Supplementary information

S.1. Description of lake models

S.1.1. FLake. FLake is a bulk fresh-water lake model (Mironov 2008, Mironov et al. 2010, Kirillin et al. 2011, see http://lakemodel.net for further information). It is based on a two-layer parametric representation of the temperature profile, and on the integral heat and kinetic energy budgets for the layers in question. 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 (assumed shape) of the temperature-depth curve. The same concept is used to describe the temperature structure of the ice and snow cover and of the thermally active upper layer of bottom sediments. FLake incorporates 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 solar radiation heating), a module to describe the interaction of the water column with bottom sediments, and a snow-ice module. Empirical constants and parameters of FLake are estimated, using independent observational 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. With the integral approach used in FLake, the problem of solving partial differential equations (in depth and time) for the temperature and turbulence quantities is reduced to solving ordinary differential equations for the time-dependent quantities that specify the evolving temperature profile. These are mixed-layer temperature and mixed-layer depth, temperature at the water-bottom sediment interface, mean temperature of the water column, shape factor with respect to the temperature profile in the thermocline, temperature at the ice upper surface, and ice thickness. If the bottom sediment module is switched on, two additional prognostic variables are computed, viz., the depth of the upper layer of bottom sediments penetrated by the thermal wave and the temperature at that depth (see Mironov

2008, for details).

In order to compute fluxes of momentum and of sensible and latent heat at the lake surface, a parameterization scheme is used that accounts for specific features of the surface air layer over lakes (see http://lakemodel.net for details). 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.

S.1.2. Hostetler models. Two independent realizations of the Hostetler lake model participate in the study. The first one is based on the code of S.W. Hostetler (Hostetler and Bartlein, 1990), and another one (CLM4-LISSS, standing for Community Land Model 4 – Lake, Ice, Snow and Sediment Simulator) (Subin et al., 2011) is developed within the scope of the Community Earth System Model 1 (CESM1), whose land surface component is the Community Land Model 4 (CLM4) (Lawrence et al., 2011; Oleson et al., 2010). The Subin et al. (2011) version is modified from the standard CLM4 version (Oleson et al., 2010) by additional physics and several corrections to errors in the surface flux and eddy diffusion calculations.

The Hostetler-based lake models solve the vertical thermal diffusion equation equation by dividing the lake water body into several discrete layers for each of the following: snow ; lake body water and ice; and in the CLM version, underlying sediments and bedrock. The basic mixing mechanisms in the water body include wind-driven eddy turbulence that adds to the thermal conductivity based on the parameterization of Henderson-Sellers, buoyant convection (Hostetler and Bartlein 1990) and molecular diffusion. Heat, water, momentum, and radiation fluxes are calculated between the surface and the atmosphere. The residual energy flux at the surface is then used as a top boundary condition for the thermal diffusion between lake layers. Shortwave radiation partially penetrates the lake body.

In the Hostetler's version there is no active sediments layer: the model assumes zero heat flux at the bottom of the lake. The latent and sensible heat fluxes for off-line simulations are calculated using a standard surface drag coefficient formulation based on surface-layer similarity theory. The drag coefficient calculations follow the BATS (Biosphere-Atmosphere Transfer Scheme) formulation (Dickinson et al., 1993).

In CLM4-LISSS, additional background diffusivity to represent unresolved 3D mixing processes is introduced (Fang and Stefan 1996). Active sediment and bedrock layers are taken into account. The albedo depends on the direct and diffuse radiation fractions and the zenith angle, and the surface solar absorption fraction is equal to the near infrared fraction in the solar radiation energy spectrum. The surface roughnesses are calculated as a function of forcing wind and friction velocity. The submodels for friction velocity, aerodynamic resistances, snow, and sediment are similar to those in CLM4 (Oleson et al. 2010).

