Lake model FLake, coupling with atmospheric model: first steps

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1 Introduction

It is well known that lakes affect surface fluxes of heat, water vapor and momentum and thus the structure of atmospheric surface layer significantly. This effects should be described correctly in fine scale atmospheric models, climate and probably NWP ones. This issue is of special importance for the "lake" regions: Sweden, Finland and North Russia. The main model variable responsible for the calculation of fluxes is surface temperature. So, the lake model, which is going to be coupled with atmospheric one, should (i) simulate surface temperature good enough for different time periods, including ice period, and for different time scales and (ii) to be computationally cheep as a parameterization. The main aim of the study is to couple climate model RCA with lake model FLake developed by Dmitrii Mironov, *Dmitrii Mironov,2003,* which posses these features. The results of the first steps of this study only are presented here. First of all, the additional independent testing of the model FLake was carried out, as it is always desirable. The second issue is connected with tiling approach used by RCA and many other atmospheric models. This approach can be interpreted in the following way: within one grid box spatial sports of one surface type are combined into one spot. If we are going to use surface type "lake", we can combine into one lake the lakes with similar parameters only. Thus we should use not one surface type "lake", but several surface types, for example, "lake A", "lake B", "lake C", that means different lake types with different parameters (many different small lakes with large total area is not the same as one big lake). So, the model sensitivity tests should be done to determine this lake types. In this study the express sensitivity testing has been carried out: direct tests with no special mathematical tools used. Such tests appeared to be enough to make the rough classification of lakes, which could be used for the purposes of atmospheric modeling. Coupling of RCA with FLake is in progress now.

2 Lake model FLake

The consept and features of the lake model FLake itself should be described here. The model is capable to calculate surface temperature on time scales from a few hours to some years. The model is based on two-layer approximation of temperature profile: mixed layer, with its temperature and depth depending on time, and stratified layer between mixed layer and bottom - thermocline, with bottom temperature and form depending on time. This thermal structure (shown in Fig. 1) is described by means of self-similarity concept.The temperature profile is parameterized by universal function of dimensionless depth ξ and represented as

$$\theta = \begin{cases} \theta_s, & 0 \leq z \leq h \\ \theta_s - (\theta_s - \theta_b)\Phi_\theta(\xi), & h \leq z \leq D \end{cases},$$

$$\xi = \frac{(z-h)}{(D-h)}, \; \Phi_\theta \equiv \frac{(\theta_s - \theta)}{\theta_s - \theta_b}.$$

Here θ is water temperature, θ_s and θ_b are surface and bottom temperatures, z is depth, h is the mixed layer depth, D is the depth of a lake, $\Phi_\theta(\xi)$ is the shape function. The shape function describes the form of thermocline and in the model it is approximated by polynom of ξ. In the model form function is not used directly: the shape factor, its integral is used instead, which is then considered to be dependent of time:

$$C_\theta = \int_0^1 \Phi_\theta(\xi) d\xi.$$

Snow and ice temperature profiles are approximated linearly in the model; bottom sediments block is based on the self-similarity concept as well, coordinates of thermal extremum in bottom sediments (maximum in winter and minimum in summer) are predicted, temperature on the outer edge of the bottom sediments layer is put to constant. Thermal structure of a lake covered by ice and snow and with bottom sediments layer is shown in Fig. 2. Probably it is too rough to approximate temperature profile in snow linearly and it is better to develop more this block of the model. The basic prognostic equations of the model are the following. For mean temperature:

$$D\frac{d\widetilde{\theta}}{dt} = \frac{1}{\rho_w c_w}[Q_s + I_s - Q_b - I(D)].$$

For bottom temperature:

$$\frac{1}{2}(D-h)^2\frac{d\theta_s}{dt} - \frac{d}{dt}[C_{\theta\theta}(D-h)^2(\theta_s - \theta_b)] =$$

$$= \frac{1}{\rho_w c_w}[C_Q(D-h)(Q_h - Q_b) + (D-h)I(h) - \int_h^D I(z)dz].$$

For mixed layer temperature:

$$h\frac{d\theta_s}{dt} = \frac{1}{\rho_w c_w}[Q_s + I_s - Q_h - I(h)].$$

These equations have been obtained from the heat transfer equation by means of its integration and double integration for different layers. Here $\widetilde{\theta}$ is mean temperature, ρ_w and c_w are water density and specific heat capacity, Q_s, Q_h and Q_b are the vertical turbulent heat fluxes on the surface and on the levels h and bottom, I is the heat flux due to radiation on the appropriate level and C_Q is the shape factor for the shape function for fluxes, analogously to the ones for temperature:

$$C_Q = \int_0^1 \Phi_Q(\xi)d\xi,$$

$$C_{\theta\theta} = \int_0^1 d\xi \int_0^\xi \Phi_\theta(\grave{\xi})d\grave{\xi}.$$

Besides, the model includes the following blocks:

- prediction of mixed layer depth in convective and non-convective cases;
- ice and snow block;
- bottom sediments block;
- short-wave radiation transfer block; and
- additional block used when the model is driven by measurements: calculation of fluxes, it could be used or not used while coupling with atmospheric model (appropriate atmospheric block could be used instead).

