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Validation of lake surface state in the HIRLAM NWP model against *in-situ* measurements in Finland

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Abstract. High Resolution Limited Area Model (HIRLAM), used for operational numerical weather prediction in the Finnish Meteorological Institute (FMI), includes prognostic treatment of lake surface state since 2012. Forecast is based on the Freshwater Lake (FLake) model integrated to HIRLAM. Additionally, an independent objective analysis of lake surface water temperature (LSWT) combines the short forecast of FLake to observations from the Finnish Environment Institute (SYKE). The resulting description of lake surface state - forecast FLake variables and analysed LSWT - was compared to SYKE observations of lake water temperature, freezing and melting dates as well as the ice and snow thickness for 2012-2018 over 45 lakes in Finland. During the ice-free period, the predicted LSWT corresponded to the observations with a slight overestimation, with a systematic error of + 0.91 K. The colder temperatures were underrepresented and the maximum temperatures were too high. The objective analysis of LSWT was able to reduce the bias to + 0.35 K. The predicted freezing dates corresponded well the observed dates, mostly within the accuracy of a week. The forecast melting dates were far too early, typically several weeks ahead of the observed dates. The growth of ice thickness after freezing was generally overestimated. However, practically no predicted snow appeared on lake ice. The absence of snow, found to be due to a technical error in HIRLAM, is suggested to be also the reason of the inaccurate simulation of the ice melt in spring.

1 Introduction

Lakes influence the energy exchange between the surface and the atmosphere, the dynamics of the atmospheric boundary layer and the near-surface weather. This is important for weather forecasting over the areas where lakes, especially those with a large yearly variation of the water temperature, freezing in autumn and melting in spring, cover a significant area of the surface. Description of the lake surface state influences the numerical weather prediction (NWP) results, in particular in the models whose resolution is high enough to account for even the smaller lakes.

The High Resolution Limited Area Model HIRLAM (Unden et al., 2002; Eerola, 2013) has been applied since 1990 for the numerical short-range weather forecast over the Northern Europe. In the beginning, the monthly climatological water surface temperature for both sea (sea surface temperature SST) and lakes (Lake Surface Water Temperature LSWT) was used.

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Since 2012, HIRLAM includes a prognostic lake temperature parameterization based on the Freshwater Lake Model (FLake, Mironov et al., 2010). An independent objective analysis of observed LSWT (Kheyrollah Pour et al. (2017) and references therein) was implemented in 2011. Fractional ice cover (lake ice concentration in each grid-square of the model) is estimated separately based on the analysed LSWT and the ice thickness predicted by FLake.

FLake was designed to be used as a parametrization scheme for the forecast of the lake surface state in NWP and climate models. It allows to predict the lake surface state in interaction with the atmospheric processes treated by the NWP model. The radiative and turbulent fluxes from the atmospheric model are combined with FLake processes at each time-step of the model integration (with a typical interval of one or several minutes) in the model grid, where the fraction and depth of lakes are prescribed.

FLake has been implemented into the main European NWP and regional climate models, first into COSMO (Mironov et al., 2010) then into ECMWF (Balsamo et al., 2012), Unified Model (Rooney and Bornemann, 2013), SURFEX surface modelling framework (Masson et al., 2016), regional climate models RCA (Samuelsson et al., 2010), HCLIM (Lindstedt et al., 2015) and REMO (Pietikäinen et al., 2018), among others. Description of lake surface state and its influence in the numerical weather and climate prediction has been validated in various ways. Results of case studies, e.g. Eerola et al. (2014) and shorter-period NWP experiments, e.g. Eerola et al. (2010); Rontu et al. (2012); Kheyrollah Pour et al. (2014); Kheyrollah Pour et al. (2017) as well as climate model results, e.g. Samuelsson et al. (2010); Pietikäinen et al. (2018), have been compared with remote-sensing satellite data and *in situ* lake temperature and ice measurements as well as validated against the standard weather observations. In general, improvement of the scores has been seen over regions where lakes occupy a significant area. However, specific features of each of the host models influence the results of the coupled atmosphere-lake system as FLake appears to be quite sensitive to the forcing by the atmospheric model.

The aim of the present study is to use *in situ* LSWT measurements, lake freezing and melting dates and measurements of ice and snow thickness by the Finnish Environment Institute (Suomen Ympäristökeskus = SYKE) for validation of the lake surface state forecast by the operational HIRLAM NWP model. For this purpose, HIRLAM analyses and forecasts archived by the Finnish Meteorological Institute (FMI) were compared with the observations by SYKE over the lakes of Finland from spring 2012 to summer 2018. To our knowledge, this is the longest available detailed dataset that allows to evaluate how well the lake surface state is simulated by an operational NWP model that applies FLake parametrizations.

2 Lake surface state in HIRLAM

FLake was implemented in the HIRLAM forecasting system in 2012 (Kourzeneva et al., 2008; Eerola et al., 2010). The model utilizes external datasets on the lake depth (Kourzeneva et al., 2012a; Choulga et al., 2014) and the lake climatology (Kourzeneva et al., 2012b). The latter is only needed in order to provide initial values of FLake prognostic variables in the very first forecast. Real-time *in-situ* LSWT observations by SYKE for 27 Finnish lakes became available for the operational HIRLAM analysis in 2011 (Eerola et al., 2010; Rontu et al., 2012). In the current operational HIRLAM at FMI FLake provides the background for the optimal interpolation (OI, based on Gandin 1965) analysis of LSWT. However, the prognostic FLake

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variables are not corrected using the analysed LSWT, which would require advanced data assimilation methods based on e.g. the extended Kalman filter (Kourzeneva, 2014). The relations between the OI analysis and the prognostic FLake in HIRLAM are schematically illustrated in Figure 1.

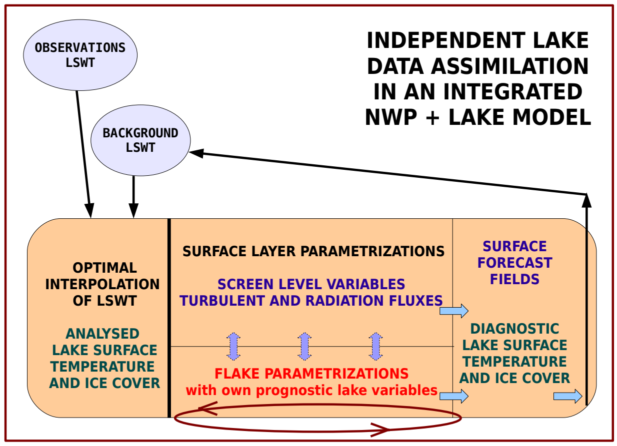

Figure 1. Coexistence of the independent objective analysis of the observed LSWT and prognostic FLake parametrizations in HIRLAM.

2.1 Freshwater lake model in HIRLAM

FLake is a bulk model capable of predicting the vertical temperature structure and mixing conditions in lakes of various depths on time-scales from hours to years (Mironov et al., 2010). The model is based on two-layer parametric representation of the evolving temperature profile in the water and on the integral budgets of energy for the layers in question. Bottom sediments and the thermodynamics of the ice and snow on ice layers are treated separately. FLake depends on prescribed lake depth information. The prognostic and diagnostic variables of HIRLAM/FLake plus the analysed lake surface variables in HIRLAM are listed in the Appendix (Table A1).

