“Parameterization of Lakes in Numerical Weather Prediction and Climate Modelling”
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The use of one-dimensional and bulk lake models in studies of lake – atmosphere interaction

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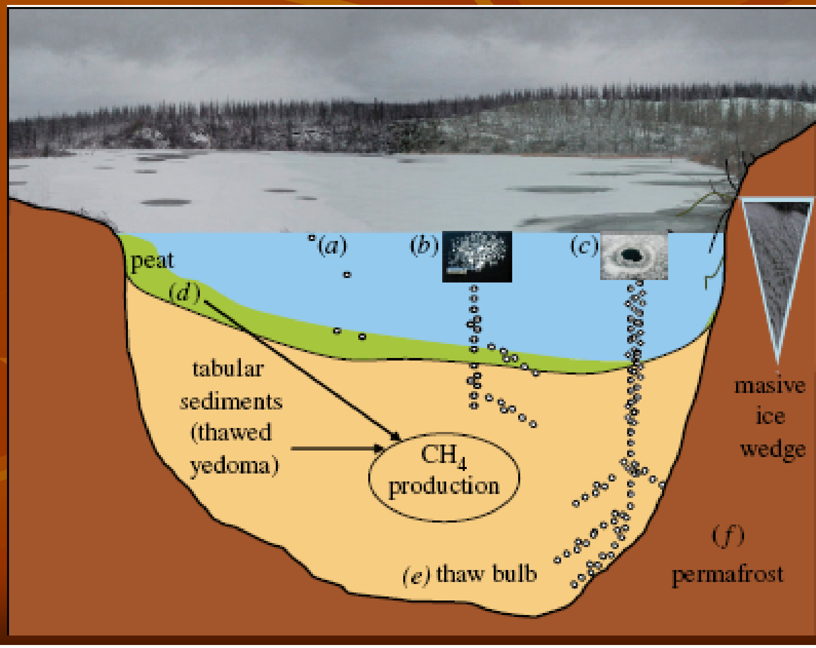
The effects of water reservoirs on atmosphere

Weather

- breezes and associated tracer transport
- severe snowfalls over large lakes in winter

Climate

- the change of regional hydrological system due to global warming
- emission of methane by Siberian lakes



Numerical water reservoir models in coupled lake – atmosphere studies

1) **3-dimensional** (~oceanic)

2) **2-dimensional**

- **vertically averaged** (Shlychkov)
- **averaged in one lateral direction** (**CE-QUAL** x.x model)

3) **1-dimensional**

- **single-column** (**GOTM** model (Burchard et al.), **Lake** model, V. M. Stepanenko & V. N. Lykosov, 2005);
- **laterally averaged models** (O. F. Vasiliev et al., 2007) – applicable in many applications

4) **½ - dimensional** models – the vertical profiles of temperature, salinity etc. are parameterized (**Flake** model, D. V. Mironov et al., 2006) – high computational efficiency → application in operational forecast

5) **0 – dimensional** (mixed models)

Lake model (SRCC MSU)

✓the equation for the horizontally averaged temperature:

$$\frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left(k_T \frac{\partial T}{\partial z}\right) - \frac{1}{c_p \rho}\frac{\partial S}{\partial z} - \frac{1}{A}\int_{\Gamma_A} (\vec{u}\cdot\vec{n}) T dl$$

Coordinate transformation:

$$z \to \xi = \frac{z}{H(t)},$$

$$\xi \in (0,1)$$

the equations for horizontal velocities:

$$\frac{\partial u}{\partial t} = \frac{\partial}{\partial z} k_M \frac{\partial u}{\partial z} + fv - g\cdot \mathrm{tg}\alpha_x - C_{veg} u \sqrt{u^2+v^2},$$

$$\frac{\partial v}{\partial t} = \frac{\partial}{\partial z} k_M \frac{\partial v}{\partial z} - fu - g\cdot \mathrm{tg}\alpha_y - C_{veg} v \sqrt{u^2+v^2}$$

✓the salinity/hydrosol transport

$$\frac{\partial S}{\partial t} = \frac{\partial}{\partial z}\left(k_S \frac{\partial S}{\partial z}\right) - w_g \frac{\partial S}{\partial z} - \frac{1}{A}\int_{\Gamma_A} (\vec{u}\cdot\vec{n}) S dl$$

- **turbulent dissipation**
- **Coriolis force**
- **horizontal pressure gradient force**
- **the friction of flow on vegetation**
- **the advection by tributaries**

- **gravitational sedimantation**

Snow and soil models

- **Ice model**

$$\frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left(k_{Ti}\frac{\partial T}{\partial z}\right) - \frac{1}{c_{pi}\rho_i}\frac{\partial S_i}{\partial z}$$

- **Snow model** (Volodina et al., 2000)

$$c_{sn}\rho_{sn}\frac{\partial T}{\partial t} = \boxed{\frac{\partial}{\partial z}\lambda_{sn}\frac{\partial T}{\partial z}} + \boxed{\rho_{sn}LF_{fr}},$$

$$\frac{\partial W}{\partial t} = -\boxed{\frac{\partial \gamma}{\partial z}} - \boxed{F_{fr}}.$$

- **Soil model** (Volodin and Lykosov, 1998)

$$\rho_s c_s \frac{\partial T}{\partial t} = \boxed{\frac{\partial}{\partial z}\left(\lambda_s \frac{\partial T}{\partial z}\right)} + \boxed{\rho_s LF_{fr}},$$

$$\frac{\partial W}{\partial t} = \boxed{\frac{\partial}{\partial z}\lambda_W \frac{\partial W}{\partial z}} - \boxed{\frac{\partial \gamma}{\partial z}} - \boxed{F_{fr}},$$

$$\frac{\partial I}{\partial t} = \boxed{F_{fr}}.$$

- diffusion terms
- freezing terms
- gravitational infiltration

Turbulent mixing parameterization

$$\overline{w'\phi'} = -k_\phi \frac{\partial \overline{\phi}}{\partial z}$$

- counter-gradient effects missing

Kolmogorov formula (1942)

$$\boxed{k_M = C_e \frac{E^2}{\varepsilon}}, \qquad C_e = C_e(M,N)$$

$$k_T = k_S = C_{eT} \frac{E^2}{\varepsilon}, \quad C_{eT} = C_{eT}(M,N)$$

M – friction frequency,
N – Brunt-Vaisala frequency

stability functions

k-ε parameterization

$$\frac{\partial E}{\partial t} = \frac{\partial}{\partial z}\left(\nu + \frac{k_M}{\sigma_E}\right)\frac{\partial E}{\partial z} + P + B - \varepsilon$$

$$\frac{\partial \varepsilon}{\partial t} = \frac{\partial}{\partial z}\left(\nu + \frac{k_M}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial z} + \frac{\varepsilon}{E}\left(c_{1\varepsilon}P + c_{3\varepsilon}B - c_{2\varepsilon}\varepsilon\right)$$

