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Parameterisation of Lakes in Numerical Weather Prediction and Climate Models

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Abstract

The application of the lake model FLake (http://lakemodel.net) to represent the effect of lakes in numerical weather prediction (NWP) and climate models is discussed. As a lake parameterization scheme, FLake is implemented into the limited-area NWP model COSMO and into the regional climate models CLM and RCA. It is on the way into the NWP model HIRLAM. First results from a numerical experiment with the coupled COSMO-FLake NWP system, including the complete COSMO model data assimilation cycle operational at the German Weather Service, are presented. Some challenging issues are discussed.

Introduction

Lakes significantly affect the structure of the atmospheric boundary layer and therefore the surface fluxes of heat, water vapour and momentum. In most numerical weather prediction (NWP) and climate models, the effect of lakes is either entirely ignored or is parameterised very crudely. In coarse resolution models, a large number of small-to-medium size lakes are indistinguishable sub-grid scale features. These lakes become resolved scale features as the horizontal resolution is increased. Then, a physically sound lake model is required to predict the lake surface temperature and its time-rate-of-change. Apart from being physically sound, a lake model must meet stringent requirements of computational economy.

The application of the lake model FLake [1] to parameterise the effect of lakes in NWP and climate models is discussed. Much attention is focused on the implementation of FLake into the limited-area NWP model COSMO (formerly LM, [3]). FLake is a bulk model capable of predicting the vertical temperature structure and mixing conditions in lakes of various depth on the time scales from a few hours to many years. The model is based on a two-layer parametric representation of the evolving temperature profile and on the integral energy budget for the layers in question. The same concept is used to describe the temperature structure of the ice cover. Using the integral approach, the problem of solving partial differential equations (in depth and time) for the temperature and turbulence quantities is reduced to solving a number of ordinary differential equations for the time-dependent parameters that specify the evolving temperature profile. This approach, that relies on "verifiable empiricism" but still incorporates much of the essential physics, offers a very good compromise between physical realism and computational economy. FLake has been favourably tested against observational data through single-column numerical experiments. A detailed description of the model is given in [1]. Further information about FLake can be found at http://lakemodel.net or http://nwpi.krc.karelia.ru/flake.

Implementation of FLake into the limited-area NWP model COSMO

As a lake parameterization scheme, FLake is implemented into the limited-area NWP model COSMO. In order to be incorporated into COSMO, or into any other NWP or climate model, FLake requires a number of two-dimensional external-parameter fields. These are, first of all, the fields of lake fraction (area fraction of a given numerical-model grid box covered by the lake water) and of lake depth. A lake-fraction field is developed on the basis of the Global Land Cover Characterization data set with 30 arc sec resolution. Since no tile approach is used in COSMO, i.e. each COSMO grid box is characterised by a single land-cover type, only the grid boxes with the lake fraction in excess of 0.5 are treated as lakes. A data set containing mean depths of a number of European lakes and of a few lakes from other regions of the world is developed at the German Weather Service (DWD). The lake-depth external-parameter field is generated using that data set and the lake-fraction field.

Each lake is characterised by its mean depth. Results from single-column numerical experiments suggest that the use of a mean depth to the bottom is the best choice as far as the prediction of the water surface temperature and of the ice characteristics is concerned. These quantities are of prime importance in NWP and climate modelling. This choice is in fact consistent with the one-dimensional character of the lake model. For lack of better data, it is the only choice for most small-to-medium size lakes. Deep lakes are currently treated with the "false bottom". That is, an artificial lake bottom is set at a depth of 50 m. The use of such expedient is justified since, strictly speaking, FLake is not suitable for deep lakes (because of the assumption that the thermocline extends down to the lake bottom). However, as the deep abyssal zones typically experience no appreciable temperature changes, using the false bottom one can expect FLake to produce satisfactory results.

