A Two-Layer Lake Model for Use in Numerical Weather Prediction

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Lakes significantly affect the structure of the atmospheric surface layer and therefore the surface fluxes of heat, water vapour and momentum. In most numerical weather prediction (NWP) systems the effect of lakes is either entirely ignored or is parameterized very crudely. A physically sound model is required to predict the lake surface temperature and the effect of lakes on the structure and transport properties of the atmospheric surface layer. Apart from being physically sound, a lake model must meet stringent requirements of computational economy. The problem is twofold. For one thing, the interaction of the atmosphere with the underlying surface is strongly dependent on the surface temperature and its time-rate-of-change. It is common for NWP systems to assume that the water surface temperature can be kept constant over the forecast period. The assumption is to some extent justified for seas and deep lakes. It is doubtful for small-to-medium size relatively shallow lakes, where the short-term variations of the surface temperature (with a period of several hours to one day) reach several degrees. A large number of such lakes will become resolved scale features as the horizontal resolution is increased. Another important aspect of the problem is that lakes strongly modify the structure and the transport properties of the atmospheric surface layer. A major outstanding question is the parameterization of the roughness of the water surface with respect to wind and to scalar quantities, such as potential temperature and specific humidity.

A lake model intended for use in NWP systems (also in climate modelling and other numerical prediction systems for environmental applications) is developed (Mironov, 2003). The model is capable of predicting the surface temperature in lakes of various depth on time scales from a few hours to a year. It is based (i) on a two-layer parametric representation (assumed shape) of the temperature profile, where the structure of the stratified layer between the upper mixed layer and the basin bottom, the lake thermocline, is described using the concept of self-similarity of the evolving temperature profile (Kitaigorodskii and Miropolsky, 1970), and (ii) on the (integral) heat and kinetic energy budgets for the layers in question. The same concept is used to describe the interaction of the water column with bottom sediments and the evolution of the ice and snow cover. In this way, the problem of solving partial differential equations (in z, t) for the temperature and turbulence quantities is reduced to solving ordinary differential equations for the time-dependent parameters that specify the temperature profile. This approach, that is based on what could be called "verifiable empiricism" but still incorporates much of the essential physics, offers a very good compromise between physical realism and computational economy.

The proposed lake model incorporates a flexible parameterization of the temperature profile in the thermocline, an advanced formulation to compute the mixed-layer depth, including the equation of convective entrainment and a relaxation-type equation for the depth of a wind-mixed layer, both mixing regimes are treated with due regard for the volumetric character of the short-wave radiation heating, a module to describe the vertical temperature structure of the thermally active layer of bottom sediments and the interaction of the water column with bottom sediments, and an advanced snow-ice module. Empirical constants and parameters of the proposed model are estimated, using independent empirical and numerical data. They should not be re-evaluated when the model is applied to a particular lake (there are, of course, lake-specific external parameters, such as depth to the bottom and optical properties of water, but these are not part of the model physics). In this way, the model does not require re-tuning, a procedure that may improve an agreement with a limited amount of data but should generally be avoided as it greatly reduces the predictive capacity of a physical model (Randall and Wielicki, 1997).

In order to compute fluxes of momentum and of sensible and latent heat at the lake surface, a parameterization scheme is developed that accounts for specific features of the surface air layer over

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lakes. The scheme incorporates a fetch-dependent formulation for the aerodynamic roughness of the water surface, advanced formulations for the roughness lengths for potential temperature and specific humidity in terms of the roughness Reynolds number, and free-convection heat and mass transfer laws to compute fluxes of scalars in conditions of vanishing mean wind.

The new lake model and the new surface-layer parameterization scheme are tested against data through single-column numerical experiments. Figure 1 shows the water surface temperature θ_s as computed by the proposed lake model againsts data from measurements in Kossenblatter See, a shallow lake (mean depth is 2 m, maximum depth is 6 m, depth to the bottom at the point of measurements is 1.2 m) located in Land Brandenburg, Germany. The lake model is forced by the fluxes of momentum and heat at the air-water interface. The fluxes of momentum and of sensible and latent heat depend on the water surface temperature and are, therefore, part of the solution. They are computed with the proposed surface-layer scheme, using mean values of meteorological quantities measured in the vicinity of the air-water interface. The downward fluxes of short-wave radiation and of long-wave radiation are not part of the solution. These fluxes are taken from measurements (details of measurements are given in Beyrich (2000). In Fig. 2, fluxes of sensible Q_{se} and latent Q_{la} heat computed with the surface-layer scheme are compared with data from flux measurements in the atmospheric surface layer over the lake. As seen from Figs. 1 and 2, the model predictions show a good agreement with observations.