At each time step of the HIRLAM forecast, FLake is driven by the atmospheric radiative and turbulent fluxes provided by the physical parameterisations in HIRLAM. This couples the atmospheric variables over lakes with the lake surface properties as provided by FLake. Implementation of FLake model as a parametrizations scheme in HIRLAM was based on the experiments described by Rontu et al. (2012). Compared to the reference version of FLake (Mironov et al., 2010), minor modifications were introduced, namely, use of constant snow density = 300 $\mathrm{kgm^{-3}}$, molecular heat conductivity = 1 $\mathrm{Jm^{-1}s^{-1}K^{-1}}$, constant albedos of dry snow = 0.75 and ice = 0.5. Bottom sediment calculations were excluded. Global lake depth database (GLDB v.2, Choulga et al. (2014)) is used for derivation of mean lake depth in each gridsquare. Fraction of lake is taken from HIRLAM physiography database, where it originates from GLCC (Loveland et al., 2000).

In this study, lake surface temperature and thickness of ice predicted by FLake were used for the model-observation comparison. Lake surface temperature is diagnosed from the mixed layer temperature for the unfrozen lake gridpoints and from the ice or snow-on-ice temperature for the frozen points. In FLake, ice starts to grow from an assumed value of one millimeter when temperature reaches the freezing point. The whole lake tile in a gridsquare is considered by FLake either frozen or unfrozen. Snow on ice is accumulated from the model's snowfall at each time step during the numerical integration.

2.2 Objective analysis of LSWT observations

A comprehensive description of the optimal interpolation (OI) of the LSWT observations in HIRLAM is given by Kheyrollah Pour et al. (2017). Shortly, LSWT analysis is obtained by correcting the FLake forecast at each gridpoint by using the weighted average of the deviations of observations from their background values. Prescribed statistical information about the observation and background error variance as well as the distance-dependent autocorrelation between the locations (observations and gridpoints) are applied. A specific feature of the lake surface temperature OI is that the interpolation is performed not only within the (large) lakes but also across the lakes: within a statistically pre-defined radius, the observations affect all gridpoints containing a fraction of lake. This ensures that the analysed LSWT on lakes without own observations may also be influenced by observations from neighbouring lakes, not only by the first guess provided by FLake forecast.

Within the present HIRLAM setup, the background for the analysis is provided by the short (6-hour) FLake forecast. However, the next forecast is not initialised from the analysis, see Figure 1. Instead, FLake continues running from the previous forecast, driven by the atmospheric state given by HIRLAM at each time step. This means that the result of OI analysis does not benefit FLake but the analysis remains to some extent as an extra diagnostic field independent of the LSWT forecast. Note that FLake background has a large influence in the analysis, especially over distant lakes where neighbouring observations are not available.

Missing LSWT observations in spring and early winter are interpreted to represent presence of ice and given a flag value of -1.2°C. If, however, the results of the statistical moving-average-type LSWT model (Elo, 2007), provided by SYKE along with the real-time observations, indicate unfrozen conditions, the observations are considered missing. This prevents appearance of ice in summer when observations are missing but leads to a misinterpretation of data in spring if the SYKE model indicates too early melting. In the analysis, fraction of ice is diagnosed from the LSWT field in a simple way. The lake surface within a gridsquare is assumed fully ice-covered when LSWT falls below -0.5°C and fully ice-free when LSWT is above 0°C. Between these temperature thresholds, the fraction of ice changes linearly (Kheyrollah Pour et al., 2014).

The HIRLAM surface data assimilation system produces comprehensive feedback information from every analysis-forecast cycle. The feedback consists of the observed value and its deviations from the background and from the final analysis at the observation point. Bilinear interpolation of the analysed and forecast values is done to the observation location from the nearest gridpoints that contain a fraction of lake. In addition, information about the quality check and usage of observations is provided. Fractions of land and lake in the model grid as well as the weights, which were used to interpolate gridpoint values to the observation location, are given. We use this information as basic material of the present study (see sections 3.4 and 4).

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Table 1. FMI operational HIRLAM

Domain	From Atlantic to Ural, from North Africa beyond North Pole
Model horizontal / vertical resolution	7 km / 65 levels
HIRLAM version	7.4
Model dynamics	Hydrostatic, semi-Lagrangian, grid-point
Atmospheric physical parametrizations	Savijärvi radiation, CBR turbulence,
	Rasch-Kristiansson cloud microphysics + Kain-Fritsch convection
Surface physical parametrizations	ISBA-newsnow for surface, FLake for lakes
Data assimilation	Default atmospheric (4DVAR) and surface (OI) analysis
Lateral boundaries	ECMWF forecast
Forecast	Up to +54 h initiated every 6h (00, 06, 12, 18 UTC)

3 Model-observation intercomparison 2012-2018

In this intercomparison we validated HIRLAM/FLake results against observations about the lake surface state. The impact of FLake parametrizations to the weather forecast by HIRLAM is not considered. This is because the archived observations and the operational HIRLAM results were used during the period from spring 2012 to summer 2018 when FLake was always an integral part of HIRLAM. This means that there are no non-FLake weather forecasts to compare with.

3.1 FMI operational HIRLAM

FMI operational HIRLAM is based on the last reference version (v.7.4), implemented in spring 2012. (Eerola (2013) and references therein). FLake was introduced into this version. After that the development of HIRLAM was frozen. Thus, during the years of the present comparison, the FMI operational HIRLAM system remains unmodified, which offers a clean time series of data for the model-observation intercomparison. The general properties of the system are summarised in Table 1. In the present study, a coding error in FLake implementation was revealed in the reference HIRLAM v.7.4. A too large critical value to diagnose snow existence prevented practically all accumulation of the forecast snowfall on lake ice in the FMI HIRLAM-FLake operational system.

3.2 SYKE lake observations

3.2.1 Lake temperature measurements

Regular *in-situ* lake water temperature (LWT) measurements are performed by SYKE. SYKE operates 32 regular lake and river water temperature measurement sites in Finland. The temperature of the lake water is measured every morning at 8.00 AM local time, close to shore, at 20 cm below the water surface. The measurements are recorded either automatically or manually and are performed only during the ice-free season (Korhonen, 2002; Rontu et al., 2012). Measurements from 27 lakes (Figure 2,

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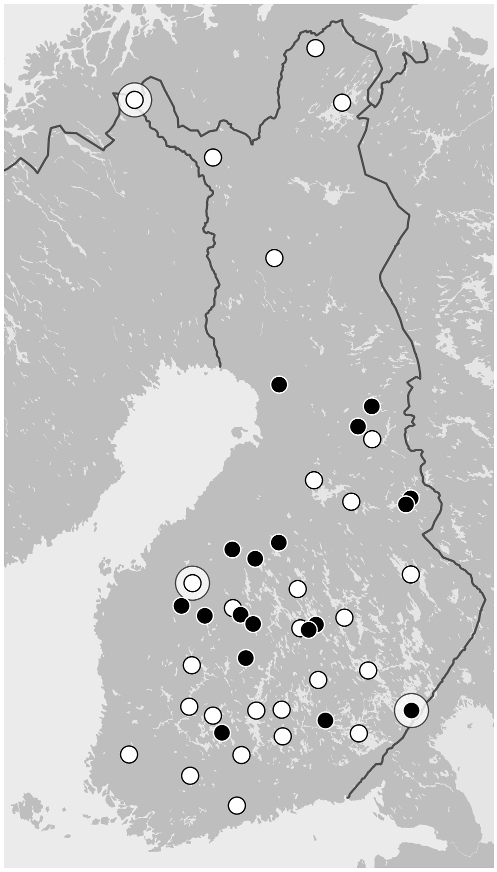


Figure 2. Map of SYKE observation points used in this study: lakes with both LSWT and LID observations (white), lakes where only LID is available (black). On Lakes Lappajärvi, Kilpisjärvi and Simpelejärvi also ice and snow thickness measurements were used (Section 4.3), they are surrounded with a large white circle. List of the lakes with coordinates is given in Appendix A2.

white dots) used by the FMI operational HIRLAM, were included in all comparisons reported in this study. These data are also available in the SYKE open data archive (SYKE, 2018).

