lake model. (a) 3 May 1994 18 UTC +6 h. (b) 13 May 1994 18 UTC +6 h.

of a cooling of low level temperatures. This difference also shows up in forecast verification scores, based upon comparison between forecasted and observed 2-m temperatures. The signal from the impact of the lake model is rather weak in verification scores based on all the Swedish weather stations (results not shown), but verification scores based on weather stations in the areas with largest forecast temperature differences give a more clear signal. Fig. 12 shows mean error verification scores from a comparison between observations from stations Karesuando, Vouggatjolme and Gunnarn, all situated in forest and mountain areas of Northern Sweden, including also many lakes. The verification scores indicate a large negative mean error in the reference HIRLAM day-time temperature forecast without the lake model. Introducing the lake model consequently results in a slightly larger negative mean error for the day-time temperature forecasts. For the night-time temperature forecast the situation is reversed. The reference

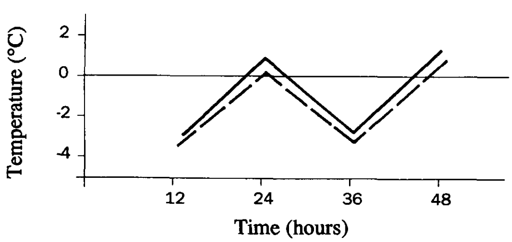

Fig. 12. Scores from verification of 2 m temperatures forecasts in Karesuando, Vouggatjolme and Gunnarn. 00UTC (midnight) initial data 2–16 May 1995 +12 h, +24 h, +36 h and +48 h. Mean error without lake model (fully drawnline), mean error with lake model (dashed line).

temperature forecasts have a 1°C positive mean error. The introduction of the lake model cools the temperatures, and the mean error becomes very small.

A separate test with the lake model forced only by standard meteorological data (applied as in the spin up of the lake model) during 2–16 May showed, by comparing the simulated lake temperatures, that in the middle of Sweden, where the lakes were icecovered and under melting, the lake model coupled to HIRLAM had several degrees lower surface temperatures than the uncoupled lake model. Taking the verification scores discussed above into account, the most likely reason for this cooling effect of the coupling to HIRLAM is the generally negative mean errors in the low level HIRLAM temperature forecasts.

7. Summary and conclusions

In the present study, we have developed and tested a simple lake model. The aim was to formulate a lake model, that could be used for parameterization of lake effects in atmospheric models. The lake model has been tested and validated in several ways, first, by comparing it with a more advanced lake model and then by comparing it with observed data from several lakes in Sweden. We have also carried out an experiment to test the model sensitivity to lake depth. Finally, the lake model was coupled to the weather forecasting model HIRLAM during a lake model impact study for the first two weeks of May 1994. The conclusions from the work can be summarized as follows:

- In comparison with a more advanced lake model, the well mixed model works well for lake temperatures. The model also works reasonably compared with a more advanced model, for the prediction of ice formation and ice break up dates.
- The validation against observed lake ice data between 1984 and 1992 confirms that the model predicts ice formation and ice break up within an accuracy of about one week, which must be considered satisfactory and a clear improvement compared to the former used climate data base.
- The test with the lake model coupled to the weather forecasting model HIRLAM supports our original hypothesis, that lake ice conditions and lake surface temperatures are important for the prediction of low level air temperatures.
- We have shown a very clear impact of the lake model on the 2-m temperature forecasts, particularly in areas where lake ice is in the process of melting.
- We have not yet shown a clear positive impact of the lake model on the forecasting of weather parameters. To do so, we must obtain a more detailed understanding of the negative mean low-level temperature forecast errors of the HIRLAM model, we must carry out lake model sensitivity studies for longer periods and for all the seasons and we must study more carefully the effects of the coupled lake model on the complete energy and water cycles of the atmospheric model. The present study is only a first step in this development process.

The present lake model seems to work well for most lakes, however, large lakes need further modelling efforts. For the large lakes it should be more appropriate to develop a vertically resolved lake model and to include a better parameterization of the ice including ridging etc. A unification of the surface flux calculations in the atmospheric model and the lake model should also be investigated.

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