Boundary conditions

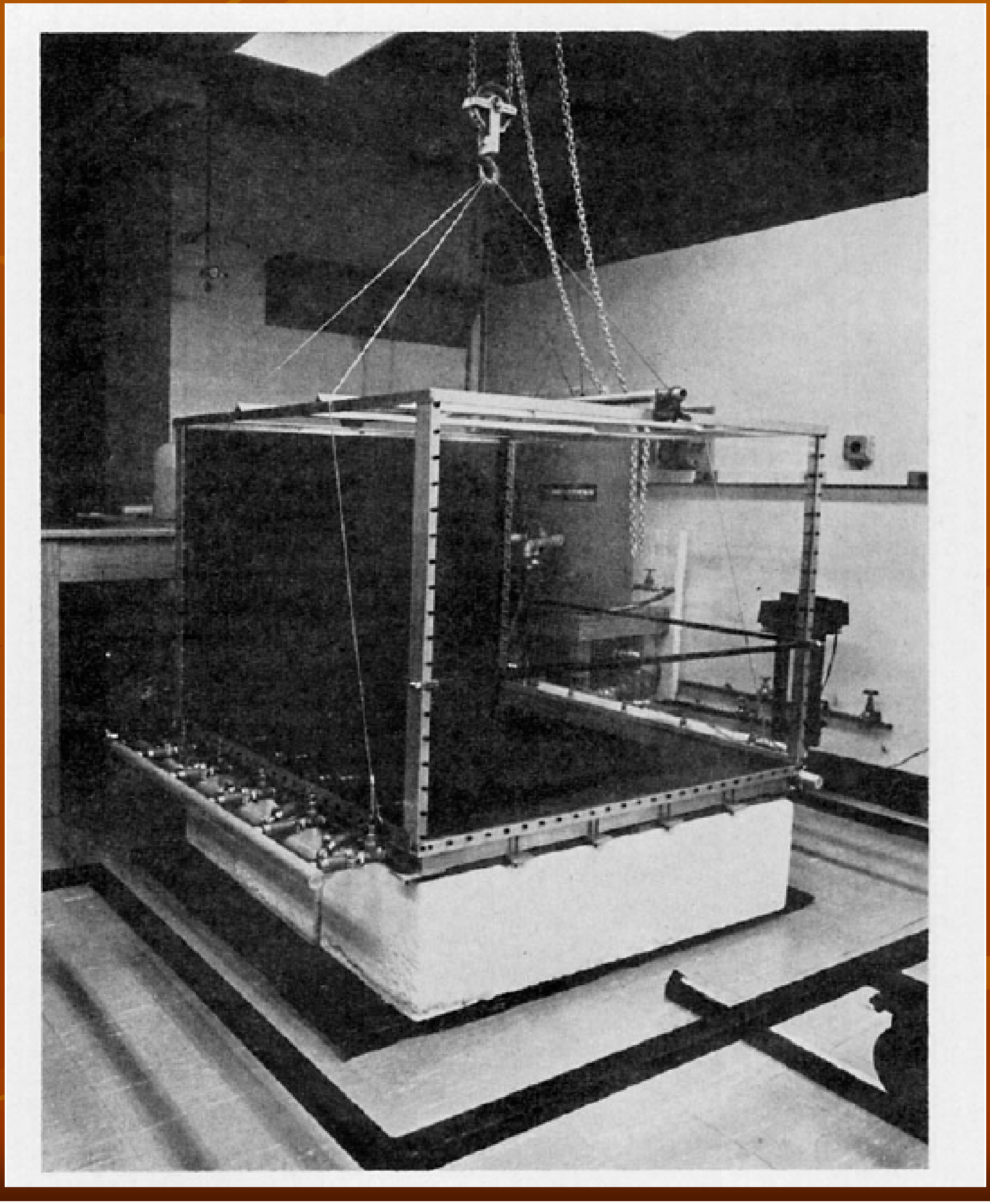
$$-\frac{k_M}{\sigma_E}\frac{\partial E}{\partial z} = c_{we}\left(\frac{\tau_s}{\rho_w}\right)^{3/2}, \quad c_{we} \approx 100$$

$$-\frac{k_M}{\sigma_\varepsilon}\frac{\partial \varepsilon}{\partial z} = \left(C_e^0\right)^{3/4}\frac{k_M}{\sigma_\varepsilon}\frac{E^{3/2}}{\kappa\left(z' + z_0\right)^2}$$

Willis-Deardorff experiment (1974)

Setup for numerical experiment:

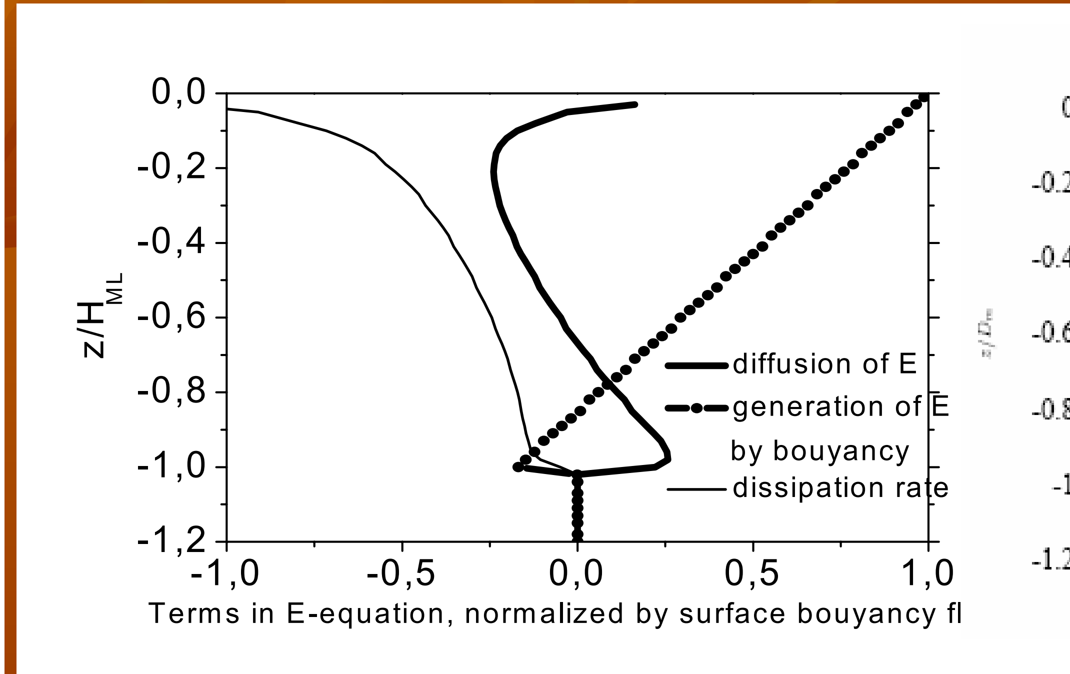
- horizontally homogeneous water layer of infinite depth;
- linear initial temperature profile with the lapse rate -1ºC/10 m;
- the constant sensible heat flux at the surface 100 W/m^2 (cooling);
- the horizontal velocities 0 m/s;
- Coriolis force is neglected

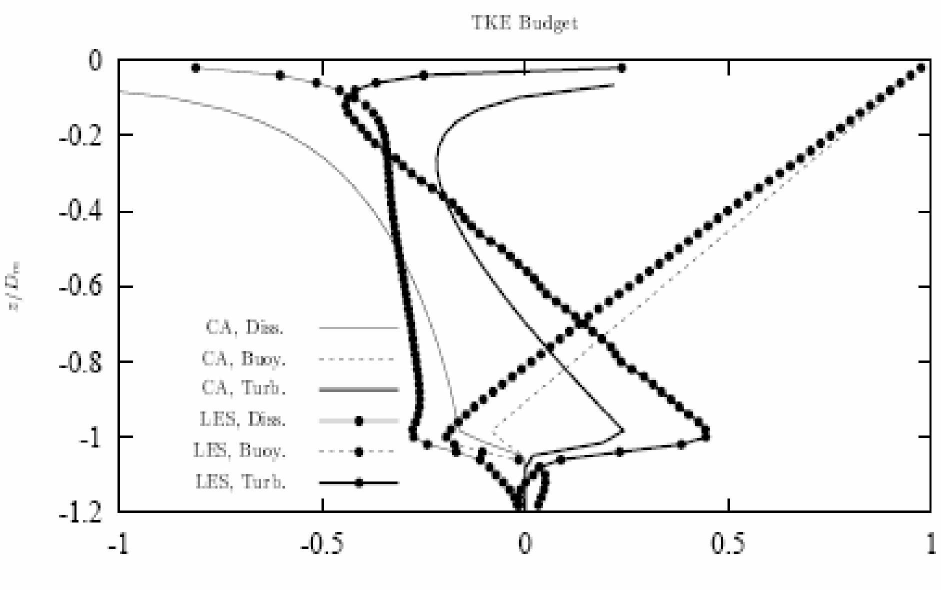


The terms of turbulent energy budget

Lake model

1) "E-ε" model by Canuto et al., 2001
2) LES results (Mironov et al., 2000)