Individual lake parameters required for the model are the following:

- depth;
- fetch (is used in the block of calculation of fluxes to estimate roughness length);
- optical parameters - extinction coefficients (used in short-wave radiation transfer block);

- besides there is an option: to use or not to use bottom sediments block, this can be considered as an additional logical parameter.

FLake requires the following driving data from the atmospheric model or from measurements:

- short-wave radiation flux;
- net radiation;
- 2m temperature and wet bulb temperature and 10m wind when driven by measurements or sensible and latent heat fluxes and momentum fluxes when driven by atmospheric model;
- precipitation;

\+ surface temperature to calculate outcoming long-wave radiation flux - when driven by measurements.

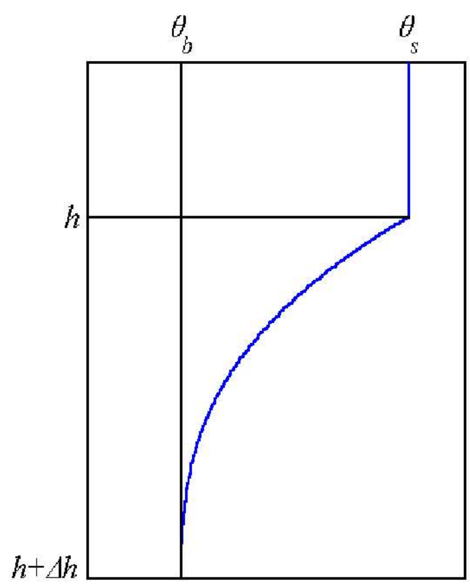

Figure 1: Thermal structure of a lake
h is mixed layer depth, D is a lake depth,
θ_b,θ_s are bottom and mixed layer temperatures

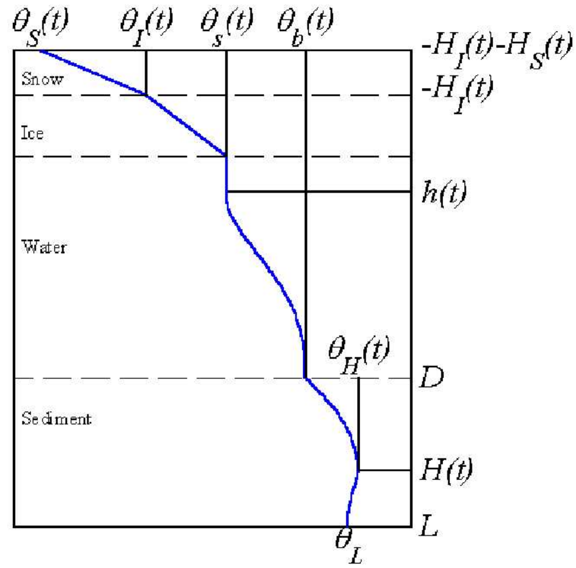

Figure 2: Thermal structure of a lake covered by ice and snow and with bottom sediments layer
θ_S,θ_I *are temperatures of snow and ice,*
H_S, H_I *are depths of snow and ice,*
θ_H,H *are temperature and depth of thermal bottom sediments extremum*

3 Experiments with FLake

3.1 Additional testing of the model

Additional testing of the model has been done for lake Erken in the Southern-Eastern part of Sweden. It's depth is 21 m, fetch is approximately 5000 m, we used data for the period from May, 1989 to October, 1990. Fig. 3 shows modeled and measured temperatures. There is the period when something happens with measured water temperature, while modeled temperature looks believable. The agreement of modeled and measured data is rather good, mean square error is 1.9^oC, but biases are mainly positive. Modeled and measured 14 m temperatures are displayed on Fig. 4. Perhaps there is again something wrong with measurements: they are very close to surface temperature and not characteristic for lakes of this region. Modeled temperature here probably looks believable or little bit too low, but it is difficult to estimate it because of ill measurements. This is in agreement with Fig. 5, where mixed layer depth is displayed - in summer it seems to be little bit too small. That means there can be some errors in estimating of shape factor. In our dataset there were no data of solid precipitation, it was impossible to test snow block of the model, plus this leads to additional errors in ice thickness. Ice thickness, shown on Fig. 6, seems to be very low here (up to 5 sm), but there are no measurements to compare; besides that winter was very mild. From ice measurements only the dates of appearing and disappearing of ice cover are available, and that dates are in not bad agreement with modeled ones.