3.2.2 Freezing and melting dates

Regular visual observations of freezing and melting of lakes have been recorded in Finland for centuries, the longest time series starting in the middle of the 19th century (Korhonen, 2005). Presently, dates of freezing and melting are available from SYKE (2018) on 123 lakes, but the time series for many lakes are discontinuous. Further, we will denote the melting and freezing dates together by "lake ice dates" (LID). For both freezing and melting the dates are available in two categories: for freezing "freezing of the visible area" (code 29 by SYKE) and "permanent freezing of the visible area" (code 30). For melting the dates are defined as "no ice visible from the observation site" (code 28) and "no ice on the outer open water areas" (code 27).

LID from the 27 lakes whose LWT measurements are used in HIRLAM were available and selected for this study. In addition, 18 lakes with only LID available (Figure 2, black dots) were chosen for comparison with HIRLAM/FLake LID.

3.2.3 Ice and snow thickness on lakes

SYKE records the lake ice and snow thickness on around 50 locations in Finland, archived data are available in total from 160 measurement sites. The manual measurements are done three times a month during the ice season. Thickness of ice and the snow on ice are measured by drilling holes through snow and ice layers along chosen tracks, normally at least 50 m from the coast (Korhonen, 2005). The locations may differ from those of the LSWT measurement or LID observation over the same lakes. In this study, measurements from lakes Lappajärvi, Kilpisjärvi and Simplejärvi were utilised as additional data for validation in Section 4.3. These lakes, sufficiently large in order to fit well the HIRLAM grid, represent the western, northern and south-eastern Finland.

3.3 Lake surface state derived from HIRLAM output

3.3.1 Lake surface water temperature

Diagnosed LSWT from HIRLAM/FLake analysis and forecast cycles was compared with the observed LWT by SYKE using data from the analysis feedback files (Section 2.2) at the observation locations on 06 UTC every day.

3.3.2 Freezing and melting dates

Both the analysed LSWT and the lake ice thickness forecast by FLake were separately used to define LID. The values were picked afterwards from the HIRLAM archive for a single gridpoint nearest to each of the 45 observation locations (not interpolated as in the analysis feedback file that was used for the LSWT comparison). For the definition of LID, it was assumed that the gridpoint value nearest to the location of the LSWT observation represents the ice conditions over the chosen lake. In autumn a lake can freeze and melt several times before final freezing. The last date when the forecast ice thickness crossed a critical value of 1 mm or the analysed LSWT fell below freezing point was selected as the date of freezing. To decrease the effect of oscillation of the gridpoint values between the HIRLAM forecast-analysis cycles, the mean of the four daily ice thickness forecasts or analysed LSWT values was used. In the same way, the last date when the forecast ice thickness fell below the critical value of 1 mm or the analysed LSWT value crossed the freezing point was selected as melting day.

3.4 Validation methods

For LSWT statistics we used data collected during the HIRLAM surface analysis at each active observation location (Section 2.2), excluding the winter periods 1 December - 31 March. The observations (ob) at 27 SYKE stations were assumed to represent the true value, while the analysis (an) is the result of OI that combines the background forecast (fc) with the observations. Time-series, maps and statistical scores, to be presented in Section 4.1, were derived from these.

LID by HIRLAM/FLake were compared to the observed dates during 2012-2018, including in the comparison data over all months. The category 29 observations (see Section 3.2.2) were used. In this category the time series were the most complete at the selected stations. For the same reason, the melting observations of category 28 were used for comparison. Furthermore, using a single gridpoint value for the calculation of LID also seems to correspond best the observation definition based on what is visible from the observation site. The statistics were calculated as ob - fc and ob - an. Hence, positive values mean that melting or freezing takes place too late in the model as compared to the observations.

4 Results

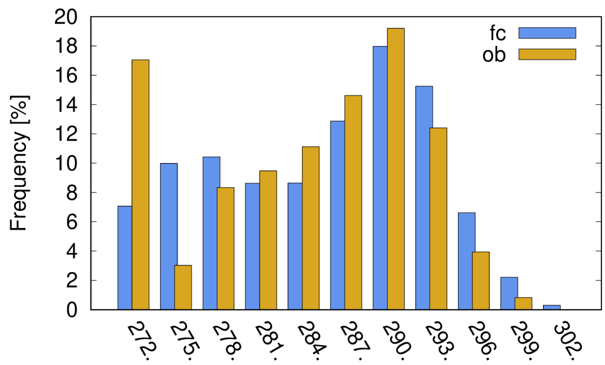
4.1 Analysed and forecast LSWT at observation points

Figure 3 shows the frequency distribution of LSWT according to FLake forecast and SYKE observations. It is evident that the amount of data in the class of temperatures which represents frozen conditions (LSWT flag value 272 K) is underestimated by the forecast (Figure 3a). When subzero temperatures are excluded from the comparison (Figure 3b), underestimation in the colder temperature classes and overestimation in the warmer classes still remains. LSWT analysis (Figure 4) improves the situation somewhat but the basic features remain. This is due to the dominance of FLake forecast via the background of the analysis. In Section 4.3, we will show time-series illustrating the physics behind these LSWT statistics.

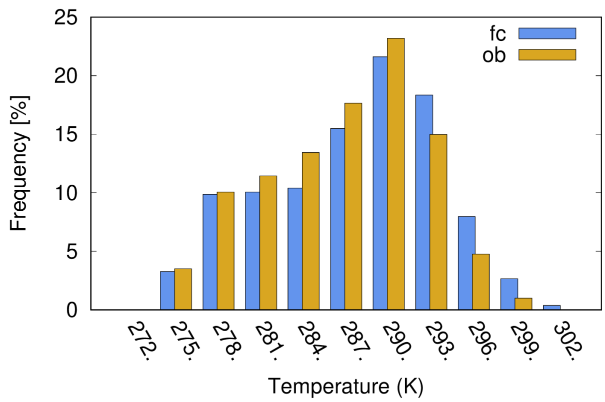
Table 2 confirms the warm bias by FLake in the unfrozen conditions. Similar results were obtained for all stations together and also for our example lakes Lappajärvi and Kilpisjärvi, to be discussed in detail in Section 4.3. There were three lakes with negative LSWT bias according to FLake forecast, namely the large lakes Saimaa and Päijänne, the smaller Ala-Rieveli. After the correction by objective analysis, a small positive bias converted to negative over 6 additional lakes, among them the large lakes Lappajärvi in the west and Inari in the north. The mean absolute error decreased from forecast to analysis in every lake.

In the frequency distributions, the warm temperatures are evidently related to summer. For FLake, the overestimation of maximum temperatures, especially in shallow lakes, is a knowm feature (e.g. Kourzeneva 2014). It is related to the difficulty of forecasting the mixed layer thermodynamics under strong solar heating. Cold and subzero temperatures occur in spring and autumn. In a few large lakes like Saimaa, Haukivesi, Pielinen, LSWT tends to be slightly underestimated in autumn both according to the FLake and the analysis (not shown). However, as will be shown in Sections 4.2 and 4.3, the cold left-hand side columns in the frequency distributions are mainly related to spring, when HIRLAM/FLake tends to melt the lakes significantly too early.

There are problems, especially in the analysed LSWT, over (small) lakes of irregular form that fit poorly the HIRLAM grid and where the measurements may represent more the local than the mean or typical conditions over the lake. These are the only ones where an underestimation of summer LSWT can be seen. Cases occur where FLake results differ so much from the observations that the quality control of the HIRLAM surface data assimilation rejects the observations, forcing also the analysis to follow the incorrect forecast (not shown).