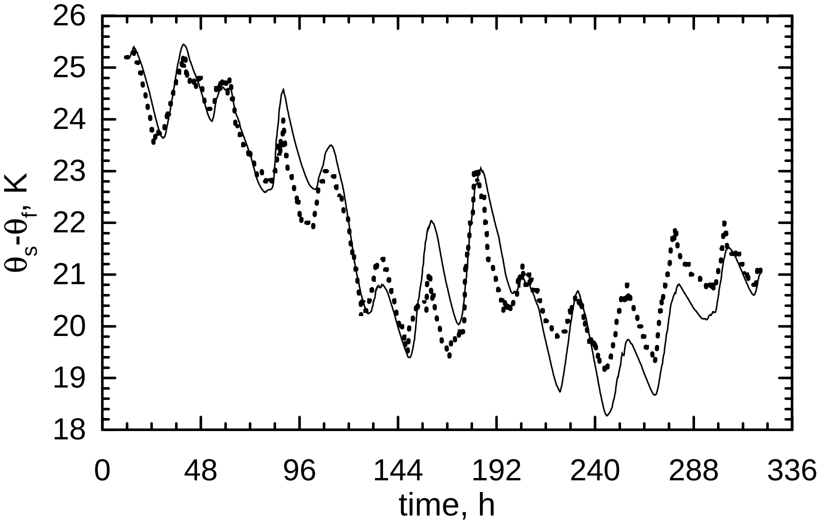

Figure 1: The water surface temperature ($\theta_f = 273.15$ K is the fresh-water freezing point) computed with the new lake model, solid curve, versus data from measurements in Kossenblatter See over the period from 8 to 21 June 1998, dotted curve.

One more example of the lake model performance is given in Fig. 3, showing a simulated perpetual-year temperature cycle in Lake Swente, a medium-depth lake (mean depth is 7.8 m, maximum depth is 35 m) located in Latvia. The model is driven by climatological-mean values of the surface-layer meteorological quantities. The year-long integration is repeated until a perpetual-year periodic solution is obtained. This solution is representative of the like climatologically-mean state. As different from Kossenblatter See, the downward fluxes of short-wave radiation and of long-wave radiation for Lake Swente are not known from measurements. These fluxes are computed using empirical recipes, possibly introducing large uncertainties into the solution. The model results are compared with four-year mean values of the water temperature measurements taken at a number of levels from the lake surface down to the bottom at 17.5 m. In spite of considerable uncertainties of the input data, results from the simulation show a satisfactory agreement with empirical data.

Work is underway at the German Weather Service to further test the new lake model against data from measurements in different lakes and to integrate it into the full three-dimensional NWP system environment.

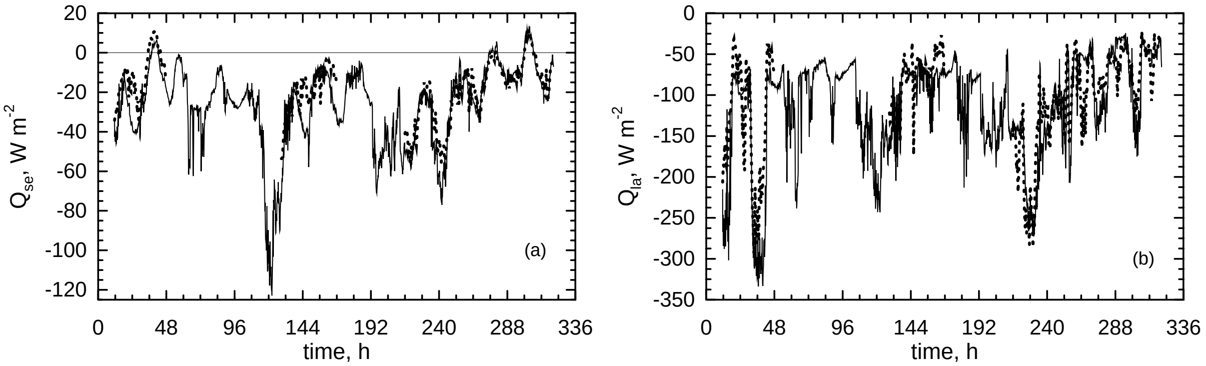

Figure 2: Computed with the surface-layer scheme, solid curves, and measured, dotted curves, fluxes of sensible heat (a) and of latent heat (b) over Kossenblatter See during the period from 8 to 21 June 1998.

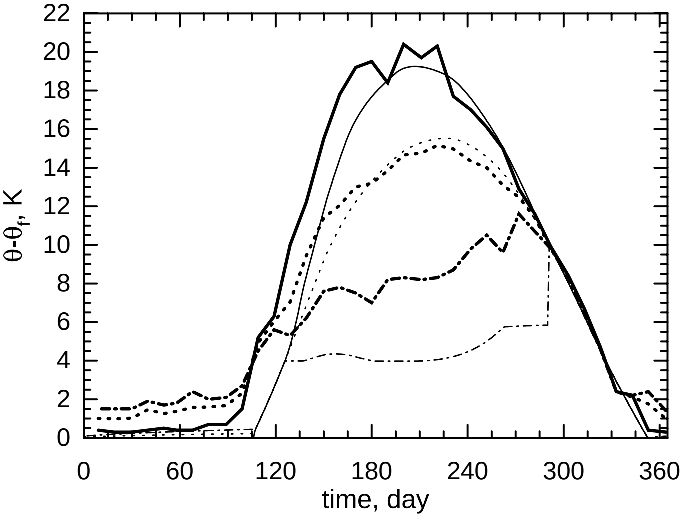

Figure 3: Perpetual-year temperature cycle in Lake Swente simulated with the lake model. Solid curves show the water surface temperature, dotted curves show the mean temperature of the water column, and dot-dashed curves show the bottom temperature. Thin curves are computed with the lake model, and heavy curves show data from measurements averaged over the period from 1961 to 1964.

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