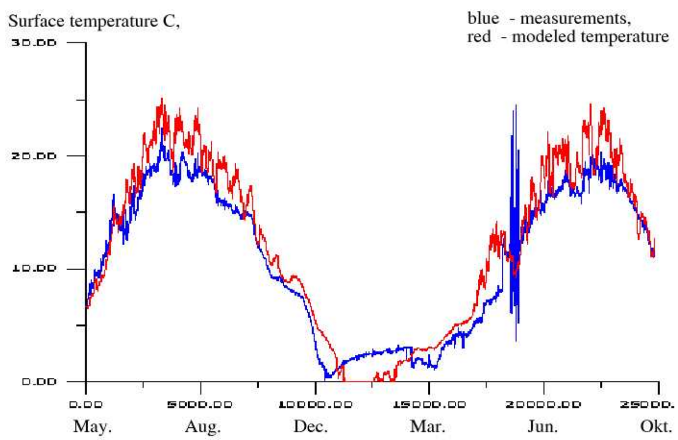

Figure 3: *Modeled and measured temperatures*

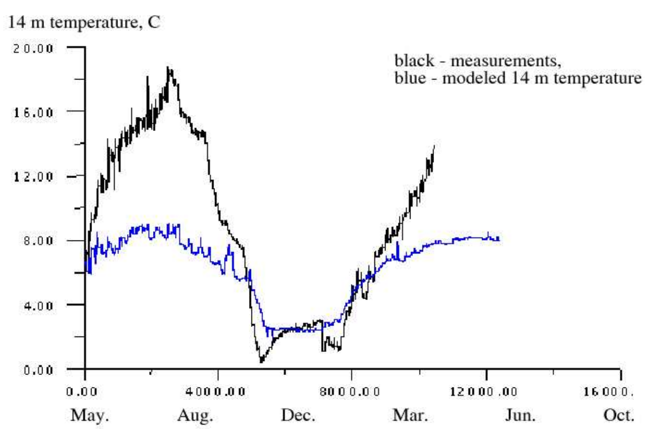

Figure 4: *Modeled and measured* 14*m temperatures*

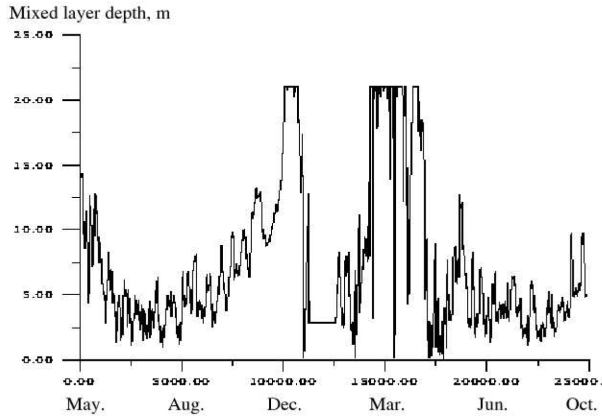

Figure 5: *Modeled mixed layer depth*

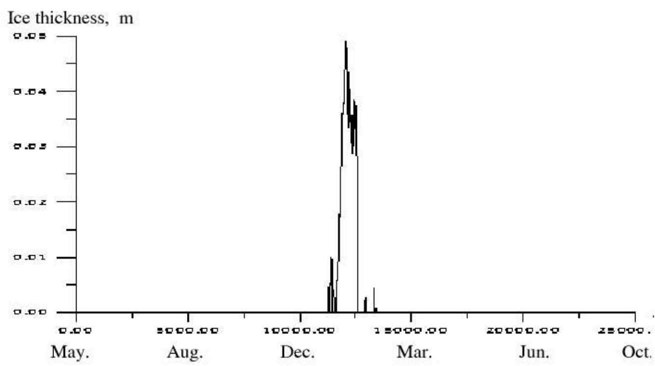

Figure 6: *Modeled ice thickness*

3.2 Sensitivity tests

Sensitivity tests of modeled surface temperature to individual lake parameters have been carried out. No special mathematical tools were used, so those were express-tests. To estimate sensitivity of the model different lakes with their individual parameters were put into the point where lake Erken is situated, and atmospheric variables over lake Erken were used as driving data (here can be some inaccuracy in estimates, of course). Then the modeling results were compared.