(a) with all temperatures (also frozen conditions) included

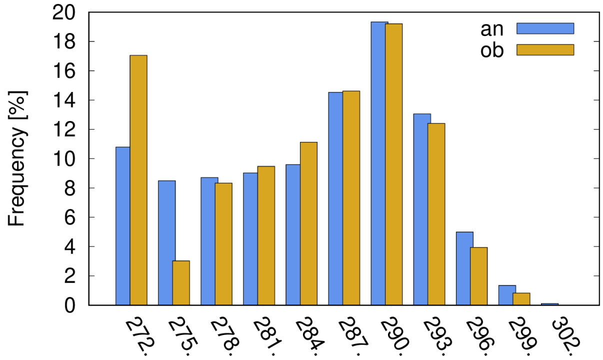


(b) only open water temperatures included

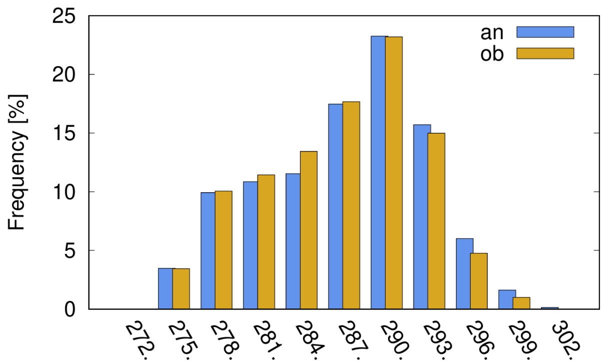
Figure 3. Frequency of observed (yellow) and forecast (blue) LSWT over all 27 SYKE lakes 2012-2018. x-axis: LSWT, unit K, y-axis: frequency, unit %.

4.2 Freezing and melting dates

Statistics of the error in melting and freezing dates are shown in Table 3. 'LSWT an' refers to the melting/freezing dates computed from analysed lake surface temperature and 'IceD fc' to those estimated from the forecast ice thickness. Over the 45 lakes included in this comparison, the number of cases of melting was 288 as estimated from the analyzed LSWT and 258 as estimated from the forecast ice thickness. The difference is due to starting time of our data. When the data started at the 1st of April 2012, at several stations the lake was already open according to FLake forecast while the analysed LSWT still indicated frozen conditions. For freezing, the number of cases was 233 according to both estimates. As the data contains the time period from the 1st April 2012 to the 30th June 2018, the maximum number of freezing events on an individual lake is six and that of melting events seven. In practice, the number may be less for some lakes because of missing observations.



(a) with all temperatures (also frozen conditions) included



(b) only open water temperatures included

Figure 4. As for Figure 3 but for observed and analysed LSWT.

Figure 5 shows the frequency distribution of the error of freezing dates. Definition of the freezing date from the ice thickness by FLake gave slightly more occurrences in the unbiased class (error between -5 - +5 days), compared to the estimate from the analysed LSWT. Of all cases 48 % and 40 % fell in this class according to ice thickness and LSWT, respectively. In 16% / 20% of cases the freezing occurs more than five days too late and only in 9% / 11% cases more than two weeks too late. This class of more than two weeks too late freezing consists of 25 cases which are distributed over 15 lakes, thus in most cases one event per lake. This suggests that the error is related more to individual years than to systematically problematic lakes. It is worth noting, that cases where the error is over 45 days, are all but one due to one lake, Kevojärvi which is situated in the very north of Finland. This lake is narrow, with an area of 1 km^{-2}, and situated in a steep canyon. Therefore it is poorly represented by the HIRLAM grid and both FLake and analysis results seem unreliable.

Concerning the cases of too early freezing, in 44% / 32% of the cases freezing occurs more than five days too early and in 19% / 15% more than two weeks too early. The last mentioned 15% (34 cases) are distributed over 19 lakes. Each of the five

Table 2. Statistical scores for LSWT at all and two selected stations

station	fc or an	mean ob	bias	mae	stde	N
ALL	fc	286.3	0.91	1.94	2.34	30877
	an	286.3	0.35	1.32	1.72	30861
Lappajärvi	fc	286.9	0.33	1.23	1.62	1243
	an	286.9	-0.65	1.06	1.10	1243
Kilpisjärvi	fc	281.7	1.82	2.13	2.15	780
	an	281.7	1.10	1.42	1.51	780

Statistics over days when both forecast/analysis and observation indicate unfrozen conditions. bias = systematic difference fc/an - ob, mae = mean absolute error, stde = standard deviation of the error, N = number of days (06 UTC comparison, no ice).

Table 3. Statistical measures of the error of freezing and melting date

		bias	sde	max	min	N
Freezing	LSWT an	-3.5	17.9	64	-52	233
	IceD fc	-0.3	17.8	67	-41	233
Melting	LSWT an	-15.2	8.5	2	-54	288
	IceD fc	-20.5	9.2	-1	-56	258

Denotation: LSWT an - LID estimated from analysed LSWT, IceD fc - LID estimated from forecast ice thickness.

large lakes Pielinen, Kallavesi, Haukivesi, Päijänne and Inari occur in this category three times while all other lakes together share the remaining 19 cases during the six winters.

Looking at the errors in melting dates (Figure 6), both estimates indicate too early melting and the distribution is strongly skewed towards too early dates. Based on the LSWT analysis, the maximum frequency (52 %) occurs in the class -14 - -5 days while based on the ice thickness, the maximum frequency (47 %) is in the class -24 - -15 days. The mean values are -15.2 and -20.5 days and the standard deviations are 8.5 and 9.2 days, respectively. FLake suggests only three cases in the unbiased class -4 - +5 while according to the LSWT analysis there are 12 cases in this class. Hence, the melting dates derived from analysed LWST correspond the observations better than those derived from FLake ice thickness forecast but both are strongly biased towards too early melting. In the class where the error is over 35 days too early there are 19 cases on 12 different lakes. Four cases of these occured in the largest error category (over 45 days) on Lake Kilpisjärvi.

If we compare the error in freezing or melting dates based on analysed LSWT on those (27) lakes where SYKE temperature observations are available and used in the analysis to the rest (18) of lakes with no observations, it appears that the differences are small (not shown). Furthermore, similar differences appear also on the error estimates based on ice thickness from FLake.

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This suggests that the differences between these groups are related to the individual properties of the lakes: their depth, size, shape etc. rather than to the usage of LSWT observations in the analysis.

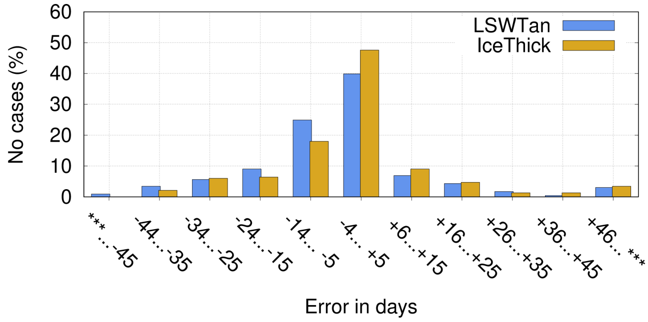

Figure 5. Frequency distribution of the difference between analysed/forecast and observed freezing days over all lakes 2012-2018. Variables used in diagnosis of ice existence: analysed LSWT crossing the freezing point (blue) and forecast ice thickness > 1 mm (orange). Observed variable: freezing date by SYKE. x-axis: difference (fc-ob), unit day, y-axis: percentage of all cases.

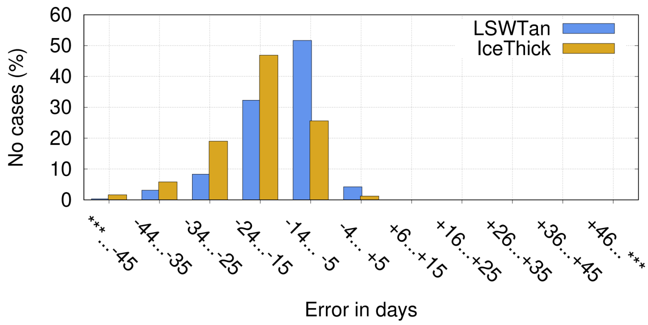

Figure 6. As for Figure 5 but for melting days.