Numerical experiment with the coupled COSMO-FLake NWP system

A numerical experiment, hereafter referred to as COFLEX, with the COSMO-FLake coupled system including the entire COSMO data assimilation cycle operational at DWD, is performed. The main goal with COFLEX is to see if the COSMO-FLake shows a reasonable performance with respect to the lake surface temperature (equal to the water temperature in the mixed layer or to the ice surface temperature if a lake is frozen), and to the lake freeze-up and melting. In order to save computational resources, the so-called LM1 numerical domain is used in COFLEX. That domain was operational at DWD until October 2005, prior to the operational implementation of the COSMO-EU whose numerical domain is much larger than the LM1 domain but the horizontal grid size is the same (ca. 7 km). A reader is referred to the COSMO web page, http://www.cosmo-model.org, for details of the COSMO model and its operational implementation at different NWP centres. Using the lake-fraction and the lake-depth external-parameter fields for the LM1 domain and a one-band exponential approximation of the decay law for the flux of solar radiation with the default value of $\gamma = 3\ \mathrm{m}^{-1}$, the COSMO-FLake is run over a year, from 1 January to 31 December 2006. The surface fluxes of momentum and of sensible and latent heat are computed with the operational COSMO surface-layer scheme [2]. COFLEX is started on 1 January 2006, using the lake surface temperature from the COSMO sea surface temperature (SST) analysis as the initial condition and assuming no ice. The bottom temperature is set to the temperature of maximum density, and the shape factor with respect to the temperature profile in the thermocline is set to its minimum value (see [1] for details of the temperature profile parameterisation used in FLake). The initial mixed-layer thickness is set to 10 m or to the lake depth, whichever is smaller. For lake grid boxes with the lake depth smaller than 10 m, mixing down to the lake bottom is assumed. Once a cold start is made, the COSMO-FLake runs freely, i.e. without any correction of the lake surface temperature and of the other FLake variables.

Preliminary analysis of the COFLEX results indicates a satisfactory performance of FLake in COSMO. Many lakes present in the LM1 domain are frozen and the ice melts in a reasonable time span. A detailed quantitative assessment of the simulated ice characteristics is difficult to make. A qualitative assessment is, however, possible on the basis of the available empirical information (see e.g. the World Lakes Database, http://www.ilec.or.jp/database, where data on the lake water temperature and on the duration of ice cover are given for a number of lakes). Examination of results from COFLEX suggests that the lakes that freeze up in reality do also freeze up in COSMO-FLake.

For three lakes, Lake Hjälmaren, Sweden, Lake Balaton, Hungary, and Lough Neagh, UK, the lake surface temperature predicted by COSMO-FLake (00 UTC values from the assimilation cycle), is compared with the lake surface temperature from the operational COSMO SST analysis (performed once a day at 00 UTC). Notice that in COFLEX the temperature from the routine COSMO SST analysis has no direct effect on the lake surface temperature that is now predicted by FLake. A substantial difference between the two temperatures is clearly seen in Figs. 1–3.

For Lake Hjälmaren and Lake Balaton, the difference is particularly striking during winter when it often exceeds ten degrees. Such a large temperature difference is brought about by the procedure used to determine the water surface temperature in the framework of the routine COSMO SST analysis. In case the observational data for a water-type COSMO grid box are not available, the surface temperature for that grid box is determined by means of interpolation between the nearest water-type boxes for which the surface temperature is known (from satellite data or from in situ measurements). Such procedure is not too harmful for sea points. Large horizontal gradients of the sea surface temperature are comparatively rare, so that the interpolated SST is expected to be a reasonably good approximation of the actual SST. In contrast to open sea, lakes are enclosed water bodies of a comparatively small horizontal extent. The lake surface temperature is a result of a complex interplay of physical processes in the lake in question. It has little or nothing to do with the surface temperature obtained by means of interpolation

