A study on effects of lake temperature and ice cover in HIRLAM

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Lake surface temperatures (LST) for a numerical weather prediction (NWP) model can be obtained in several ways: by utilizing climatic information, by assimilating LST observations and by applying lake parametrizations for prediction of LST. We tried these approaches in the High Resolution Limited Area Model (HIRLAM) and show that, indeed, they result in different predicted screen-level temperatures and ice cover. In our experiments, the differences tended to remain local in the atmospheric surface layer over areas close to lakes. Usage of climatic LST information may lead to inaccurate atmospheric temperature forecasts, especially when the lake surface state (frozen/unfrozen) is incorrectly described. Assimilation of the LST observations would produce the most reliable results, but presently such observations are not available for the operational NWP. Use of the Freshwater Lake Model (FLake) as a parametrization scheme in HIRLAM showed promising results, but further development is needed in order to reduce the inertia of the scheme and to improve handling of the lake freezing. Melting of lake ice was not considered in this study.

Introduction

Large lake areas can influence significantly the local weather and climate. For instance, in the Great Lakes area in North America it is estimated that, at the maximum, the lake-effect doubles the amount of precipitation in winter and decreases the amount of precipitation by 10%–20% in summer. In summer, the lakes reduce the temperature variation by reducing the maximum temperatures and rising the minimum temperatures (Scott and Huff 1996). In autumn, the lakes warm the atmosphere (Long *et al*. 2007). In single weather situations the amount of snowfall

can be considerable and the snowfall can occur in narrow bands along the shores of the lakes (Braham 1983, Niziol *et al*. 1995). Although the so-called lake-effect is a combination of large spectrum phenomena in time and space, these lakes are so large that their influence can be seen even in large-scale numerical weather prediction (NWP) models (Miller 2002).

Concerning smaller lakes, which are not properly resolved by the NWP models, the situation is different. Their properties and effects have so far been described crudely, although they affect the local weather by modifying the air temperature, wind and precipitation in their

surroundings. With increasing resolution of the NWP models, it becomes possible and necessary to improve the handling of the lake-atmosphere interactions. Meteorologically this means that we should describe better the energy exchange between the atmosphere and the lake surface. For this, we must know the temperature, ice-coverage and other properties of the lake surface, based either on observations or reliable simulations.

The size and depth of the lakes differ significantly from lake to lake. Therefore, different lakes affect the local weather conditions differently and their effect depends on the weather situation. Freezing and melting of lakes is crucially influenced by their size and depth. For instance, the large and deep Lake Inari in the northern Finland normally freezes at the end of November, while small lakes in the same area get the permanent ice cover about one month earlier. It is most important for a NWP model to know if lakes are frozen or not, because the physical properties of the lake surface — such as the surface temperature, albedo and roughness — are very different in these two cases. These properties in turn determine the atmospheric energy balance at the surface: the net radiation, turbulent sensible and latent heat fluxes.

This study presents an attempt to improve the handling of lakes in the High Resolution Limited Area Model (HIRLAM) (Undén *et al.* 2002), which is a complete synoptic and mesoscale NWP system, consisting of a three-dimensional variational data assimilation system and a hydrostatic primitive equation forecast model, including a sophisticated parametrization of the subgrid-scale physical processes. It is presently used for operational weather forecasting in ten European countries, also in Finland.

In this study, we seek answers to several basic questions. Do we need a prognostic model (lake parametrization) to treat the lake surface temperature (hereafter LST) and ice conditions correctly? Or is it sufficient to keep these properties constant during the forecast and rely on the assimilation of available LST observations? Is it perhaps necessary to combine the prognostic and diagnostic approach? Availability of the real-time observations about the lake surface properties and the methods of their usage are also discussed.

To estimate the overall effect of the lake surface temperatures on the HIRLAM forecasts, we chose the autumn 2006 as our test period. At that time, the lakes in Finland remained unfrozen unusually long in winter and the observed lake surface temperatures were much higher than their long-term mean (climatological) values. In the reference HIRLAM system — as in many other NWP models — the climatological temperatures determine the lake surface properties in the model. Introduction of more realistic LST values, based on observations, allowed us to study the sensitivity of the predicted near-surface temperatures to the properties of the underlying lakes. We focus on the local temperatures in eastern Finland, where numerous lakes of different sizes cover a significant fraction of the surface.

Lakes in HIRLAM

The treatment of surface processes in the HIRLAM data assimilation and forecasting system is based on the ISBA scheme (Noilhan and Planton 1989, Manzi and Planton 1994, Rodriguez *et al.* 2003, Samuelsson *et al.* 2006). In this scheme, each grid-square is divided into five different surface types (tiles): water, lake/sea ice, bare land (which contains also glaciers), low vegetation and forest. In the so-called tile schemes, such as ISBA, the surface fluxes and prognostic surface variables are computed separately for each surface type (tile), while the grid-scale flux or tendency is an area-average of the tile values. This allows applying, in a natural way, different methods for handling different surface types. The fraction of each tile in a grid square of any computational grid of HIRLAM is defined using global physiographic data bases like the Global 30 Arc Second Elevation Data Set (GTOPO30´´) and the Global Land Characteristics Data Base (GLCC) of the U.S. Geological Survey. In ISBA, water tile comprises both the sea and freshwater bodies (lakes), but in addition the fraction of lake relative to the grid-square is provided by the physiography description.