We can conclude that HIRLAM/FLake succeeds rather well in predicting the freezing of Finnish lakes. Almost in half of the cases the error is less than ± 5 days. Some bias towards too early freezing can be seen. Melting is more difficult. FLake predicts melting always too early, with a mean error of over two weeks, and the LSWT analysis mostly follows it. The statistics suggest that only on a few stations the freezing or melting dates were systematically wrong during most of the years. Instead, most of the large errors were distributed among many lakes. The result of the freezing or melting dates diagnostics is somewhat sensitive to how the tresholds for freezing and melting are set. Here we used 1 mm for ice thickness and the freezing point for the LSWT analysis as the critical values.

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4.3 Comparisons on three lakes

In this section we combine the analysis of LWST time-series and LID for two representative lakes, Kilpisjärvi in the north and Lappajärvi in the west (see the map in Figure 2). Observed and forecast ice and snow thickness are discussed, using also additional data from Lake Simpelejärvi in the south-east of Finland.

Lake Kilpisjärvi is an Arctic lake at the elevation of 473 m, surrounded by fells. Its average/maximum depth is 22.5/57 m and the surface area 37.33 km^2. The heat balance as well as the ice and snow conditions on Lake Kilpisjärvi have been a subject of several studies (Leppäranta et al., 2012; Lei et al., 2012; Yang et al., 2013). Typically, the ice season lasts there seven months from November to May. Lake Lappajärvi is formed from a 23 km wide meteorite impact crater, which is estimated to be 76 million years old. It is Europe's largest crater lake with a surface area of 145.5 km^2 and an average/maximum depth of 12/36 m. Here the climatological ice season is shorter, typically about five months from December to April. The average/maximum depth of Lake Simpelejärvi is 9.3/34.4 m and the surface area 88.2 km^2. This lake is located at the border between Finland and Russia and belongs to the catchment area of Europe's largest lake, Lake Ladoga in Russia.

Figures 7 - 10 show the frequency distributions of LSWT according to the observations v.s. forecast and analysis for these lakes. Features common to the majority of lakes (Section 4.1) are seen, i.e. underestimation of the amount of cold temperature cases and overestimation of the warmer temperatures by the forecast and analysis. On Lake Lappajärvi, only the amount of below-freezing temperatures is clearly underestimated, otherwise the distributions look quite balanced. According to the observations, on Lake Kilpisjärvi the days with frozen surface dominate during the April–November periods. According to both FLake forecast and HIRLAM LSWT analysis the amount of these days is clearly smaller.

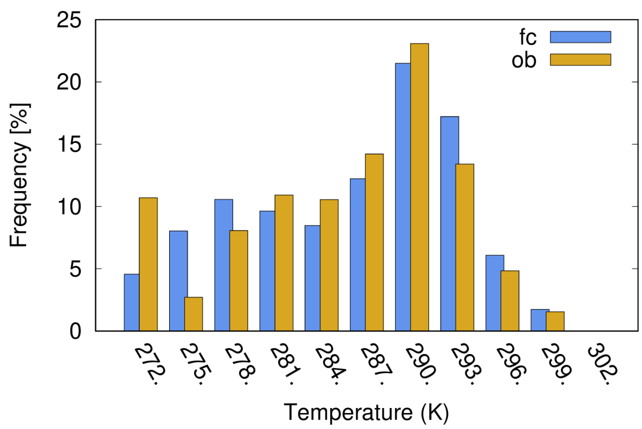

Figure 7. As for Figure 3a) but for Lake Lappajärvi, with all temperatures included.

Yearly time series of the observed, forecast and analysed LSWT, with the observed LID marked, are shown in Figures 11 and 12. In the absence of observations, the HIRLAM analysis follows the forecast. Missing data in the time series close to freezing and melting are due to missing observations, hence missing information in the feedback files (see Section 2.2). Differences between the years due to the different prevailing weather conditions can be seen in the temperature variations.

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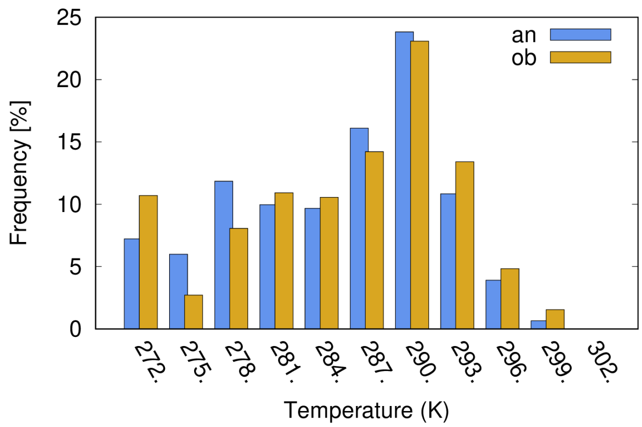

Figure 8. As for Figure 4a) but for Lake Lappajärvi

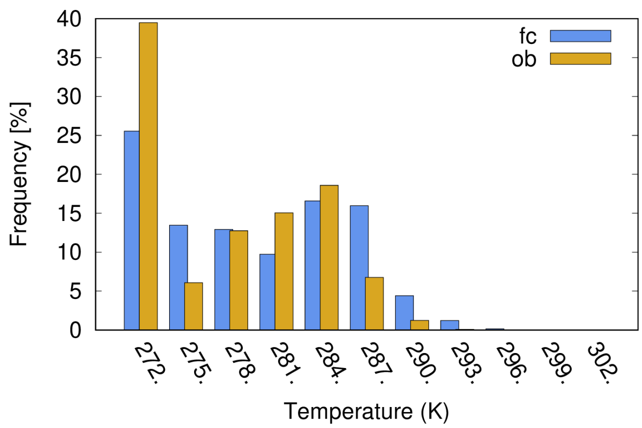

Figure 9. As for Figure 7 but for Lake Kilpisjärvi.

Generally, in spring FLake tends to melt the lakes too early, as already indicated by the LID statistics (Section 4.2). The too early melting and too warm LSWT in summer show up clearly in Kilpisjärvi (Figure 12). In Lappajärvi, the model and analysis are able to follow even quite large variations of LSWT in summer, but tend to somewhat overestimate the maximum temperatures. Overestimation of the maximum temperatures by FLake is still more prominent in shallow lakes (not shown). In autumn over Lakes Lappajärvi and Kilpisjärvi, the forecasts and analyses follow closely the LSWT observations and reproduce the freezing date within a few days, which is also typical to the majority of lakes.

Figure 13 shows a comparison of forecast and observed evolution of ice and snow thickness on Lappajärvi, Kilpisjärvi and Simpelejärvi in winter 2012-2013, typical also for the other lakes and years studied. In all three lakes, the ice thickness starts to grow after freezing both according to the forecast and the observations. In the beginning HIRLAM/FLake ice grows faster than observed. However, according to the forecast ice thickness starts to decrease in March of every year but according to the

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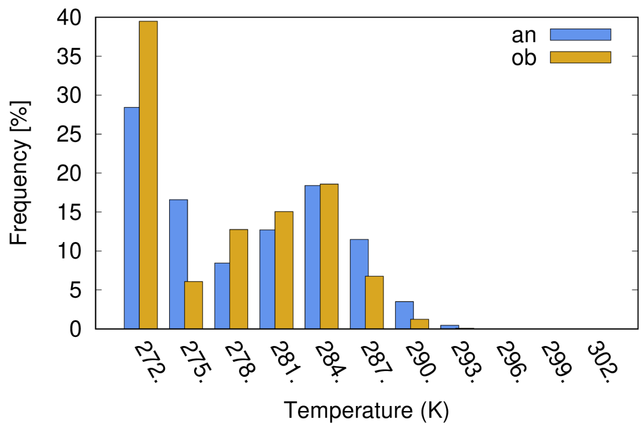

Figure 10. As for Figure 8 but for Lake Kilpisjärvi.

observations only a month or two later. The most remarkable feature is that there is no snow in the FLake forecast. It was found that this was due to a coding error in the HIRLAM reference version 7.4 which is applied operationally in FMI.