3.2.1 Sensitivity to initial values

First of all the sensitivity of the model to initial value which is often unknown from measurements - mixed layer depth - has been studied. The experiments were started from spring, when most lakes are mixed down to the bottom. The results of experiments are displayed on Fig. 7. Modeled temperatures does not much differ from each other, so the sensitivity is not high. But this conclusion can be made for climate modeling only, besides, simulation should be started from spring or probably from autumn, when most lakes are mixed down to the bottom, not from summer.

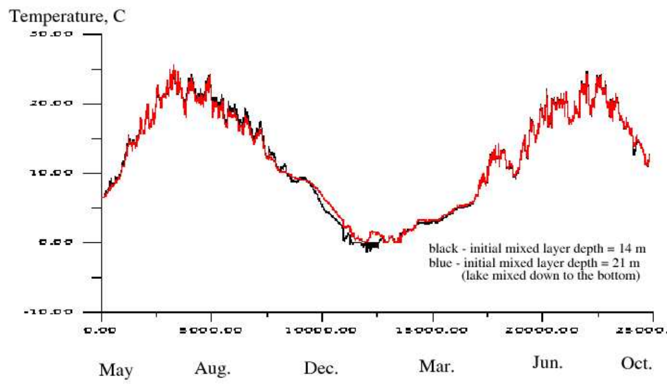

Figure 7: *Sensitivity to initial values*

3.2.2 Sensitivity to fetch parameter

Fetch parameter is used in surface layer turbulent fluxes block to calculate roughness length. If we use surface layer turbulent fluxes block from atmospheric model, which differs from one used in FLake, we may have no fetch parameter. Curves with different fetch parameters ($1km, 5km, 10km$), displayed on Fig. 8, practically coincides. These are results for a lake of $21m$ depth. There is no high sensitivity to this parameter - only in winter, it is connected with singularity ice - no ice.

3.2.3 Sensitivity to optical parameters

3 types of lakes with different depth were considered: shallow lakes with depth of $5m$, lakes of $10m$ depth, and deep lakes of $20m$ depth. For each lake type experiments with different extinction coefficients were fulfilled: from $5m^{-1}$ - normal water to $1m^{-1}$ - pure water, and additionally for $0.1m^{-1}$ -

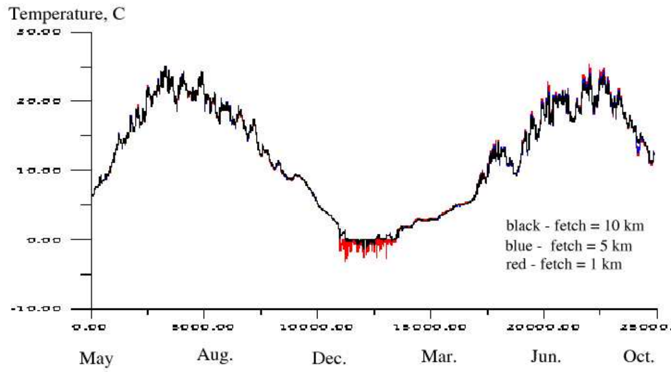

Figure 8: *Sensitivity to fetch parameter*

very transparent water. It was expected that shallow lakes are more sensitive to optical parameters, but according to the numerical experiments the sensitivity to optical parameters is rather low and approximately equal for all lake types: curves for $20m$ lake are displayed on Fig. 9, for other lake types results are the same.

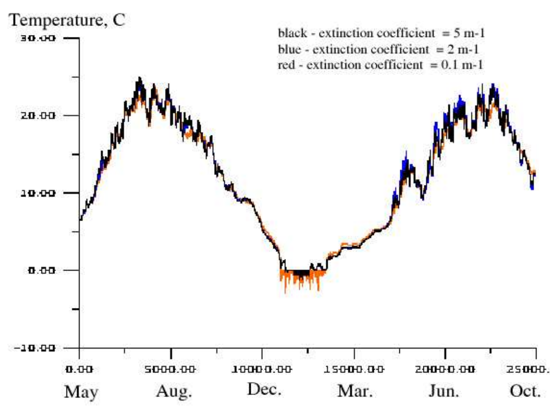

Figure 9: *Sensitivity to optical parameters*

3.2.4 Sensitivity to bottom sediments block on/off

As in the experiments with optical parameters, 3 types of lakes with different depth were considered. Modeling results for $10m$ depth lake are displayed on Fig. 10. Bottom sediments block influence surface temperature only after a year of modeling, beginning from the next summer. Probably this influence could be higher when many-year modeling. Besides, as for the sensitivity to optical parameters, it was expected that sensitivity is higher for shallow lakes, but again numerical experiments do not confirm this.