Surface data assimilation system

In the HIRLAM data assimilation system, the lake water surface temperature and the pres-

ence of ice are determined by using a similar approach as for the sea surface temperature (SST) and sea ice analysis (Rodriguez *et al.* 2003). Observations on SST are provided by the sea surface weather reports (SHIP and BUOY) and various satellite-based systems. However, real-time LST observations are in practice not available for operational NWP. Such information is only occasionally available in the satellite measurements over the largest lakes. Thus, some climatological or model-based information about lake water temperature must be used instead.

In HIRLAM, LST information has either been interpolated from global SST climatology, derived from locally available lake temperature climatology, or even estimated from the model deep soil temperatures. All these methods are able to provide only a rough estimate of the LST values over the areas of interest. Over the area covering approximately Finland, the climatological LST information is presently introduced into the HIRLAM reference surface data assimilation system in the form of so-called pseudo-observations. They represent long-term average LST on about twenty lakes in different parts of Finland. These pseudo-observations are further processed and used by the surface data assimilation in the same way as the real observations. As a result, the climatological lake temperatures in Finland and surroundings enter the model grid. In the following, we will refer to this method as "Finlake".

For the assimilation of both SST and LST observations (including the Finlake pseudo-observations) the successive correction method (e.g. Daley 1991) is applied. During the assimilation, SST or LST measurements within a chosen influence radius (for example, in our case decreasing with consecutive iterations from 600 km to 100 km) are selected for the gridpoints representing seas or lakes, respectively. Besides, for the sea points maximum weight is given to the SST observations and minimum to the LST observations, and vice versa for the lake points. This is done in order to minimize contamination of the model's LST values with the SST observations and the SST values with the LST observations.

A previous (normally +6 hour) forecast is used as a first guess for the assimilation of obser-

vations. In the reference HIRLAM, LST and SST do not change during the forecast (*see* below). Thus, only assimilated observations can change the water surface temperature. When there are no LST observations available, the background monthly climatological values prevail. If the climatological LST values are treated as pseudo-observations (Finlake) and represent the only source of observations, they influence even more actively within their radius of influence. An additional effect of using the same influence radius for the LST and SST observations is that the influence of LST observations spreads too far. Because the lake temperatures are local, the observations on one lake do not necessarily represent the conditions of the nearby lakes. The method gives spatially too smoothed LST field, without patchiness which actually exists in reality.

Ice coverage is determined from the analysed lake surface water temperature: if the temperature falls below the freezing point, the lake starts to freeze. If the temperature is less than –0.5 °C, the lake is considered to be totally frozen. The possible presence of snow on ice is not presently taken into account by the surface data assimilation.

Forecast model

In the reference HIRLAM (Undén *et al.* 2002, Rodriguez *et al.* 2003), the lake water surface temperature (LST), as well as the fraction of ice are kept constant during the forecast. In addition, if the underlying water (lake or sea) is ice-covered, the ice temperature is predicted by the forecast model using the same ISBA parametrization as for the land tiles, but with the properties of sea/lake ice (Samuelsson *et al.* 2006, *see* also Tables 1 and 2).

Presently, the Freshwater Lake model (FLake, Mironov 2008) is being implemented (Kourzeneva *et al.* 2008) as a parametrization scheme in a development version of the HIRLAM forecast model. In FLake, lake water and ice temperature as well as the thickness of ice are prognostic variables. Hence they can change during the forecast. The specific features of the FLake implementation in HIRLAM include:

Table 1. Main analysed and predicted lake variables in the HIRLAM experiments.

	Water temperature	Ice temperature	Fraction of ice
REF	Finlake climatology	Predicted by ISBA	Diagnosed from water temperature
OBS	Assimilated observations	Predicted by ISBA	Diagnosed from water temperature
FLK	Predicted by FLake	Predicted by FLake	Predicted by FLake

— FLake is implemented in the framework of the tiled surface scheme of HIRLAM so that the water tile is further divided into the sea and lake partitions. Within the tiled structure, the LST and lake ice produced by FLake influence the water and ice properties and, consequently, the grid-square averaged screen-level temperature, components of the surface energy balance and other model variables.

— FLake parametrization takes care of the lake-related processes in the forecast model. However, for the time being the LST observations are not assimilated to the model, i.e. these observations are not used at all with FLake. Instead, the prognostic variables enter the next forecast cycle directly from the output of the previous one, in the same way as in climate models.

— The initial state of the very first forecast is estimated, based on available (observed or climatological) LST data. Presently it is assumed that at the initial time there is no ice and all lakes are mixed down to the bottom.

Table 2. Common properties of the HIRLAM experiments.

Domain	Nordic (Fig. 3)
Resolution	0.068° (ca. 7 km), 60 vertical levels
Period	28 Oct.–31 Dec. 2006
Cycles	Analysis every 6 h, max. forecast lead time 27 h
Data assimilation	3DVAR[1], surface data assimilation active
Model physics	"newsnow" surface parametrizations[2]
Boundary conditions	interpolated ECMWF[3] analyses

[1] Three-dimensional variational data assimilation for atmospheric variables, [2] Samuelsson *et al.* 2006, [3] European Centre of Medium Range Weather Forecasting, operational analyses.

These assumptions are more or less valid for the northern Europe in late autumn.

— The parameters of lake depth and fraction of lake, required by FLake, are created by external software (Kourzeneva 2010). They are further included in the HIRLAM physiography data base and replace there the reference HIRLAM fraction of lake. In fact, the original and modified lake fractions are quite similar, as both are derived from the same basic (GLCC) data.

— Lake ice temperature and the thickness of lake ice are forecast by FLake. Lake ice fraction in a grid-square is either unity or zero, corresponding to a non-zero or a zero value of the simulated ice thickness. Snow on the lake ice is not yet taken into account by the HIRLAM FLake parametrization.