The too early melting of ice in the absence of snow could be explained by the wrong absorption of the solar energy in the model. In reality, the main factor of snow and ice melt in spring is the increase of daily solar radiation. In HIRLAM, the downwelling short-wave irradiance at the surface is known to be reasonable, with some overestimation of the largest clear-sky fluxes and all cloudy fluxes (Rontu et al., 2017). Over lakes, HIRLAM/FLake uses constant values for the snow and ice shortwave reflection, with albedo values of 0.75 and 0.5, correspondingly. When there was no snow, the lake surface was thus assumed too dark. 25 % more absorption of an assumed maximum solar irradiance of 500 Wm^{-2} (valid for the latitude of Lappajärvi in the end of March) would mean availability of extra 125 $\mathrm{Wm}-2$ for melting of the ice, which corresponds the magnitude of increase of available maximum solar energy within a month at the same latitude.

The forecast of too thick ice can also be explained by the absence of snow in the model. When there is no insulation by the snow layer, the longwave cooling of the ice surface in clear-sky conditions is more intensive and leads to faster growth of ice compared to the situation of snow-covered ice. In nature, ice growth can also be due to the snow transformation, a process whose parametrization in the models is demanding (Yang et al., 2013; Cheng et al., 2014).

5 Conclusions and outlook

In this study, *in-situ* lake observations from the Finnish Environment Institute were used for validation of the HIRLAM NWP model, which is applied operationally in the Finnish Meteorological Institute. It contains Freshwater Lake prognostic parametrizations and an independent objective analysis of lake surface state. We focused on comparison of observed and forecast lake surface water temperature, ice and snow thickness in the years 2012 - 2018. Because the HIRLAM/FLake system was unmodified during this period, a long uniform dataset was available for evaluation of the performance of FLake integrated in an operational NWP model.

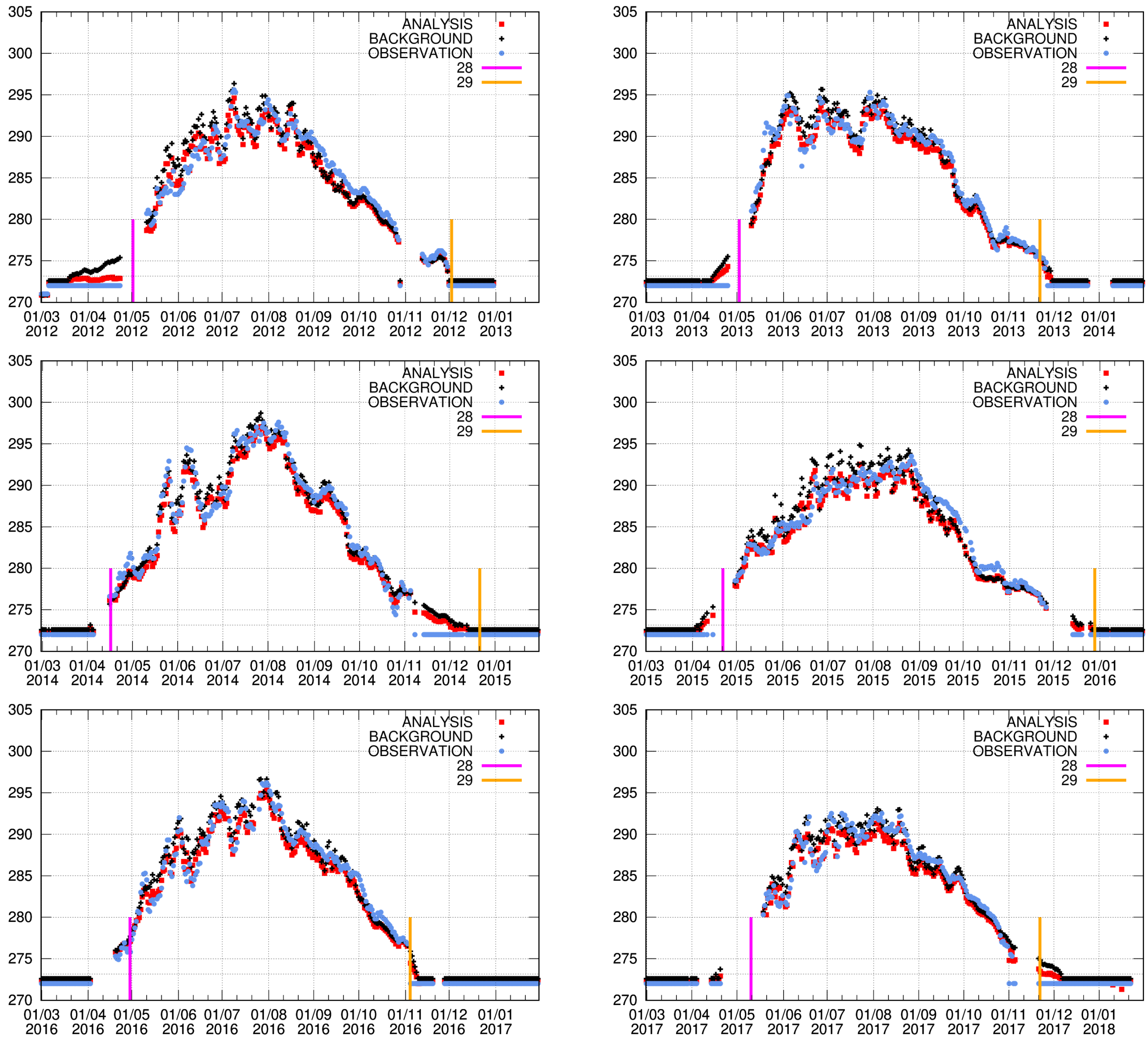

Figure 11. Time-series of the observed, analysed and forecast LSWT at the Lappajärvi observation location 23.67 E, 63.15 N for the years 2012-2018 based on 06 UTC data. Markers are shown in the inserted legend. Observed freezing date (blue) and melting date (red) are marked with vertical lines.

On average, the forecast and analysed LSWT were warmer than observed with systematic errors of 0.91 K and 0.35 K, correspondingly. The mean absolute errors were 1.94 and 1.32 K. Thus, the independent observation-based analysis of *in-situ* LSWT observations was able to improve the FLake +6 h forecast used as the first guess. However, the resulting analysis is by definition not used for correction of the FLake forecast but remains an independent by-product of HIRLAM.