The k-closure

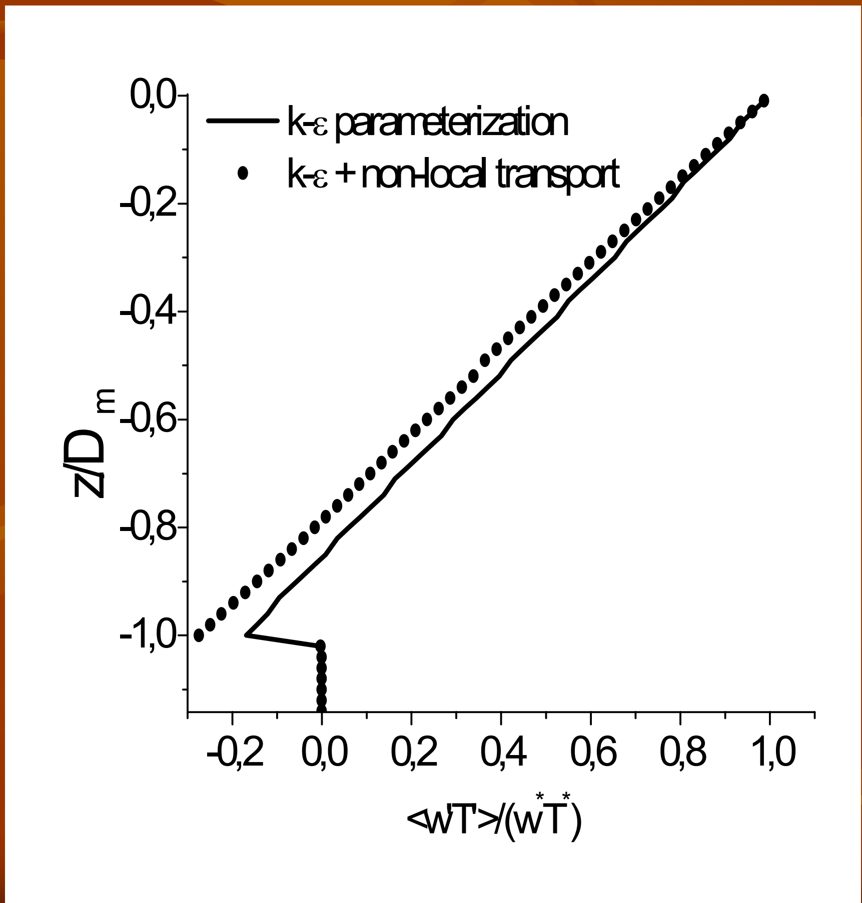
$$\overline{w'\phi'} = -k_{\phi} \frac{\partial \overline{\phi}}{\partial z}$$

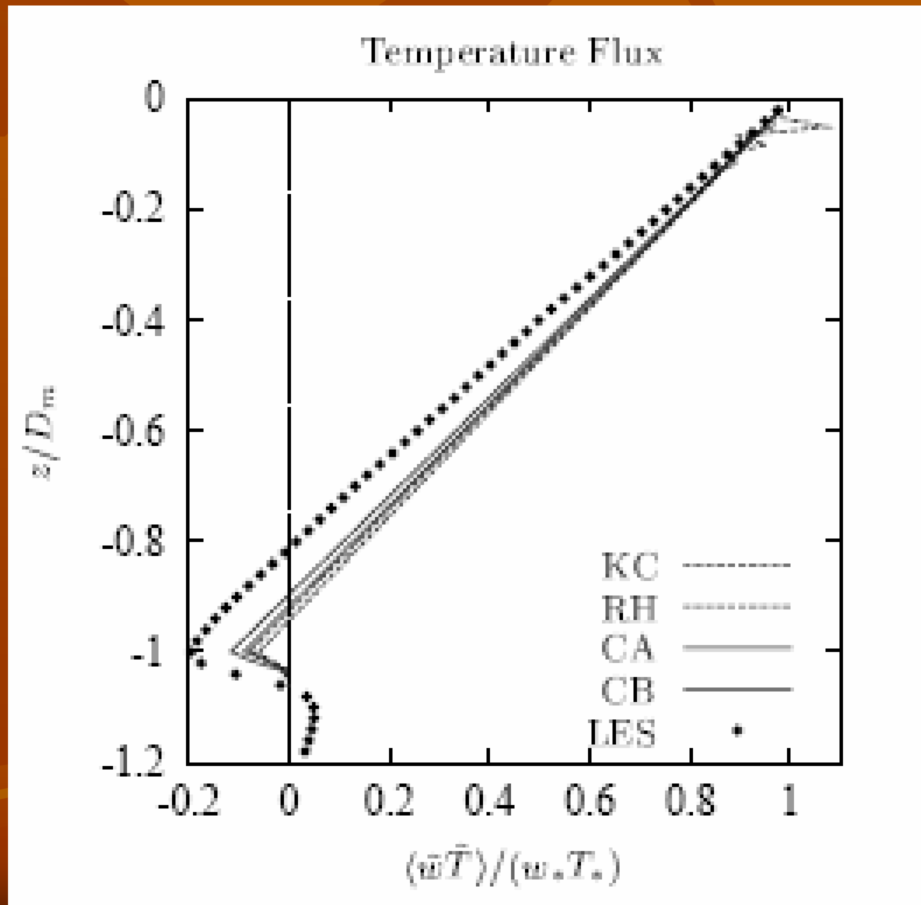
<u>The shortcoming</u>: does not take into account non-local effects of convective thermals → does not reproduce uniform temperature profile

The counter-gradient heat transport by convective thermals

$$\overline{w'\phi'} = -k_\phi \frac{\partial \overline{\phi}}{\partial z} \Rightarrow \overline{w'\phi'} = -k_\phi \frac{\partial \overline{\phi}}{\partial z} + \boxed{M\left(\phi_d - \overline{\phi}\right)}$$ (Soares et al. 2004)

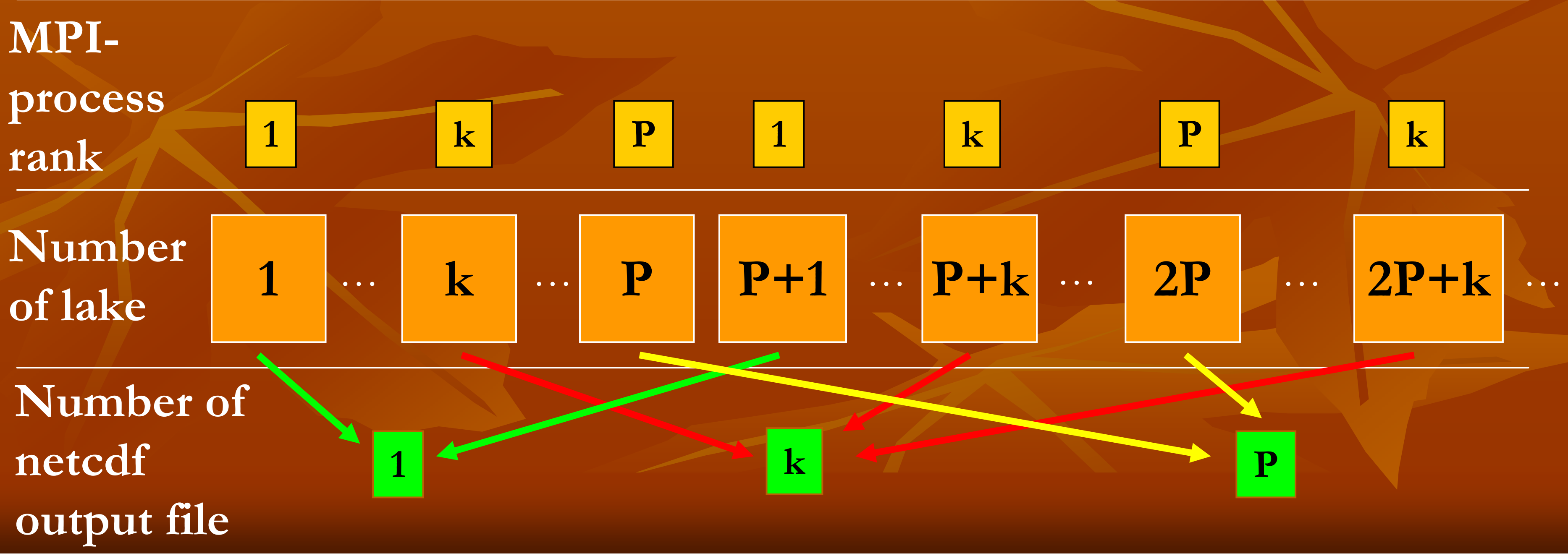
Temperature flux (Lake model) Temperature flux (other models and LES)