Observations of lake surface temperature and ice

One aim of the current study was to estimate the influence of the real LST observations in the HIRLAM system. For this purpose, three observation data sets were obtained from the Finnish Environment Institute. The first data set consisted of daily observations, manual or automatic, of lake water surface temperatures on about 30 lakes in different parts of Finland. However, water temperatures were observed in ice-free conditions only; neither the surface temperatures of the frozen lakes nor the freezing dates were indicated. Furthermore, at most stations the observations are not made after the end of October, although many lakes were still ice-free even in December 2006. This means that the amount of instrumental measurements per day decreased towards the end of the period. In the whole December, only 31 instrumental measurements in total were available at three lake observation points.

The second data set consisted of satellite (AVHRR) observations. Water temperature can be interpreted from the satellite-measured radiances in cloud-free conditions over non-frozen lakes. During the autumn, clouds are frequent over Scandinavia and Karelia. Also during October–December 2006 cloudy conditions prevailed and reliable satellite measurements were available only during a few days. The basic spatial resolution of the water surface temperature measurements from the satellite is 1 km. However, the reliability of the data decreases close to the coastline. Normally, only measurements further than 4 km from the coastline are taken into account. Reliable satellite observations are thus available only for lakes large enough, while plenty of small lakes remain invisible in terms of the satellite surface temperature measurement. On the contrary, over the central parts of large lakes the satellite observations are spatially too dense to be assimilated by the atmospheric model. To thin the coverage, we averaged the observations so as to get one value of water surface temperature per each grid-square of the atmospheric model (in our experiments, the size of grid-squares was about 7 km × 7 km).

The third data set consisted of manual on-shore observations on freezing of lakes. In this set, the dates of appearance of ice cover — first temporary, then permanent — were registered on 60 lakes in Finland. Dates were available for several years, including our experiment period in the autumn 2006. Because the first and second data sets were not complete enough for our purposes, we used also the freezing dates to estimate the temperature and ice conditions for the HIRLAM surface data assimilation.

The freezing date information was processed as follows. We assumed that the lake temperature was 0 °C (273.16 K) on the day, when the lake was reported to be frozen (possibly temporarily) for the first time. The temperature was given a value of –0.5 °C on the day of reported permanent freezing. Between these dates the temperature was linearly interpolated in time. Before the first freezing date, the temperature was linearly interpolated in time from the last observed temperature given by the first dataset. After the date of permanent freezing, a fixed temperature value –2.2 °C was defined for the ice-covered lakes.

Note that the HIRLAM surface analysis uses the below-zero (water) temperature, as defined here, only to determine the fraction of ice over sea and lakes. The forecast model attempts to predict a more realistic value of lake/sea ice temperature. After this rather crude estimation, a careful manual check of the daily values was performed. The suggested method, albeit approximate, takes into account the features of the HIRLAM data assimilation and gives correct freezing times of the lakes.

Based on these three datasets, we constructed a time-series of daily lake surface water temperatures for the period starting in mid-October and ending at the end of December 2006. These data were further fed as input to the HIRLAM surface data assimilation system for the final interpolation into the model's computational grid. Examples of the daily LST are shown in Fig 1. For 24 October (Fig. 1a), we had a good coverage of the instrumental observations (provided by the first data set, see above). For 18 November (Fig. 1b) all temperatures were estimated from the freezing dates (based on the third data set). For 19 December (Fig. 1c), we see both freezing-date and satellite-based (from the second data set) observations. The satellite observations are dense enough, but are limited to a small area. Note that there were almost no observations available for our study outside the borders of Finland.

For the validation, available SYNOP observations were used to calculate the standard verification scores. In addition, eight stations over lake areas in Finland (Table 3 and Fig. 2) were chosen for a detailed comparison of observed and predicted screen-level temperatures. Differences between the experiments were investigated also by comparing the components of the surface energy balance over the chosen points. However, flux measurements were available for comparison only at the control station Sodankylä.

HIRLAM experiments

The warm period of November–December 2006 was chosen for the HIRLAM experiments over a Nordic domain (Fig. 3). The aim of the experiments was to study the sensitivity of HIRLAM forecast results, in particular the near-surface
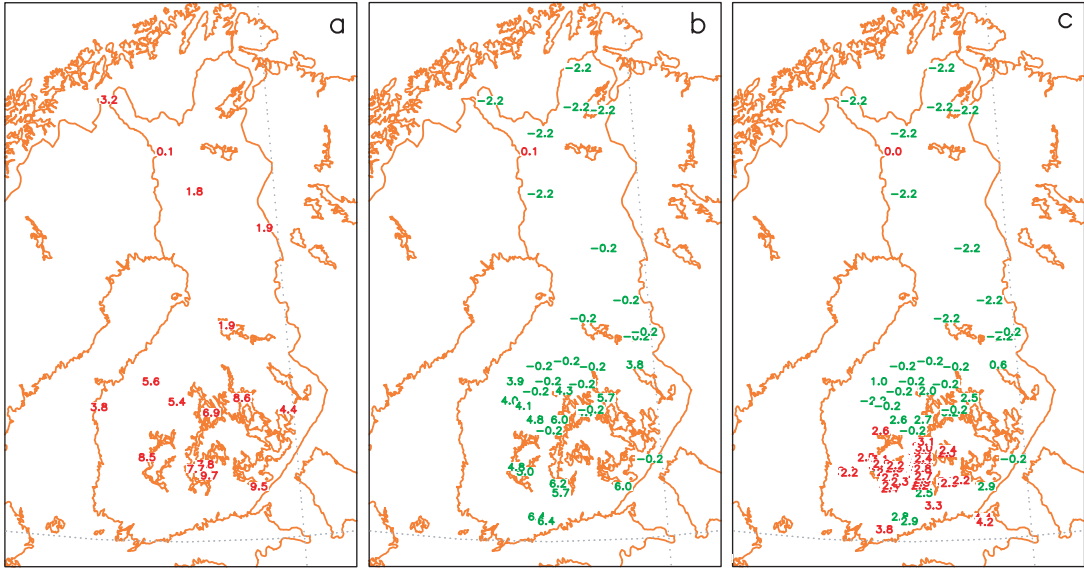
Fig. 1. Observed and estimated lake surface water temperatures (°C) on (**a**) 24 October 2006, (**b**) 18 November 2006 and (**c**) 19 December 2006. Temperature below 0.0 °C indicates that a lake is at least partly frozen. The red numbers denote instrumental and satellite measurements, while the green numbers indicate temperatures estimated from freezing dates. *See* text for details.