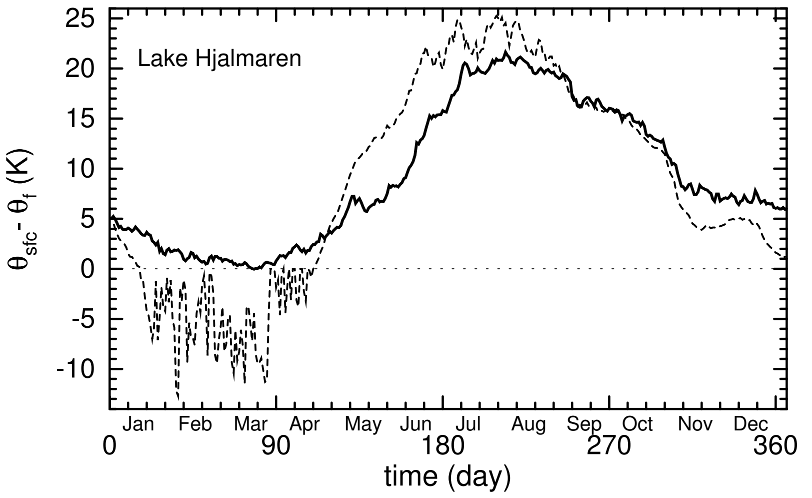

Figure 1: Lake surface temperature θ_{sfc} ($\theta_f = 273.15$ K is the fresh-water freezing point) in Lake Hjälmaren over the period from 1 January to 31 December 2006. Dashed curve shows the lake surface temperature predicted by FLake, and solid curve shows the temperature from the routine COSMO SST analysis. Curves are the results of averaging over the adjacent COSMO grid boxes that constitute the lake in question.

between the alien water bodies. Notice also that the COSMO SST analysis does not explicitly account for the presence of ice.

For many lakes the interpolation is likely to occur between the sea points. During winter, the above procedure yields a too high lake surface temperature that stays well above the freezing point even though the lake considered is frozen in reality. As clearly indicated by empirical data, both Lake Hjälmaren and Lake Balaton are frozen up over a long period of time (typically, over four and a half and over one and a half months, respectively), whereas the surface temperature from the routine COSMO SST analysis indicates that both lakes remain ice free. This proves to be the case for many other lakes in the model domain (not shown). The situation is not encountered if FLake is used to predict the lake characteristics. Since FLake allows the lake surface temperature to adequately respond to atmospheric forcing, lakes freeze up and the lake surface temperature, which is then equal to the ice surface temperature, drops in response to surface cooling.

An overestimation of the water (ice) surface temperature in the routine COSMO SST analysis may have far-reaching implications

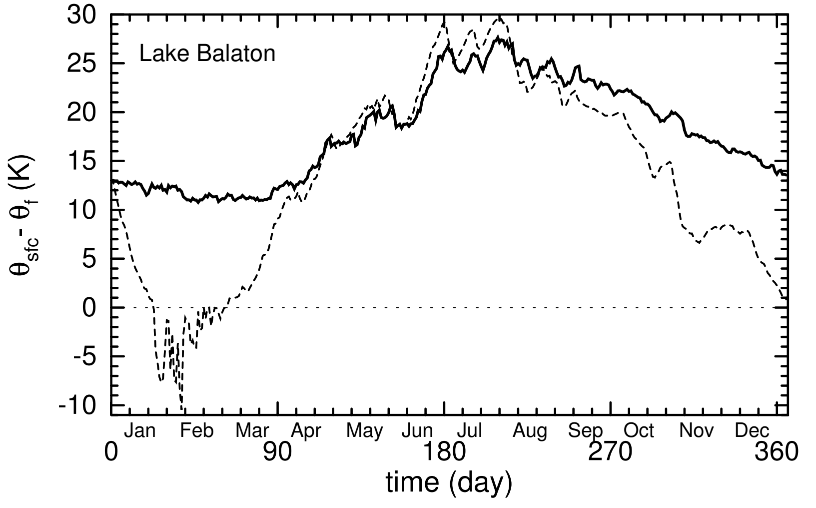

Figure 2: The same as in Fig. 1 but for Lake Balaton.

for the forecast quality. It leads to drastically increased surface fluxes of sensible and latent heat, particularly during winter. This in turn may result in the development of artificial cyclones over water bodies, leading to a considerable degradation of the COSMO performance. The situation will not occur if FLake is used to predict the lake surface temperature.