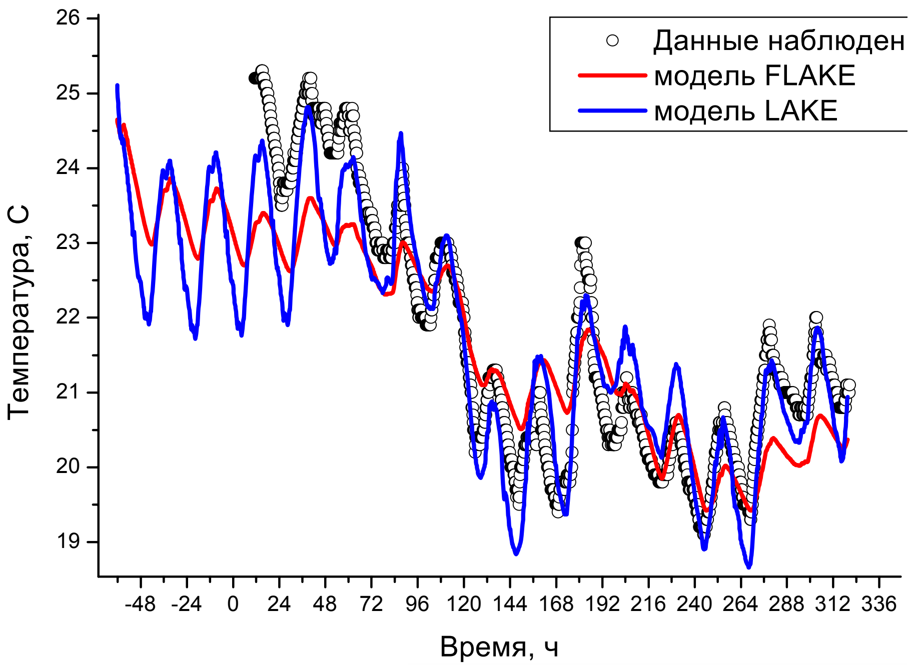
Implementation issues

- Fortran 90 code
- MPI libraries
- Netcdf libraries
- Lake driver implementation for N points (lakes) at P processors, N≥P