temperature and the surface energy balance, to the different approaches of handling lakes in the model. Three series of experiments were run (Tables 1 and 2): a reference experiment (REF) with climatological LST information; a data-assimilation experiment (OBS) with assimilated LST observations; a prognostic experiment (FLK) with FLake parametrizations but without LST data assimilation. In the present study, we concentrated on temperature, leaving e.g. wind and precipitation mostly out of consideration.

In the experiment REF, Finlake climatology (as explained earlier) was used for estimation of the lake surface temperature and presence of ice. The Finlake climatology covers only the area of Finland. In the experiment OBS, observations were prepared for the surface data assimilation as described above. Instrumental observations and lake freezing dates were available for the lakes in Finland, a few satellite observations also over Lake Ladoga. The experiment FLK applied FLake parametrizations in the forecast model. Note again that no LST analysis or related ice diagnosis were done in this experiment. However, the first forecast of the experiment FLK started on 28 October from LST, assimilated by the experiment OBS (Fig. 3).

Results, comparisons and validation

Temperature and ice cover

The differences between the lake surface temperatures produced by the three experiments increase towards the end of the year. An example is shown by the forecasts valid for 10 December 2006 at 12:00 UTC (Fig. 4). In the reference experiment REF, practically all lakes in Finland are frozen (Fig. 4a, temperatures below 0.0 °C). The data-assimilation experiment OBS keeps the southern Finland lakes unfrozen (Fig. 4b)

Table 3. List of the synoptic stations used for validation.

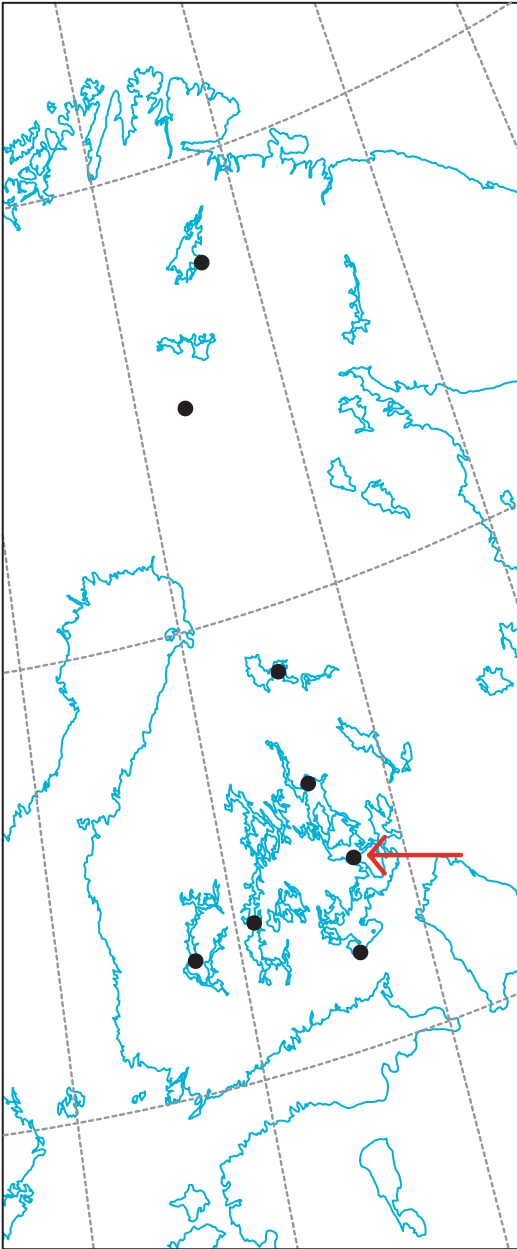| Synoptic station	Long. °E	Lat. °N	Fraction of lake (%)
Nellim	28.30	68.85	19
Sodankylä	26.63	67.37	0
Kajaani	27.68	64.28	55
Kuopio	27.80	63.00	54
Rukkasluoto	28.57	62.06	65
Judinsalo	25.51	61.70	64
Tampere	23.75	61.47	15
Lappeenranta	28.15	61.04	26

Fig. 2. Location of selected synoptic stations in Finland, used for validation of screen-level temperatures. The station Rukkasluoto at Lake Haukivesi is indicated with an arrow. Geographic coordinates and percentages of lake in the HIRLAM grid-square around the station are shown in Table 3. The station Sodankylä in northern Finland (with zero percentage of lakes in the grid-square) was chosen as control.