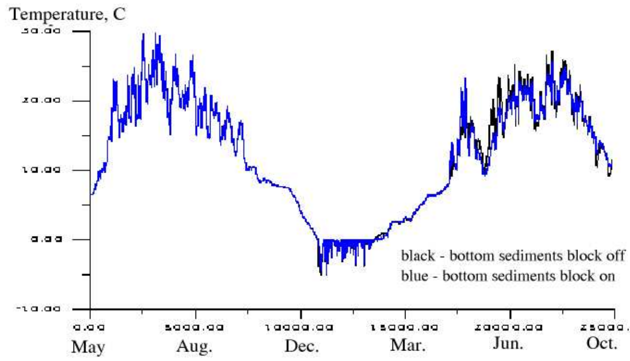

Figure 10: *Sensitivity to bottom sediments block on/off*

3.2.5 Sensitivity to the depth of a lake

Models surface temperature appeared to be most sensitive to the depth of a lake, as it was expected from the very beginning. Experiments for 18 "lakes" of different depth were carried out, only the main are displayed here on Fig. 11. It can be seen from the curves, the higher the depth, the more the amplitude of the annual cycle of the surface temperature (plus there is time shift), the more shallow the lake - the longer is the ice period. Besides, this dependency of annual cycle amplitude of lake depth is non-linear, annual cycle amplitude changes with depth quickly for shallow lakes and slowly for deep lakes:
- for 16 - 40 m deep lakes: annual cycle amplitude changes for 1 K when depth changes for 3 m;
- for 7 - 16 m deep lakes: annual cycle amplitude changes for 1 K when depth changes for 2 m;
- for 1 - 7 m deep lakes: annual cycle amplitude changes for 1 K when depth changes for 1 m.

4 Conclusion

The main conclusions are the following:
There is good agreement for of the modeled surface temperature and dates of appearance - disappearance of ice with measurements for lake Erken.

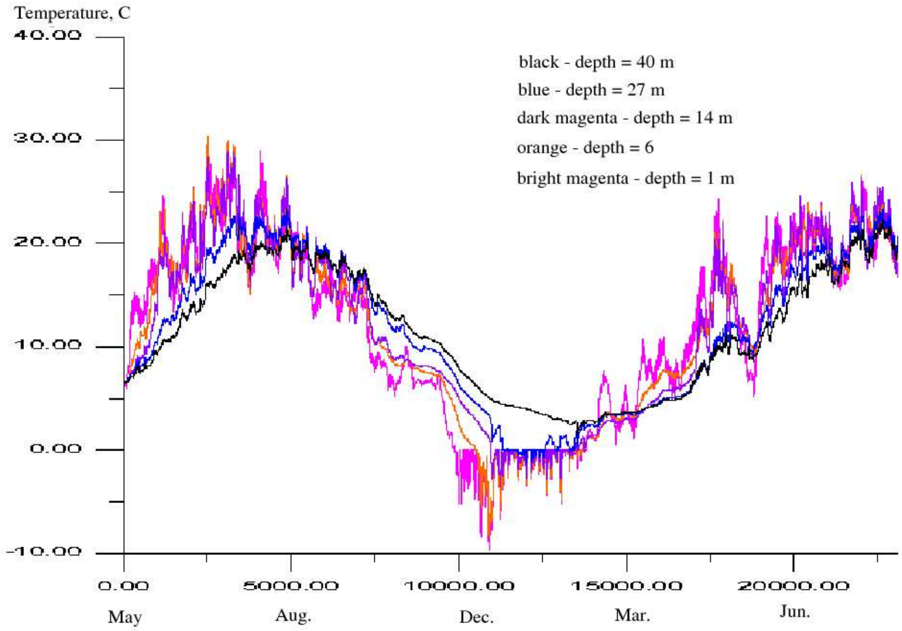

Figure 11: *Sensitivity to the depth of a lake*

In summer mixed layer depth is probably underestimated, that could be resulted from the errors in shape-factor.
The sensitivity of the model to fetch and optical parameters is not high.
The sensitivity to bottom sediments block on/off appears only for probably long periods of modeling.
Depth of a lake is the main parameter to which model is sensitive.
Modeled amplitude of surface temperature annual cycle depends of lake depth nonlinearly.

5 Acknowledgments

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