S.1.3. LAKE model. LAKE model is a numerical one-dimensional model using finite-difference scheme to explicitly calculate vertical temperature profile in a water body, underlying ground, snow and ice, if the latter two exist. It uses 1D k-ε closure to calculate eddy diffusivity and heat conductance as $\lambda_T = Ck^2/\varepsilon$ (*k* being turbulent kinetic energy and ε – its dissipation rate). Here C is either constant (implying "standard k-ε model") or the so-called stability function dependent on momentum shear and Brunt-Väisälä frequency according to Galperin (Galperin et al., 1988) or Canuto (Canuto et al., 2001) formulations. In this paper Canuto stability functions for eddy diffusivity and heat conductance as being applicable for the more general hydrodynamic flows are used. To provide momentum shear for k-ε closure 1D non-stationary equations for two horizontal velocities are solved, including Coriolis force and eddy diffusion. Exponential decay of solar radiation with depth using the constant attenuation coefficient is assumed in temperature equation. The model takes into account lake morphometry by horizontal cross-section area entering diffusion terms of temperature, momentum and k-ε equations (in this study morphometry effect, however, was omitted since there were no digital bathymetry data available). The ground beneath a lake is represented by a multilayer model including temperature conductance, liquid moisture transport (both diffusive and gravitational), ice content and water phase transitions thus making the model applicable for permafrost regions. Water leakage from lake body to unsaturated ground below is explicitly calculated which enters the water balance of a lake. However, in actual calculations the ground soon becomes saturated as lateral soil moisture movement is not included. Heat and momentum fluxes in the surface air layer are parameterized by Monin-Oboukhov similarity theory, employing interpolation formulas following Paulson (1970), Beljaars and Holtslag (1991), Large et al. (1994). The model was applied for a number of shallow lakes, e.g. Vendyurskoe (Russia, Karalee, data available at http://www.flake.igb-berlin.de/data.shtml), Tiksi (data collected during GAME-Siberia project) and Shuchi (data collected by K.Walter and colleagues, University of Alaska) (Stepanenko et al., 2011).

S.1.4. SimStrat. SimStrat is a numerical lake model that simulates the evolution of vertical profiles of water temperature in a water body (Goudsmit et al., 2002). This model is a modified version of the buoyancy-extended k-ε model described in Rodi (1993) and Burchard et al. (1998), adapted to specific conditions of an enclosed basin. It computes heat transfer through the profile by estimating the vertical turbulent diffusivity from the turbulent kinetic energy (*TKE*) k and dissipation ε of *TKE*, using finite difference scheme. The turbulent viscosity and diffusivity are computed as $\sim C * k^2/\varepsilon$, with C, stability functions, as given by Galperin et al. (1988). The source of *TKE* is generated by shear stress at the surface due to wind forcing and buoyancy production in case of unstable stratification. The momentum shear with depth is computed by means of both horizontal velocity components, U and V, the Coriolis forces and the molecular and turbulent viscosity. The *TKE* induced by seiche motion is included in this version of the model and become the main source of energy below the epilimnion. This scheme is not activated in this study since it requires estimates of bottom basin area. To reduce heat penetration and turbulence in the water column during lake freezing periods, the model assumes that no-flux enters the lake surface when the surface water temperature drops below the freezing point and the heat fluxes are negative. The horizontal cross sections, varying with the morphometry of the basin, are used to compute the diffusion terms of temperature, momentum and k-ε equations, though in this study morphometry effects were omitted due to the absence of digital data on horizontal cross-section area change with depth. The heat flux from the bottom area is given by a constant geothermal value that needs to be specified for each lake. SimStrat accurately predicted temperature profiles in a number of peri-alpine lakes, ranging from medium depth [Lake Alpnach (34 m), Lake Baldegg (64 m), Goudsmit et al., 2002] to very deep lakes [Lake Zurich (136 m), Lake Geneva (309 m), Peeters et al., 2002; Perroud et al., 2009]. However, it has not been tested in very shallow lakes.

S.1.5. LAKEoneD

LAKEoneD is a vertical one-dimensional k-ε turbulence model (Jöhnk, 2011; Jöhnk et al., 2008; Jöhnk and Umlauf, 2001) driven by hourly (or shorter) meteorological data to simulate temperature structure and turbulent diffusivities ("mixing") of a lake with prescribed hypsometric data in depth and time. To account for ice cover a very simple ice model, depending only on meteorological information but not on lake temperature, is implemented.

Simulations of temperature and turbulent diffusivity are based on a one-dimensional k-ε turbulence model (Svensson, 1978). LAKEoneD considers small lakes, where the Coriolis effect is insignificant. The turbulence model is based on a system of five partial differential equations, describing the dynamics of momentum, heat, turbulent kinetic energy, and turbulent dissipation rate, respectively. The horizontal bathymetry of the lake is implicitly taken into account via its area-depth relation, A(z). In this study A(z) was set to constant, as in the other k- ε models.

Horizontal momentum is driven by wind stress at the surface, and vertically distributed by diffusion. An additional boundary stress term is formulated as a sliding law with constant drag coefficient chosen according to the lake's settings.