Fig. 3. Experiment domain (whole area). The colours (scale below the figure) show the lake surface temperatures (°C), i.e. the water temperature of the lake fraction of the grid-square, if present, on 28 October 2006 as assimilated in the experiment OBS (*see* Table 1) and used as initial values for the experiment FLK. Temperatures below zero indicate the presence of lake ice.

according to the observations. In the FLake-based experiment FLK (Fig. 4c), only the Lapland lakes are frozen. Continuation of the experiment FLK beyond the present experiment period did not lead to freezing of the lakes in central or southern Finland even until the end of January. However, according to the observations, the last unfrozen lakes — the large southern Finland lakes Päijänne and Näsijärvi — were reported frozen on 23 January 2007. Note that because no observations outside Finland were available, the influence of the Finnish LST observations and climatology (Finlake) tends to propagate too far: compare e.g. the temperatures of the northern Lake Ladoga in Russian Karelia or Lake Peipsi in Estonia. This is an artefact of the data assimilation method used.

A time series of the simulated screen-level temperatures at the synoptic station Rukkasluoto (marked by an arrow in Fig. 2), situated on a small island on the Lake Haukivesi (part of Saimaa), illustrates further the differences between the experiments (Fig. 5). At the beginning of November, when all three experiments
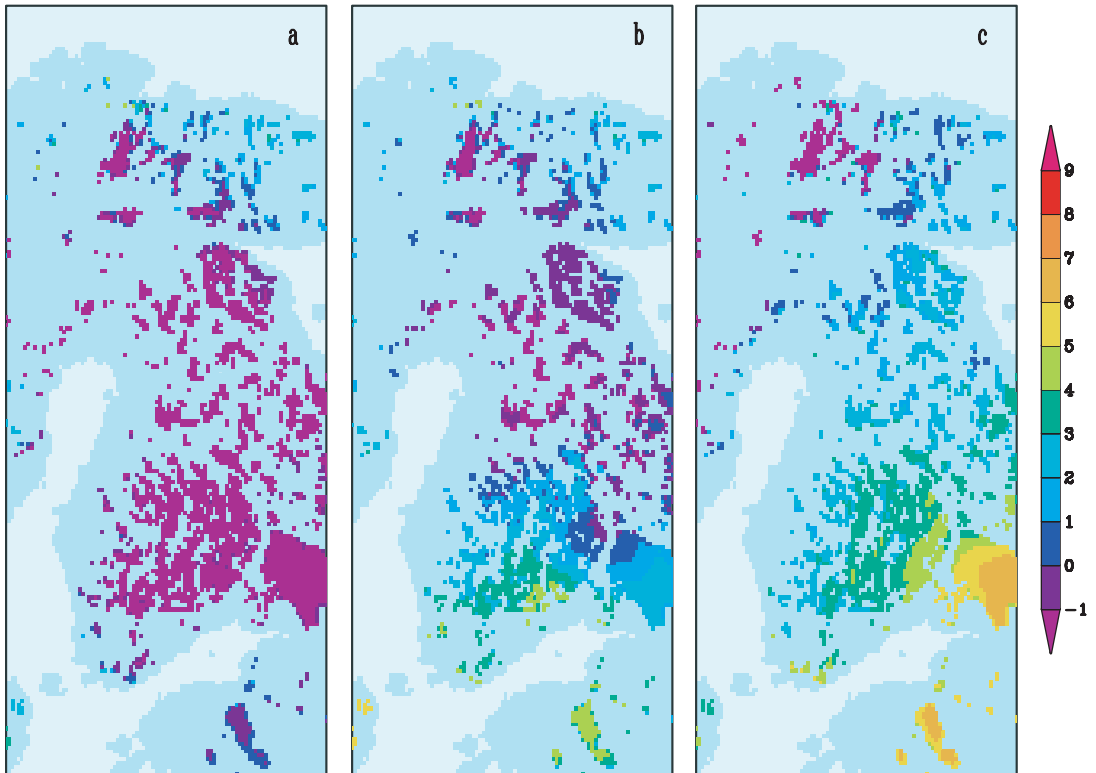
Fig. 4. Lake surface-water temperatures as given by 12-hour forecasts on 10 December 2006 at 00:00 UTC +12 h: (**a**) REF (Finlake climate), (**b**) OBS (observed estimate), and (**c**) FLK (FLake simulated). The colour scale is given by the legend, and temperatures below 0 °C indicate that the lake is at least partly frozen.

consider the lake unfrozen, the differences in the screen-level temperatures over the lake tile are small. This is in spite of the difference in handling the lake water temperature: it is kept constant in REF and OBS, but predicted in FLK. Our best estimate of the lake surface temperature (shown in Fig. 5 based on the data-assimilation experiment OBS) indicates a decrease from ca. 5 °C at the beginning of November to zero at the end of December. In REF, water temperature decreased to the freezing point before the end of November, while in FLK it remained around 6 °C during the whole period.

Lake Haukivesi freezes in the experiment REF around 26 November, in OBS around 28 December, while in FLK it stays unfrozen until the end of the year and beyond. After the freezing dates, the surface properties of the lakes become different in the experiments. Consequently, we can see more differences in the predicted temperatures, most notably during the

cold days (presumably characterized by stable stratification and clear sky). Where there is ice in the model, the screen-level temperatures tend to be lower and follow the predicted ice temperatures. If in one experiment the lake is frozen and in another unfrozen, it is not surprising that their forecasts differ. Similar features were seen at all lake stations (not shown), while at the control station Sodankylä, where the lakes do not influence, the differences in the predicted temperatures were small. Thus, the lake effects on temperature remained local.