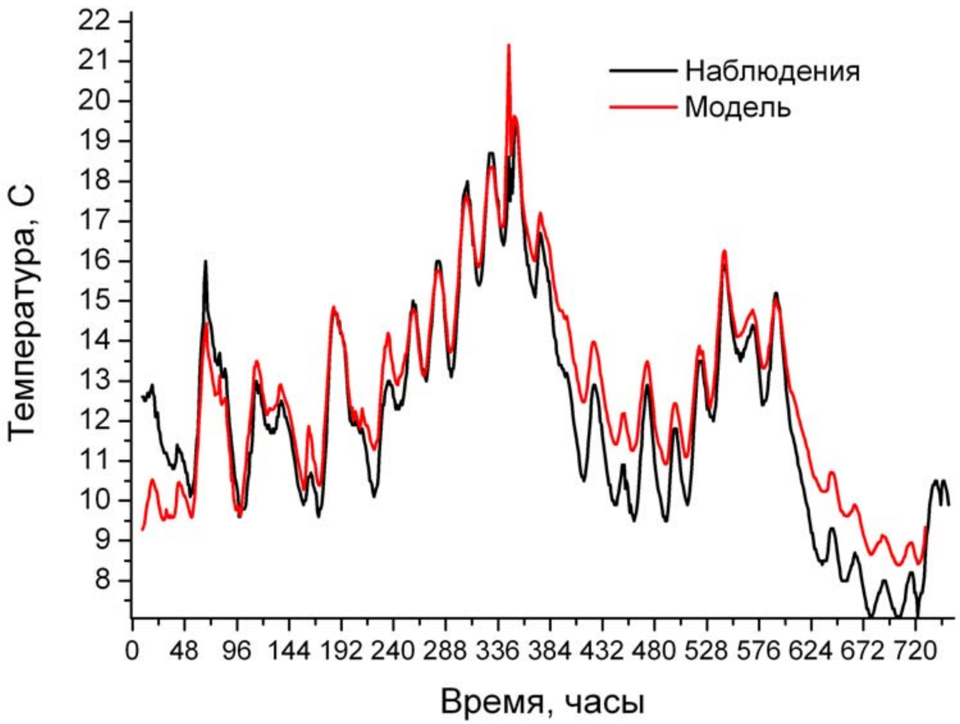


Surface temperature from Lake model and from observations

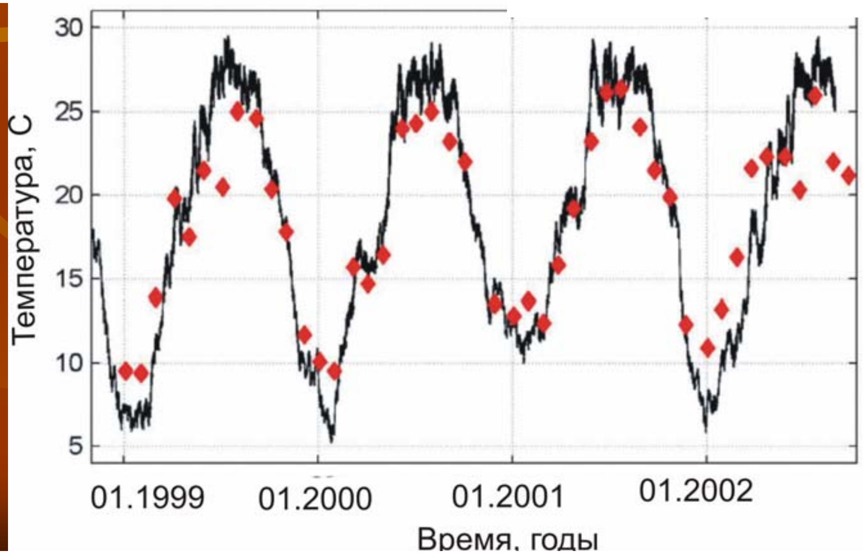
Kossenblatter lake, Germany, June, 1998



Tiksi lake, Siberia, July, 2002

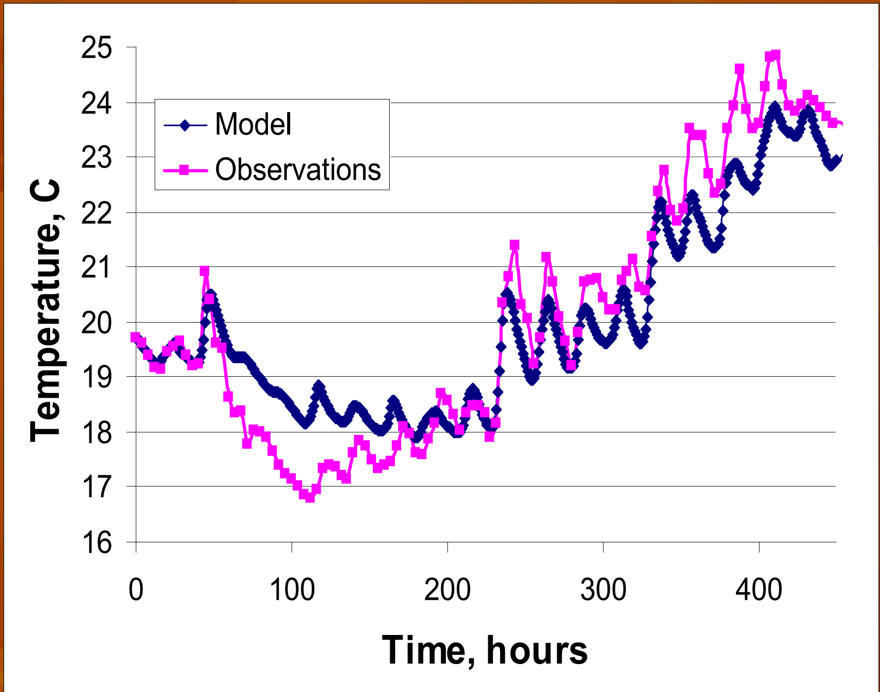


Monte-Novo lake, Portugal, 1999 - 2002

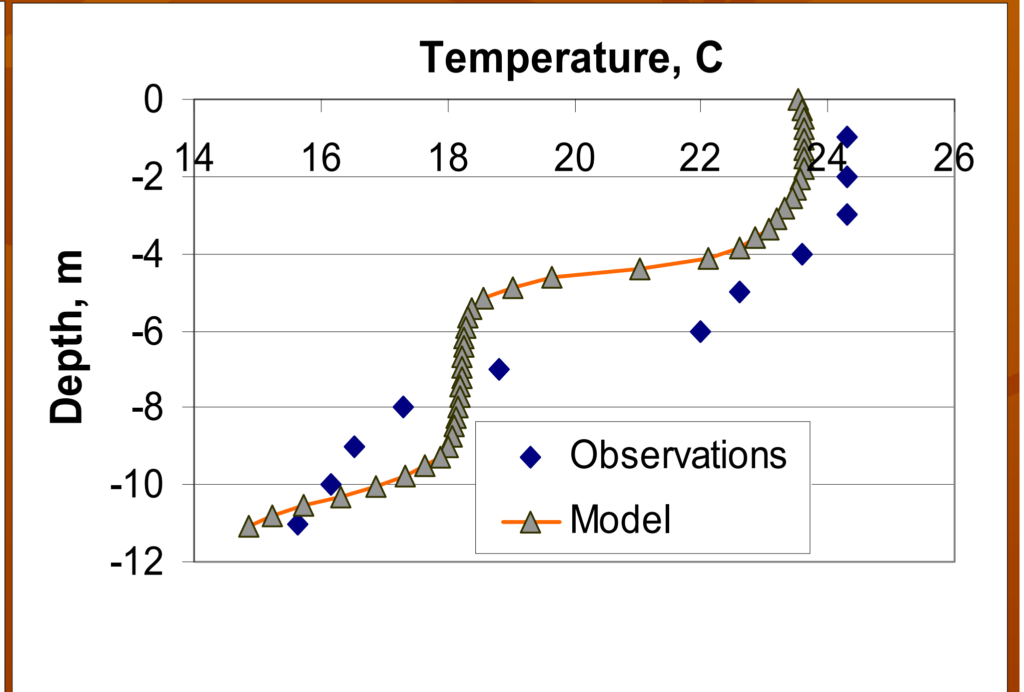


The temperature in Mogaiskoe reservoir

Surface temperature time series, 26.06.1996 – 13.07.1996



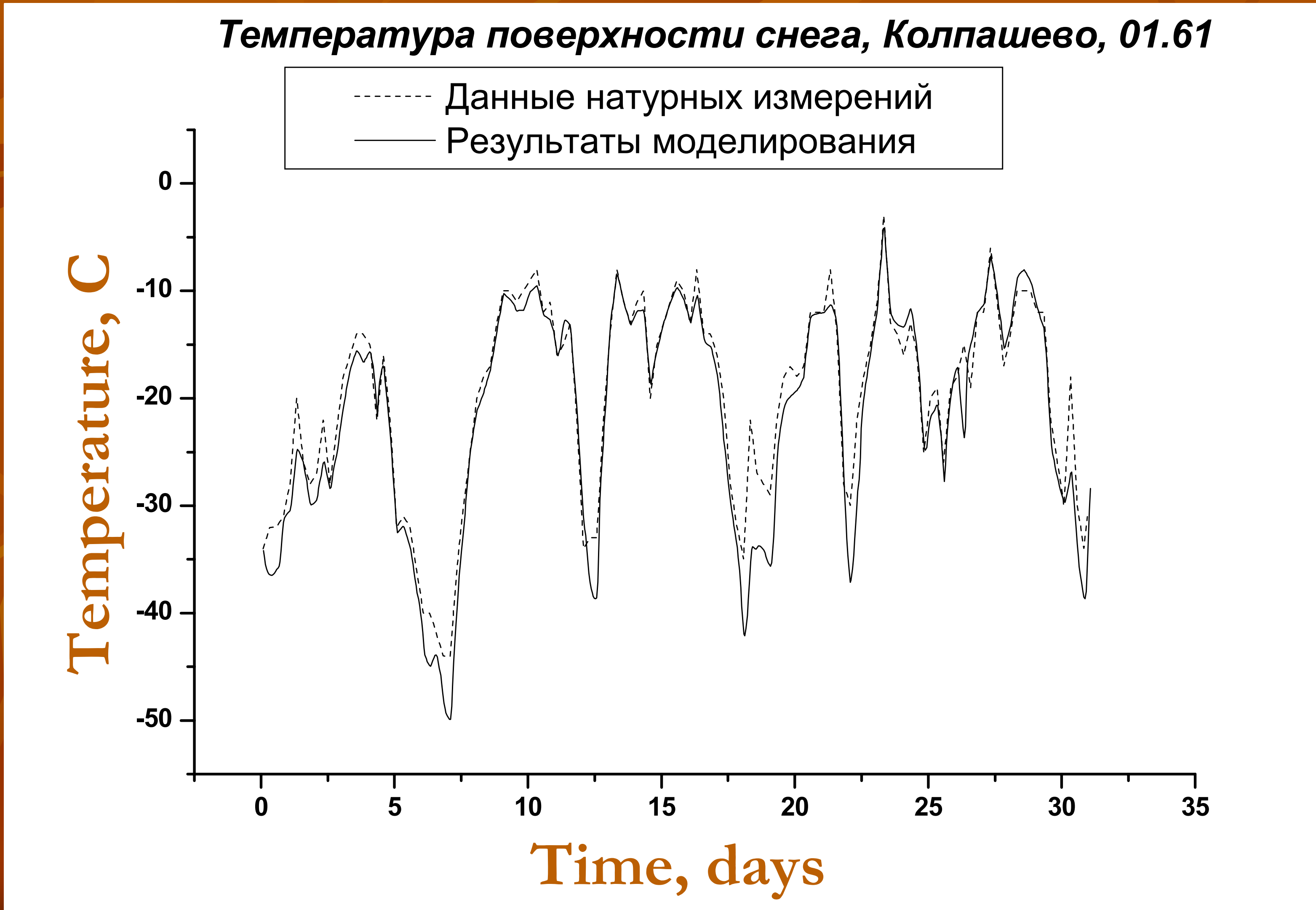
Vertical temperature profile, 01:00, 13.07.1996



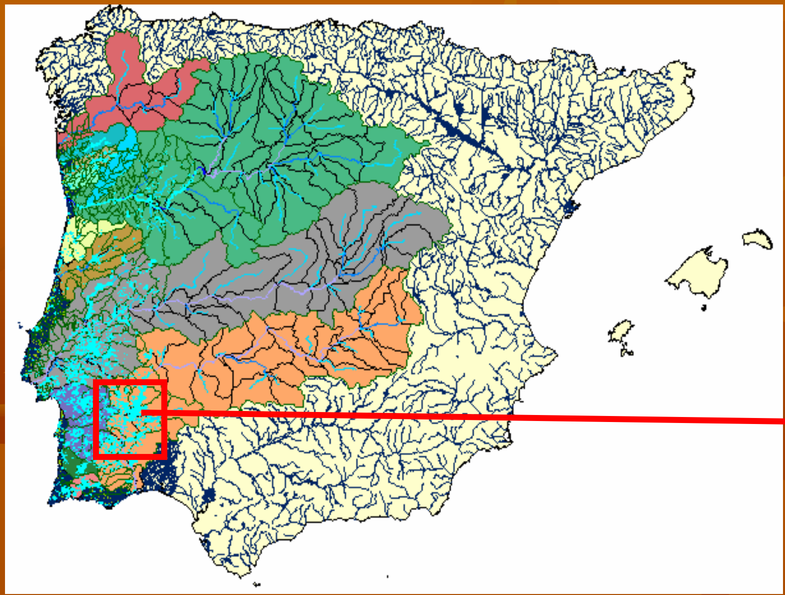
<u>Important features not taken into account:</u>