For Lough Neagh, the difference between the two temperatures proves to peak during summer. Again, the temperature from the COSMO SST analysis may result from the interpolation between the sea points. As the sea thermal inertia is high, the temperature from the SST analysis is likely to underestimate the actual lake surface temperature during summer. A considerably higher temperature is predicted by FLake as it allows the lakes to adequately respond to the summer heating.

Conclusions and outlook

The lake model FLake is incorporated as a lake parameterization scheme into the limited-area NWP model COSMO. Results from a numerical experiment with the coupled COSMO-FLake system, including the complete COSMO data assimilation cycle, indicate a good performance with respect to the lake surface temperature and to the freeze-up of lakes and the ice break-up. In particular, the use of FLake allows to do away with a significant overestimation of the lake surface temperature during winter that is typical of the routine

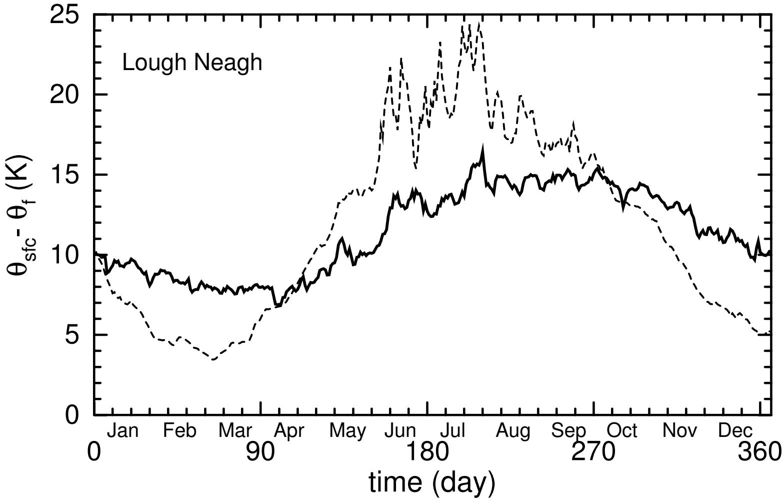

Figure 3: The same as in Figs. 1 and 2 but for Lough Neagh.

COSMO SST analysis. Work is underway at DWD to comprehensively assess the effect of FLake on the quality of the COSMO forecasts. Subject to successful verification of results from numerical experiments, FLake is expected to come into operational use.

Further development of FLake in terms of the model physics should address an extension of the temperature profile parameterisation to include the abyssal layer below the lake seasonal thermocline. What is even more important from an application standpoint is the extension of the lake-depth data base in order to eventually cover the entire globe. This should allow the application of FLake over an arbitrary numerical domain. Apart from the lake depth, it is advantageous to collect data on other lake characteristics, first of all, on the optical properties of the lake water.

One more challenging issue is the lake temperature spin-up following a cold start of FLake in an NWP or climate model. Lakes have a long memory. That is, erroneous initial conditions result in an erroneous heat content of the lake in question, leading to erroneous predictions of the lake surface temperature until the memory is faded. For stratified lakes this may last several months. Observations usually offer data on the water-surface temperature only, whereas the information about the entire temperature profile that is required for the FLake initialisation is lacking. A way out is to generate the so-called perpetual year solutions for a number of typical lakes present in a given numerical domain, using climatological mean meteorological data to specify atmospheric forcing. A perpetual year solution is obtained by repeating a year-long simulation, using one and the same annual cycle of forcing, until a periodic "perpetual year" state is achieved. That is, running the model for one more year will not change the annual cycle of the lake-model variables. Although a perpetual year solution represents a climatological mean state of the lake in question, not the state of that lake at a particular date, it is a reasonable zero-order approximation that should considerably reduce the lake-temperature spin-up time. As the perpetual year solutions are generated through the stand-alone single-column FLake runs, the procedure is computationally inexpensive.

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