The ice surface temperature was a prognostic variable in all experiments. Thus the freezing, brought to the model by the surface data assimilation (in REF and OBS), activates a different parametrization over the lakes in the forecast model, with its inherent assumptions and sources of inaccuracy. The experiments REF and OBS used the same lake and sea ice parametrizations, while FLK applied its own prognostic approach
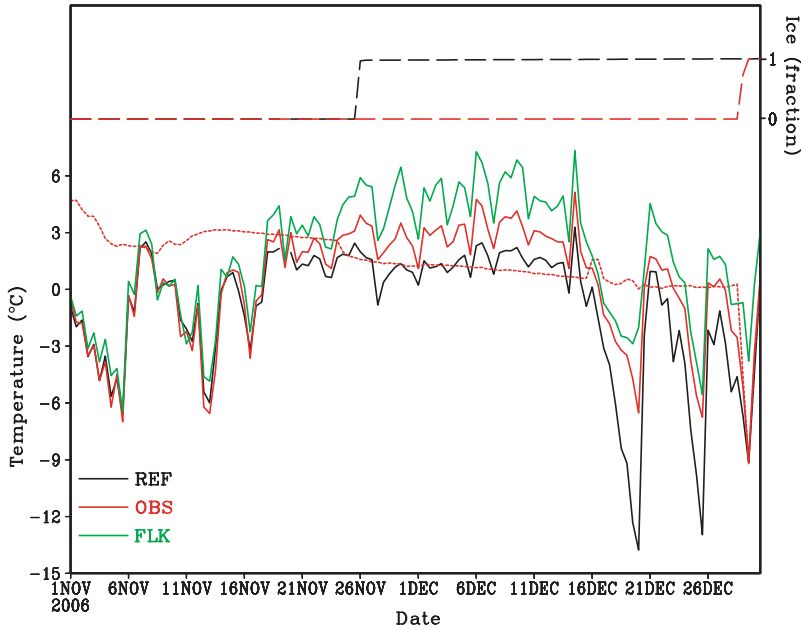
Fig. 5. Time series of the simulated (forecast length +12 h) screen-level temperature over the lake tile (solid) and fraction of ice (dashed) at the observation site Rukkasluoto (*see* map in Fig. 2): REF (black), OBS (red) and FLK (green). In addition, the lake surface temperature (water or ice) from the experiment OBS is shown (dotted red). *x*-axis shows the dates, *y*-axis the temperatures in °C (left) or fraction of ice (right, 1 = all water in the grid-square frozen, 0 = no ice). Note that in the experiment FLK there was no ice at this site.
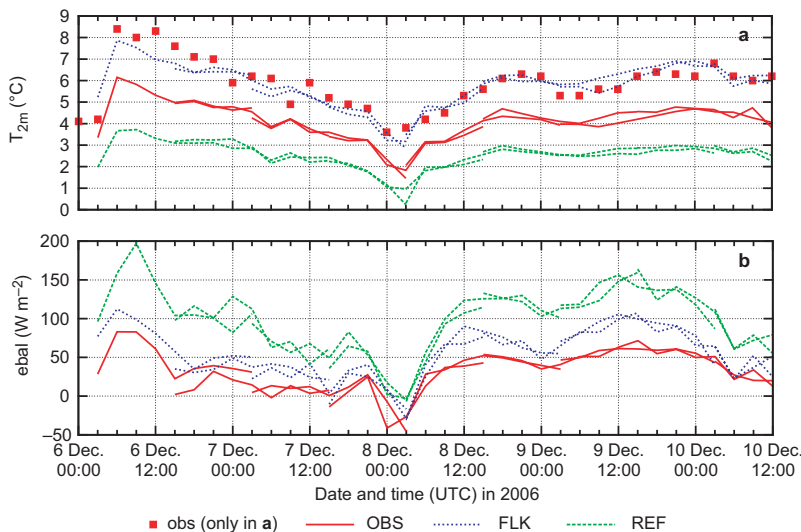

Fig. 6. Predicted screen-level temperature (**a**, unit °C) and atmospheric surface energy balance (**b**, unit W m^{-2}, positive downwards) over the grid-square around Rukkasluoto in 6–10 December (dates shown along the *x*-axis) according to the experiments OBS (red), FLK (blue) and REF (green). All +3-h … +27-h forecasts, starting from the initial analyses at 00:00 UTC and 12:00 UTC each day, are shown with the partly overlapping curves.

for handling the lake ice (Mironov 2008). At the observation site Nellim, at the coast of the Lake Inari, lake water was considered frozen in November–December by all three experiments. There the differences between the experiments in the predicted screen-level temperature were minor (not shown). Thus, it seems that the differences due to the different approaches to the ice parametrizations are of minor importance. Note however, that the fraction of lake in the Nellim grid point does not exceed 19%.

Continuing the detailed analysis, we chose one typical short period (6–10 December, Fig. 6) from the Rukkasluoto time-series for comparison with temperature observations (Fig. 6a) and evaluation of the surface energy balance (Fig. 6b). According to the climatology, Lake Haukivesi is normally frozen at this time of the year, but in autumn 2006 there was no ice. The experiment REF assumed, according to the Fin-lake climatology, that the lake in the model was frozen, while OBS and FLK kept it unfrozen.

In the experiment FLK, LST was close to the observed screen-level temperature, while in the other two experiments LST was colder. Hence, the grid-averaged screen-level temperature predicted by FLK follows closely the observations while the other two experiments give clearly colder values, with the maximum differences between FLK and REF up to four degrees.