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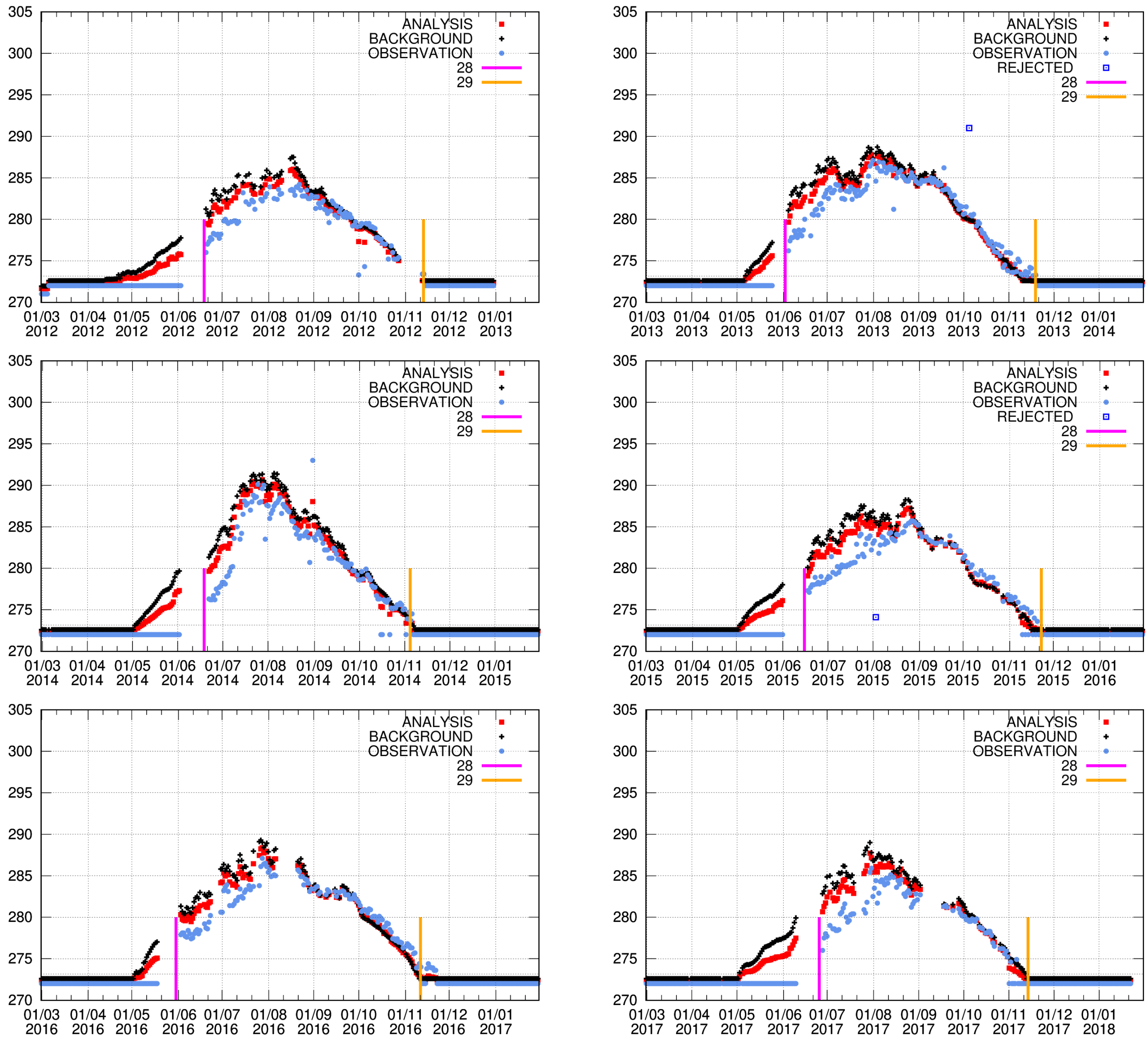

Figure 12. As for Figure 11 but for lake Kilpisjärvi, 20.82 E, 69.01 N.

An overestimation of the LSWT summer maxima was found, especially for shallow lakes. This behaviour of FLake is well known, documented earlier e.g. by Kourzeneva (2014). It arises due to the difficulty to handle correctly the mixing in the near-surface water layer that is intensively heated by the sun.

Forecast freezing dates were found to correspond the observations well, typically within a week. The forecast ice thickness tended to be overestimated, still the melting dates over most of the lakes occured systematically several weeks too early. Practically no forecast snow was on found on the lake ice, although the snow parametrization by FLake was included in

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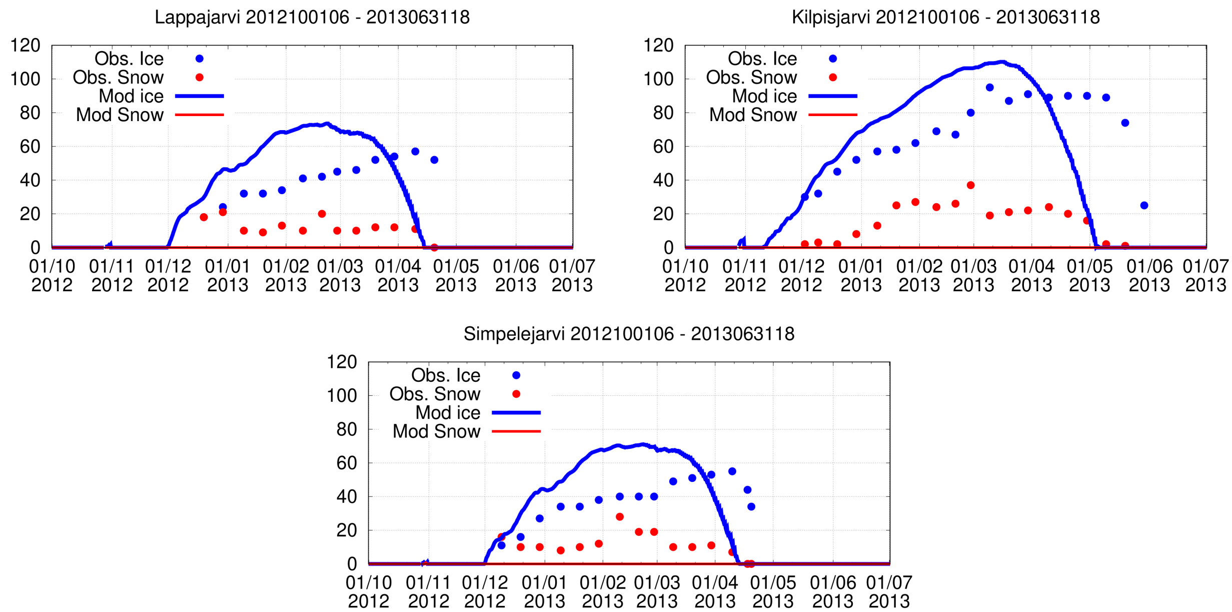

Figure 13. Evolution of ice (blue) and snow (red) thickness at Lakes Lappajärvi, Kilpisjärvi and Simpelejärvi during winter 2012-2013.

HIRLAM. The reason for the wrong behaviour in HIRLAM was evidently related to a coding error that prevented snow accumulation on lake ice. The too early melting and overestimated ice thickness differ from the results by Pietikäinen et al. (2018); Yang et al. (2013); Kourzeneva (2014), who reported somewhat too late melting of the Finnish lakes when FLake with realistic snow parametrizations was applied within a climate model or independently, driven by NWP data. It can be concluded that a realistc parametrization of snow on lake ice is importart in order to describe correctly the lake surface state in spring.

Small lakes and those of complicated geometry cause problems for the relatively coarse HIRLAM grid of 7 - kilometre resolution. The problems are related to the observation usage, forecast and validation, especially when interpolation and selection of point values are applied. The observations and model represent different spatial scales. For example, the comparison of the freezing and melting dates was based on diagnostics of single-gridpoint values that were compared to observations representing entire lakes as seen from the observation sites. Also the results of LID diagnostics were sensitive to the criteria for definition of the ice existence in HIRLAM/FLake. All this adds unavoidable inaccuracy into the model-observation intercomparison but does not change the main conclusions of the present study.

SYKE LSWT observations used for the real-time analysis are regular and reliable but did not always cover the days immediately after melting or close to freezing, partly because the quality control of HIRLAM LSWT analysis utilizes the SYKE statistical lake water temperature model results in a too strict way. Although the 27 observations are located all over the country, they cover a very small part of the lakes and their availability is limited to Finland. SYKE observations of the ice and snow depth as well as the freezing and melting dates provide valuable data for the validation purposes.