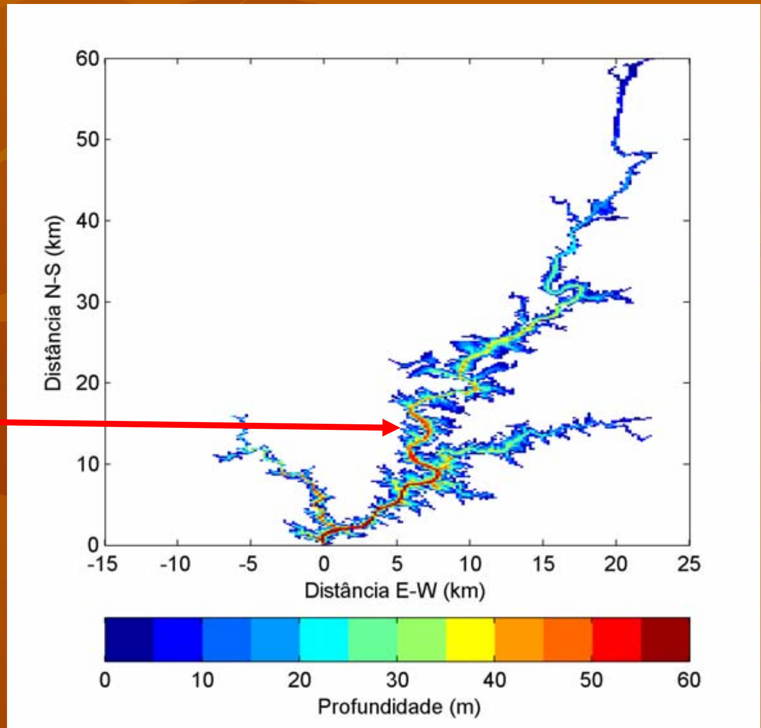
- Lengmuir circulations;
- Seiches;
- advection by tributaries.

Snow surface temperature,
(Kolpashevo, Western Siberia, February, 1961)



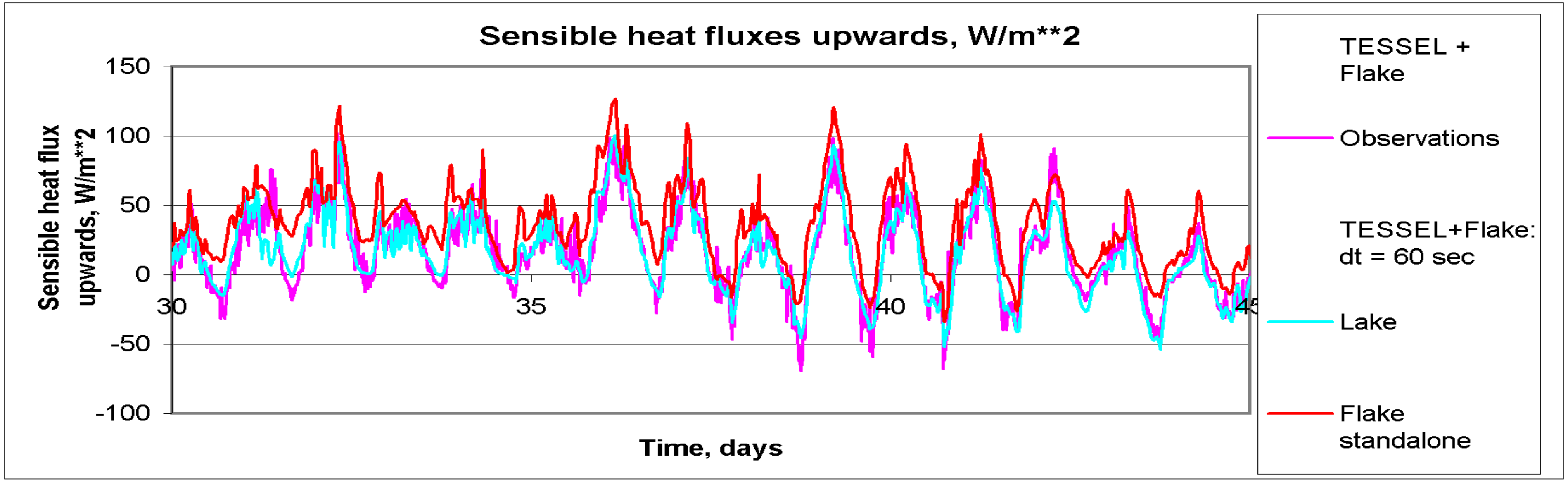
Lake Alqueva (Portugal)

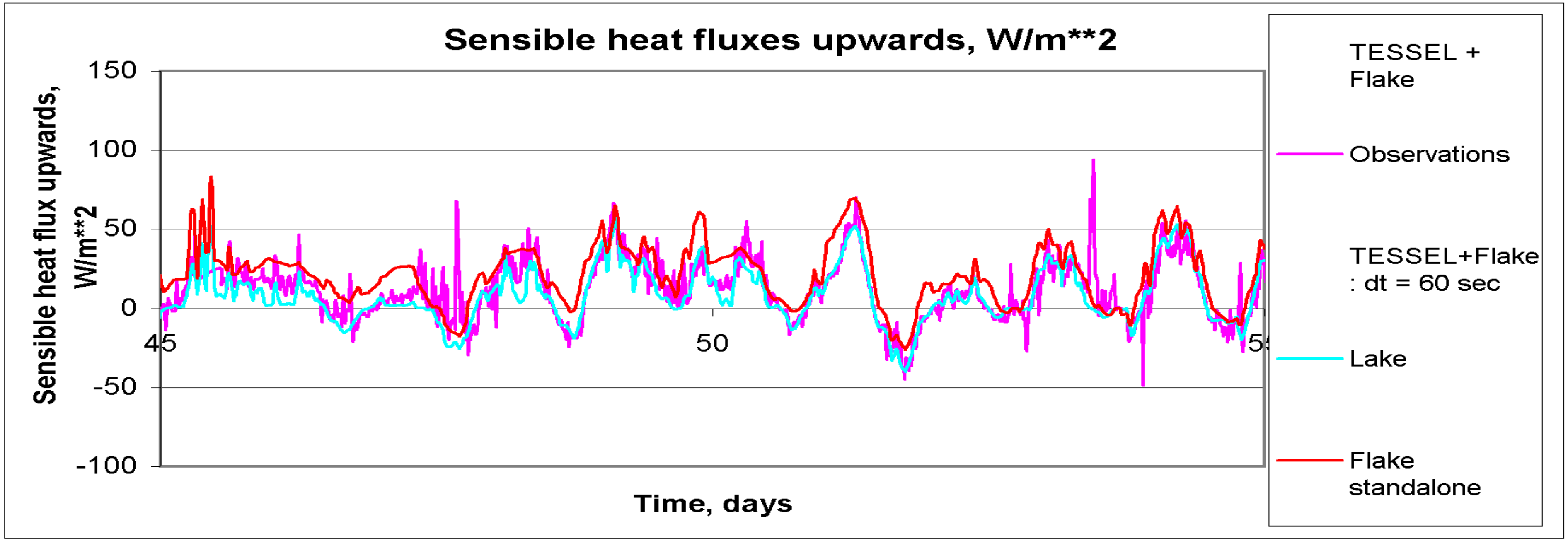




Sensible heat flux (Flake and Lake)

lake Alqueva, summer 2007





Sensible heat fluxes (Flake and Lake)

Averaging interval	TESSEL+ Flake	Flake	Lake	Observations
15 days	**29.8 W/m^2**	**23.4 W/m^2**	**22 W/m^2**	**26.6 W/m^2**
55 days	**30 W/m^2**	**27 W/m^2**	**14.6 W/m^2**	**16.5 W/m^2**