The screen-level (two-metre) temperature is not a direct prognostic variable in HIRLAM. It is diagnosed from the surface and the lowest model level (around 30 m above the surface) temperatures, taking into account the stability of the surface layer. All atmospheric parametrizations and model dynamics influence in the predicted lowest model level temperature, while the surface temperature is largely determined by the surface properties and the surface parametrizations. The grid-square around Rukkasluoto contains lake (65%) and forest (35%). Thus the surface layer parametrizations in the (possibly snow-covered) forest also influence the resulting screen-level temperatures. However, in our case the differences between the grid-averaged screen-level temperature and that over the lake tile were small (not shown). More important here is to note the lake surface state: frozen in REF, open in OBS and FLK. Thus, in the experiment REF the main contribution to the screen-level temperature is due to the predicted lake ice temperature, while in the other experiments the lake contribution is due to the assimilated (in OBS) or predicted (in FLK) water temperature. This explains the difference between REF and OBS. The difference between OBS and FLK might be explained first of all by the approximations used in processing the lake surface observations for the data assimilation of the experiment OBS, that may result in too cold water temperatures. Another reason for the differences between OBS and FLK is the evident inertia of the FLake parametrizations to change the lake water and ice temperatures in time, i.e. the initial values dominated during the whole period.

Surface energy balance

The (atmospheric) surface energy balance is defined as a sum of turbulent sensible and latent heat fluxes and net radiation (long-wave and short-wave). It should balance the heat transfer from below (ground or ice) towards the surface. In the atmospheric model, the surface energy balance is used for determination of the surface temperature. Thus, it was applied for prediction of the land and ice surface temperatures in all current experiments and for prediction of the water temperature in FLK. (In FLake, the short-wave radiation can penetrate deeper into the lake water. This makes the definition of the surface energy balance slightly more complicated in this case.) Comparison of the experiments in terms of the energy balance (Fig. 6b) and its components during 6–10 December indicates, that the balance is mainly positive (from warmer air towards the colder surface), with the largest values in REF. As the grid-averaged surface temperature did not increase (not shown), the energy has been assumed by the model to be consumed for melting of the ice (REF) or not taken into account (OBS), or stored deeper (FLK).

In December at the latitudes of central Finland, the radiation balance is in practice determined by the long-wave radiation only because of the low solar angles and clouds, resulting in a maximum down-welling short-wave radiation flux of the order of 50 W m^{-2} at noon. Thus, the existing differences in short-wave albedo (ice or water) between the experiments play almost no role here in winter. The situation would be very different in spring, during the melting period. The down-welling radiation fluxes are similar in all experiments as expected, because they depend on the properties of the atmosphere (cloudiness), not those of the surface. The up-welling long-wave radiation fluxes are different (within ca. 10 W m^{-2}), as this flux is directly related to the surface (skin) temperature itself.

The main contribution to the energy balance difference between the experiments is in this case due to the turbulent heat fluxes. The latent heat flux towards the surface was quite small: less than 20 W m^{-2} in OBS and FLK but in REF twice larger. The sensible heat flux towards the surface varied between 20 and 100 W m^{-2}, where again the values in REF were typically two times larger than in the other experiments. The predicted heat fluxes depend on the surface properties and on the way the surface layer processes
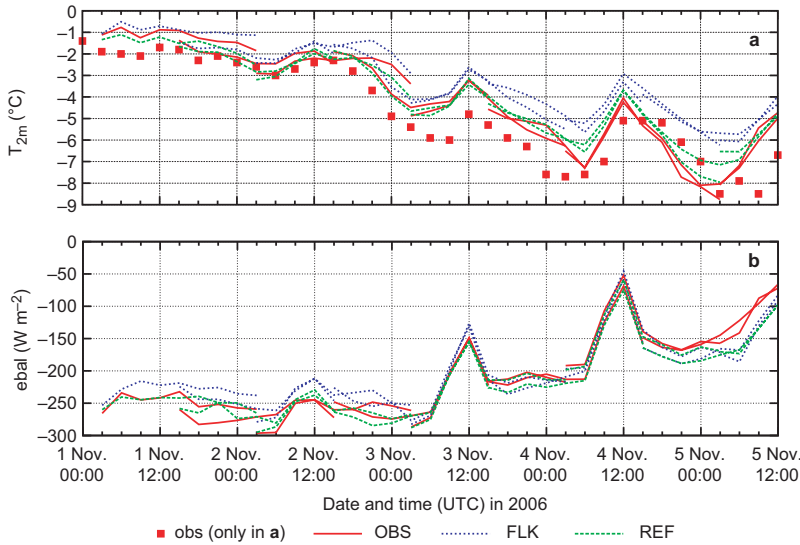
Fig. 7. As Fig. 6 but for the beginning of November. Note the different scales in the figures.

are parametrized in the model. Note again that during this period, REF assumed an ice surface, but OBS and FLK (correctly) an unfrozen water surface.

Another example, from the beginning of November, illustrates a cold-spell situation when the atmospheric temperature over Lake Haukivesi decreased quickly and the lake was close to freezing. During this period, all experiments still assumed the lake unfrozen (Fig. 5) and their forecasts were close to each other. During 1–3 November, a low pressure centre moved across the southern Finland from south-west towards north-east. This caused a strong easterly, later northerly wind, with a related strong turbulent mixing. The energy balance (Fig. 7) is hence negative, due to the large heat flux towards atmosphere: the maximum sensible heat flux was 100 W m^{-2} and maximum latent heat flux (evaporation) 150 W m^{-2}. Later, on 3–5 November, a high pressure ridge formed over the eastern Finland. In the calm clear-sky conditions, the simulated net radiation was close to zero during daytime (the maximum down-welling short-wave radiation flux was still ca. 150 W m^{-2}) but strongly negative (ca. –120 W m^{-2}) during the night. This example indicates that the basic atmospheric boundary and surface layer parametrizations of HIRLAM, both with and without FLake, work in an expected and physically realistic way, at least when there is no lake (sea) ice around.