The vertical profile of space and time dependent turbulent diffusivity is calculated from the relation $D_z = c_\mu \frac{k^2}{\varepsilon}$ where turbulent kinetic energy, *k*, and turbulent dissipation rate, ε, are described by two partial differential equations. This second order turbulence closure uses standard coefficients (Rodi, 1993; Mohammadi and Pironneau, 1994).

Heat is produced internally by the absorption of shortwave radiation and vertically distributed by diffusion. The horizontal bathymetry of the lake is implicitly incorporated via the area-depth relation in such a way that heat is conserved and radiation reaching the lake bottom is absorbed by the sediment. Two boundary conditions for the heat equation describe the continuity of heat flux at the surface, driven by meteorological conditions (sensible and latent heat fluxes, and longwave radiation), and at the bottom with a constant heat flux value (zero in this study).

2.6. MINLAKE96. A verified deterministic, process-oriented, dynamic and one-dimensional (vertical) year-round lake water quality model, MINLAKE96 (Fang and Stefan, 1996) was used for daily water temperature simulations in Kossenblatter See. The model can be run in a continuous mode over many simulation years for both the open water seasons and the ice cover periods. The model was developed for simulations in different types of lakes in a cold region (Minnesota) and over the contiguous USA. The model has linked calibration parameters and initial conditions to lake geometry and/or geographic location. For example, the hypolimnetic eddy diffusion coefficient (K_z in cm^2 sec^{-1}) is a function of lake surface area (A_s in km^2) and stability frequency [$N^2 = -(\partial\rho/\partial z)(g/\rho)$ in sec^{-2}, where ρ is density of water, z is water depth, and g is acceleration of gravity] (Hondzo and Stefan 1993):

$$K_z = 8.17*10^{-4}(A_s)^{0.56}(N^2)^{-0.43} \qquad \text{(S.1.1)}$$

The maximum vertical hypolimnetic eddy diffusivity, K_{zmax}, occurs when temperature profiles are under weakly stratified conditions that were defined as $N^2 = 7.0*10^{-5}$ sec^{-2}. The MINLAKE96 model includes a bulk mixed-layer model in response to wind and convection, and a wind sheltering coefficient adjusts the wind speed for fetch over the lake in the direction of wind and is used to compute turbulent kinetic energy from a wind speed that is typically measured at an off-site weather station at 10-m elevation. The wind sheltering coefficient, $W_{str} = 1.0 - \exp(-0.3 * A_s)$, is set as a function of lake surface area based on model calibrations using various Minnesota lakes (Hondzo and Stefan, 1993). The one-dimensional lake model conjunctively uses a vertical eddy diffusion expression, mechanical energy balance (wind turbulent kinetic energy and potential energy due to density difference), and a convection algorithm for natural cooling to distribute heat energy and predicts surface mixed layer thickness and water temperature profiles.

The model uses a stacked layer system; the layers include lake sediments and water during the summer open-water season, and self-forming additional ice cover and snow cover layers for the winter period. The water column is divided into well-mixed horizontal layers having a thickness from 0.02 m (near the water surface) to 1 m when the layer depth is greater than 1 m. The one-dimensional, unsteady heat transfer equation is solved to obtain daily water temperature profiles in a lake. Solar radiation absorption in the water column is the main contributor to the heat source term during the open-water season. Heat exchange between lake sediment and water is calculated separately for all horizontal layers and then included as a source or sink term in the lake water temperature model. To determine heat flux between water and sediment, the one-dimensional (vertical), dynamic heat conduction equation is solved to simulate sediment temperature distribution up to 10 meters below the lake bottom. It was found that heat can transfer into or out of the lake sediment during both the open water season and the winter ice cover period.

S.1.7. Completely-mixed model. Since Kossenblatter See is a very shallow and polymictic lake one may expect that very simple modeling approaches such as «zero-dimenional» model assuming water temperature being constant with depth could provide satisfactory agreement with observation data. In order to check if neglection of stratification effects is applicable to Kossenblatter See case we supplemented the set of lake models with «completely-mixed model». The basic equation of this model can be obtained by integrating one-dimensional heat conductance equation and then assuming temperature to be constant with depth

$$\rho c_p \frac{dT_{cm}}{dt} = \frac{Q_{z=0} + F_{h,z=0} - Q_{z=h} - F_{h,z=h}}{h}, \qquad \text{(S.1.2)}$$

where ρ - mean water density, c_p - water specific heat at constant pressure, T_{cm} - the temperature of completely-mixed model varying only with time, Q - solar radiation flux, F_h - heat flux, both downward, z - vertical downward coordinate with $z=0$ associated with the water surface, h - lake depth. Bottom radiation and bottom heat fluxes are neglected in the model.

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