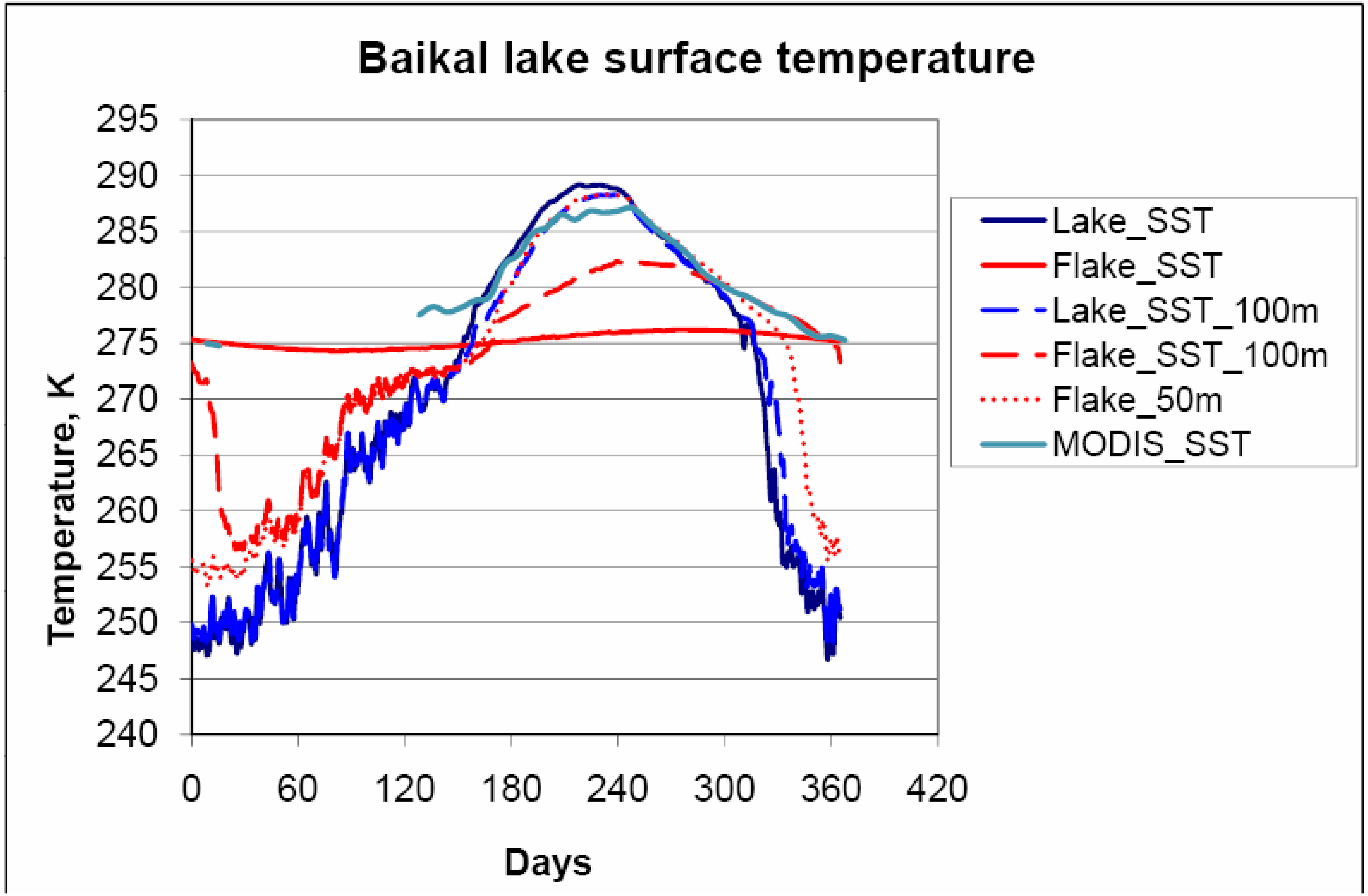
Source code of Lake model and data for verification

http://www.inm.ras.ru/laboratory/models_en.htm

The role of lake depth (Baikal)