Verification

Standard statistical verification against synoptic observations, evaluated over the two-month period, reveals that in all experiments the simulated screen-level temperature is lower than observed (not shown). The scores from the three experiments are very similar, when calculated over the whole model domain shown in Fig. 3. The scores differ slightly when evaluated over Finland only: the cold bias is largest in the experiment REF (–1.13 °C), while the experiments OBS and FLK show comparable systematic forecast and observation difference of –0.88 and –0.97 °C, respectively. Differences between observations and forecasts of various lead times (+6 h, +12 h, +24 h) were combined when calculating these scores. However, the bias does not significantly depend of the forecast length. The other verified variables (relative humidity, wind and surface pressure) show only small differences between the experiments.

The result seems to indicate the following: (1) assimilation of the LST observations improves the forecasts slightly as compared with the experiments where such observations were not used; (2) the cold bias is a property of this HIRLAM version, nor caused nor solved by the lake-related formulations in the model (within the international HIRLAM-A program there is additional evidence to support this conclusion);

and (3) the lake effects remain local. Thus even over Finland, where lakes cover a significant fraction of the area, an improved temperature forecast at the lake points changes the overall verification scores only a little.

Conclusions

We have studied different ways of taking into account the influence of (small) lakes in the numerical weather prediction system HIRLAM. Three series of numerical experiments were performed for the period November–December 2006, with the emphasis on eastern Finland. Over this area, lakes are numerous and may cover large fractions of the model's grid-squares. Our first experiment (REF) used climatological lake surface temperature and ice coverage, while in the second experiment (OBS), lake surface temperature (LST) observations were assimilated in order to create the most reliable initial state for the daily forecasts. The third experiment (FLK) applied prognostic lake parametrizations based on the FLake model. The three series of simulations led to different grid-averaged screen-level temperatures. The differences remained local even over the areas where the fraction of lakes was large in the model. The temperature differences were largest where also the simulated ice cover was different. This emphasises the importance of knowing the correct timing of lake freezing and melting.

According to observations, during the warm autumn of 2006 over the Nordic experiment domain, only the northern lakes were covered by ice. In the experiment REF, there was too much ice and the predicted temperatures were too cold. In OBS, the ice cover is believed to be realistic, and the predicted screen-level temperatures were warmer than in REF. The experiment FLK kept all but the northernmost lakes in Finland ice-free, with the water temperature several degrees above zero. This resulted in the warmest screen-level temperatures among the experiments over the lake-related grid-points.

Statistical verification over the entire Nordic domain showed only small differences between the experiments. This confirms that the lake-effect indeed remained local in these simula-

tions. In terms of the screen-level temperatures, evaluated at the synoptic stations of Finland, the experiment OBS corresponded best to the observations. However, all experiments showed a cold bias of 0.9–1.1 °C, which is believed to be related to other than lake-related processes in the version of HIRLAM used in this study.

Thus, we could conclude that the usage of climatological lake surface temperatures in the numerical weather prediction model is not an optimal solution, simply because "the years are not brothers". In autumn 2006, the best predicted local screen-level temperatures were obtained when the model's lakes were not frozen (experiments OBS and FLK). Assimilation of lake surface temperatures should lead to good results in any conditions, but real-time LST and ice observations are presently not available for operational weather forecasting. Obtaining *in-situ* and satellite-based observations and development of the methods of their assimilation are thus tasks of high priority.

During this period of unfrozen lakes, good observation and forecast comparison results at chosen stations near the Finnish lakes were also produced by a version of HIRLAM that used FLake parametrizations without data assimilation. However, handling of lake freezing within FLake parametrizations requires further improvement. The question of freezing within FLake seems to be related to too strong inertia of the lake model, and also to the definition of the first initial conditions in the beginning of the forecast-assimilation cycles. The reasons of the inertia are not clear and require more investigation. We cannot exclude the possibility of a technical error in the NWP implementation, since in climate simulations (*see* e.g. Samuelsson *et al.* 2010) the FLake scheme describes freezing and melting realistically. It is also possible that in the NWP framework, a continuous assimilation of LST and lake ice observations combined with the lake parametrizations is required for an optimal performance. Melting of lakes was not considered here and remains a topic for a further study.

For our limited-area experiments, we had sufficiently realistic lake physiography description available. From the point of view of the operational numerical weather prediction (NWP) models, possibly covering any area of our planet,

a global data base of the lake properties, in particular the depth and fraction of lake, is necessary.

We would summarize our experience by suggesting a few development tasks of the highest priority for handling of lakes in NWP models:

— Make a feasibility study of the availability of real-time satellite-based and local measurements of lake surface temperature and ice cover. Develop methods for assimilation of these observations for NWP models.
— Improve and make available a global lake depth data base for the use in NWP and climate models.
— Explore the question of initial (cold start) conditions needed for starting the NWP and climate model simulations that apply lake parametrizations (FLake) at any time and at any point over the globe.
— Combine the lake parametrizations with assimilation of the lake surface temperature and ice conditions.

While this manuscript was being prepared for print, a technical error in the FLake interface in HIRLAM was found. Correction of this error solved the problem of inertia, discussed above, which prevented most of the lakes from freezing in the experiment FLK. In a newly run experiment, Lake Haukivesi got permanently frozen on 20 December, a week earlier than observed. The surface temperatures of the southern and eastern Finland lakes became, in general, lower. All comparisons presented in this paper are still valid, if the experiment FLK is understood to represent a simulation where all lakes are kept unfrozen. We will continue a systematic analysis of the role of observed *vs.* predicted lake surface temperatures in the simulations of the atmospheric processes. For this, studies during the freezing and melting periods of the lakes are needed.

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