A need for minor technical corrections in the FMI HIRLAM/FLake system was revealed. The snow accumulation bug was corrected in October 2018, based on our findings. Further developments and modifications are not foreseen because the HIRLAM NWP systems, applied in the European weather services, are being replaced by kilometre-scale HARMONIE-AROME-based operational systems (Bengtsson et al., 2017), where the prognostic FLake parametrizations are also available. HARMONIE/FLake uses the newest version of the global lake database (GLDB v.3) and contains updated snow and ice properties that were suggested by (Yang et al., 2013). The objective analysis of lake surface state is yet to be implemented into HARMONIE-AROME, taking into account the HIRLAM experience summarized in this study and earlier by Kheyrollah Pour et al. (2017).

Data availability. All observational data was obtained from SYKE open data archive SYKE (2018). The data files picked from HIRLAM archive are attached as supplementary files: data from the objective analysis feedback files (observed, analysed, forecast LSWT interpolated to the 27 active station locations) and from the gridded output of the HIRLAM analysis (analysed LSWT, forecast ice and snow thickness from the nearest gridpoint of all locations used in the present study).

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Table A1. Prognostic and diagnostic lake variables within HIRLAM

variable	unit	type
temperature of snow on lake ice	K	prog by FLake
temperature of lake ice	K	prog by FLake
mean water temperature	K	prog by FLake
mixed layer temperature	K	prog by FLake
bottom temperature	K	prog by FLake
temperature of upper layer sediments	K	prog by FLake
mixed layer depth	m	prog by FLake
thickness of upper layer sediments	m	prog by FLake
thermocline shape factor	-	prog by FLake
lake ice thickness	m	prog by FLake
snow depth on lake ice	m	prog by FLake
LSWT	K	diag by FLake
		= mixed layer temperature if no ice
lake surface temperature	K	diag by FLake
		uppermost temperature: LSWT or ice or snow
LSWT	K	anal by HIRLAM
		flag value 272 K when there is ice
lake surface roughness	m	diag by HIRLAM
screen level temperature over lake	m	diag by HIRLAM
screen level abs.humidity over lake	m	diag by HIRLAM
anemometer level u-component over lake	m	diag by HIRLAM
anemometer level v-component over lake	m	diag by HIRLAM
latent heat flux over lake	Wm^{-2}	diag by HIRLAM
sensible heat flux over lake	Wm^{-2}	diag by HIRLAM
scalar momentum flux over lake	Wm^{-2}	diag by HIRLAM
SW net radiation over lake	Wm^{-2}	diag by HIRLAM
LW net radiation over lake	Wm^{-2}	diag by HIRLAM
depth of lake	m	pres in HIRLAM grid
fraction of lake	[0-1]	pres in HIRLAM grid
fraction of lake ice	[0-1]	diag in HIRLAM grid

Denotation: prog = prognostic, diag = diagnostic, pres = prescribed, anal = result of OI

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Table A2. Lakes with SYKE observations used in this study. Part 1

NAME	LON	LAT	MEAND	HIRD	HIRFR	HIRID
Pielinen	29.607	63.271	11.1	10.0	0.916	4001
Kallavesi	27.783	62.762	12.1	10.0	0.814	4002
Haukivesi	28.389	62.108	9.0	10.0	0.725	4003
Saimaa	28.116	61.338	17.0	10.0	0.950	4004
Pääjärvi1	24.789	62.864	3.9	3.0	0.430	4005
Nilakka	26.527	63.115	4.9	10.0	0.866	4006
Konnevesi	26.605	62.633	15.9	10.0	0.937	4007
Jääsjärvi	26.135	61.631	4.6	10.0	0.750	4008
Päijänne	25.482	61.614	14.1	10.0	0.983	4009
Ala-Rieveli	26.172	61.303	11.3	10.0	0.549	4010
Kyyvesi	27.080	61.999	4.4	10.0	0.810	4011
Tuusulanjärvi	25.054	60.441	3.2	3.0	0.174	4012
Pyhäjärvi	22.291	61.001	5.5	5.0	0.922	4013
Längelmävesi	24.370	61.535	6.8	10.0	0.875	4014
Pääjärvi2	25.132	61.064	14.8	14.0	0.350	4015
Vaskivesi	23.764	62.142	7.0	10.0	0.349	4016
Kuivajärvi	23.860	60.786	2.2	10.0	0.419	4017
Näsijärvi	23.750	61.632	14.1	10.0	0.850	4018
Lappajärvi	23.671	63.148	12.0	10.0	1.000	4019
Pesiöjärvi	28.650	64.945	7.3	7.0	0.290	4020
Rehja-Nuasjärvi	28.016	64.184	8.5	10.0	0.534	4021
Oulujärvi	26.965	64.451	7.6	10.0	1.000	4022
Ounasjärvi	23.602	68.377	6.6	10.0	0.166	4023
Unari	25.711	67.172	6.1	10.0	0.491	4024
Kilpisjärvi	20.816	69.007	22.5	22.0	0.399	4025
Kevojärvi	27.011	69.754	7.0	10.0	0.016	4026
Inarijärvi	27.924	69.082	14.4	14.0	0.979	4027

Denotation: LON and LAT are the longitude E and latitude N in degrees, MEAND is the mean depth of the lake from GLDB v.3 preliminary material, HIRD and HIRFR are the mean lake depth and fraction of lakes [0. . . 1] interpolated to the selected HIRLAM gridpoint, HIRID is the lake index used by HIRLAM and in this study. Above the middle line are the 27 lakes with both LWT and LID observations, below the 18 lakes where only LID was available.

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Table A2. Lakes with SYKE observations used in this study. Part 2

NAME	LON	LAT	MEAND	HIRD	HIRFR	HIRID
Simpelejärvi	29.482	61.601	9.3	10.0	0.548	40241
Pokkaanlahti	27.264	61.501	7.00	10.0	0.299	40261
Muurasjärvi	25.353	63.478	9.10	10.0	0.060	40263
Kalmarinjärvi	25.001	62.786	5.80	5.0	0.330	40271
Summasjärvi	25.344	62.677	6.70	10.0	0.555	40272
Iisvesi	27.021	62.679	17.2	18.0	0.456	40277
Hankavesi	26.826	62.614	7.00	18.0	0.100	40278
Petajävesi	25.173	62.255	2.70	3.0	0.245	40282
Kukkia	24.618	61.329	6.00	10.0	0.299	40308
Ähtärinjärvi	24.045	62.755	7.00	10.0	0.266	40313
Kuortaneenjärvi	23.407	62.863	7.00	10.0	0.277	40328
Lestijärvi	24.716	63.584	7.00	10.0	0.513	40330
Pyhäjärvi	25.995	63.682	7.00	10.0	0.266	40331
Lentua	29.690	64.204	7.60	7.0	0.600	40335
Lammasjärvi	29.551	64.131	4.40	3.0	0.200	40336
Naamankajärvi	28.246	65.104	7.00	7.0	0.299	40342
Korvuanjärvi	28.663	65.348	18.50	10.0	0.342	40343
Oijärvi	25.930	65.621	7.00	10.0	0.333	40345

Denotation: LON and LAT are the longitude E and latitude N in degrees, MEAND is the mean depth of the lake from GLDB v.3 preliminary material, HIRD and HIRFR are the mean lake depth and fraction of lakes [0. . . 1] interpolated to the selected HIRLAM gridpoint, HIRID is the lake index used by HIRLAM and in this study. Above the middle line are the 27 lakes with both LWT and LID observations, below the 18 lakes where only LID was available.

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Author contributions. Laura Rontu computed the LSWT statistics based on HIRLAM feedback files. Kalle Eerola performed the freezing and melting date, snow and ice thickness comparisons based on data picked from HIRLAM grib files. Matti Horttanainen prepared observation data obtained via SYKE open data interface and lake depths from GLDB v.3. Laura Rontu wrote the manuscript text based on input from all authors.

Competing interests. No competing interests are present.

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