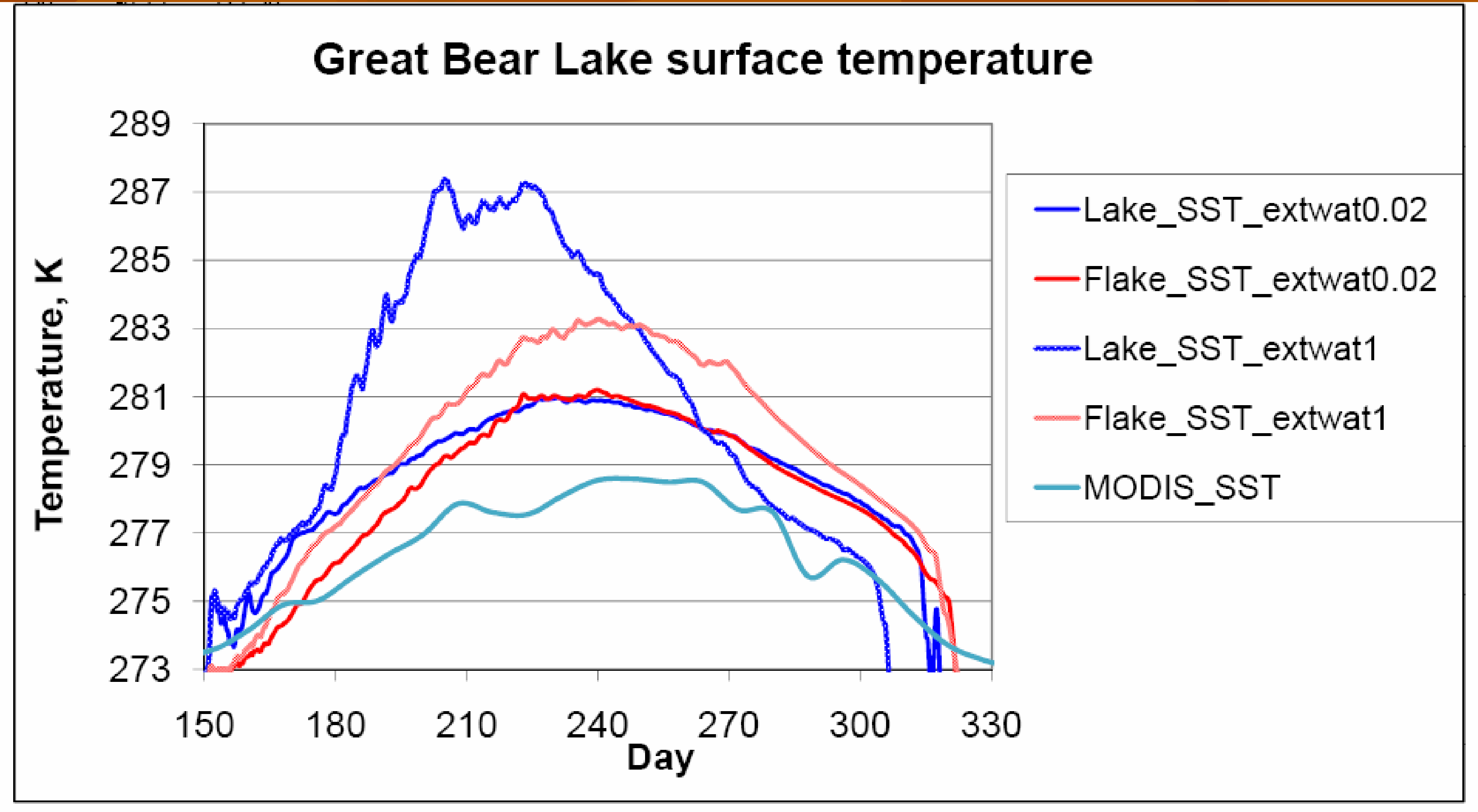
1) The real depth - 740 m

2) The depth 100 m

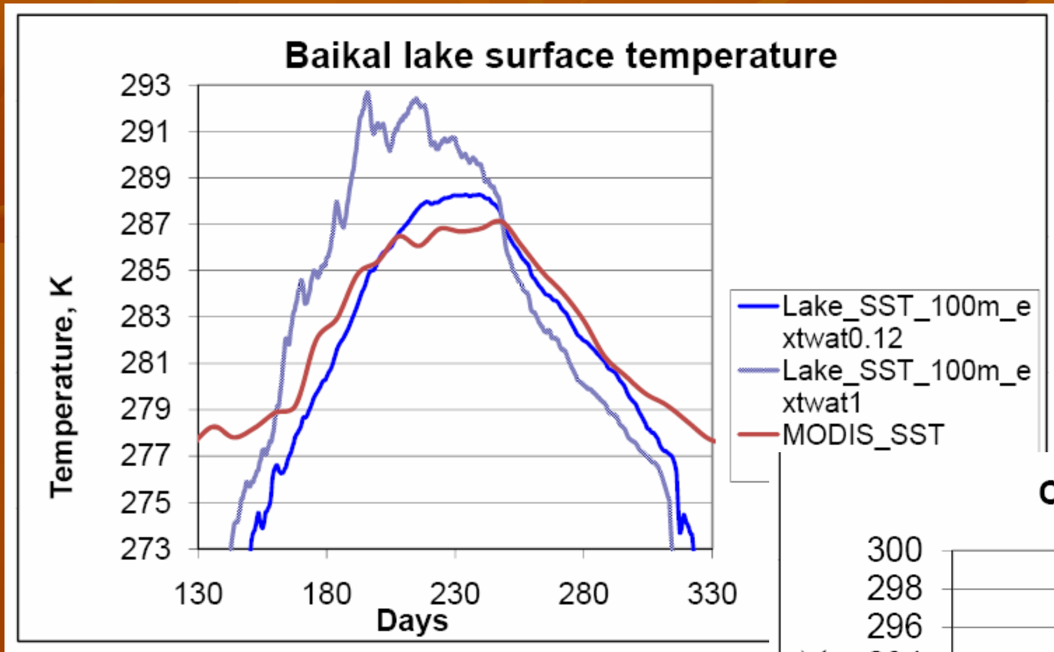


The role of radiation extinction coefficient

$$\lambda_e = 0.02 \quad m^{-1}, \quad \lambda_e = 1 \quad m^{-1}$$

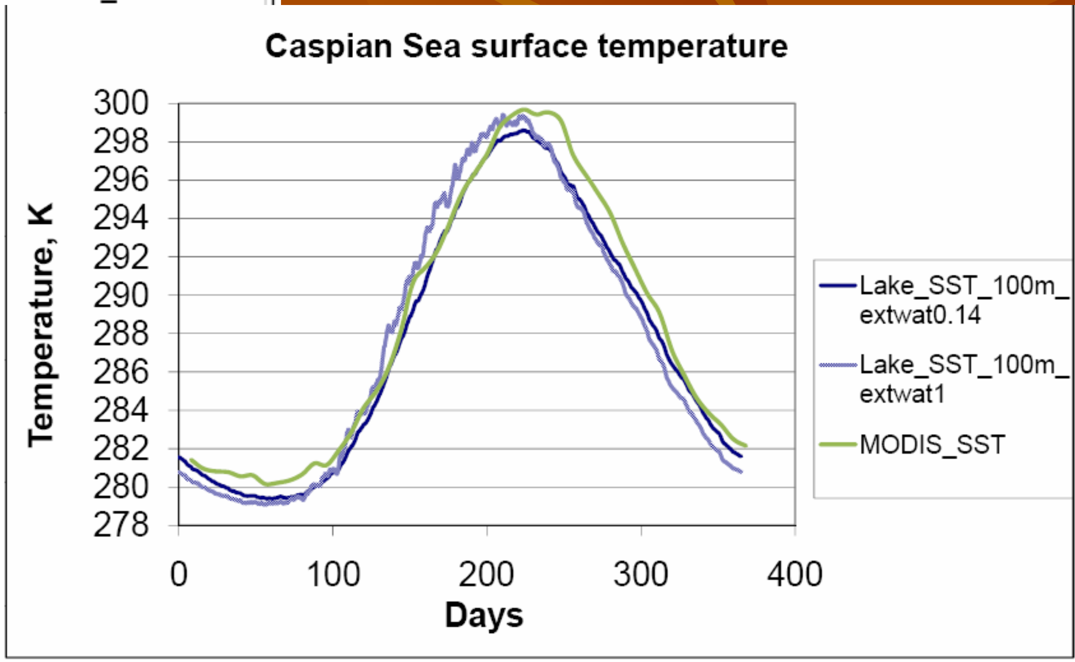


The role of radiation extinction coefficients (Baikal and Caspian sea)



$$\lambda_e = 0.12 \quad m^{-1},$$

$$\lambda_e = 1 \quad m^{-1}$$



$$\lambda_e = 0.14 \quad m^{-1},$$

$$\lambda_e = 1 \quad m^{-1}$$

Mesoscale atmospheric model

The code of **Nh3d model**

(Miranda & James, 1992)

- 3-dimensional
- σ-coordinates
- non-hydrostatic equation set
- "warm" cloud microphysics
- ISBA soil model

New features:

- shortwave (Clirad-SW) and longwave (Clirad-LW) radiation parameterization
- lake model
- aerosol transport scheme

Aerosol transport scheme

$$\frac{\partial q}{\partial t} + u\frac{\partial q}{\partial x} + v\frac{\partial q}{\partial y} + (\dot{\sigma} - \sigma_s)\frac{\partial q}{\partial \sigma} = D_q + R_q + S_q$$

σ_s - sedimentation speed,

S_q - aerosol source,

D_q - turbulent diffusion (1-st order closure),

R_q - Raileigh damping term

Boundary conditions: $q = 0$ at all boundaries

Numerical scheme: Smolarkiewich monotonous scheme

- spatial discretization – 2-d order
- temporal discretization – 2-d order

Aerosol distribution in test case

Hanty-Mansiisk region

Resolution:

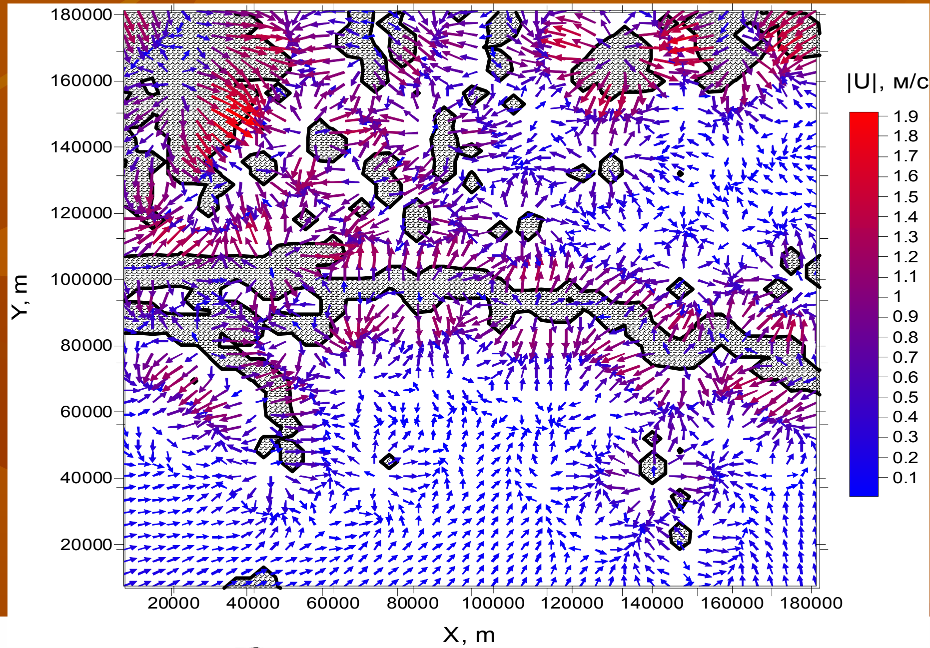
- ❑ $\Delta x = \Delta y = 3.7$ km
- ❑ 21 σ – levels

Time integration

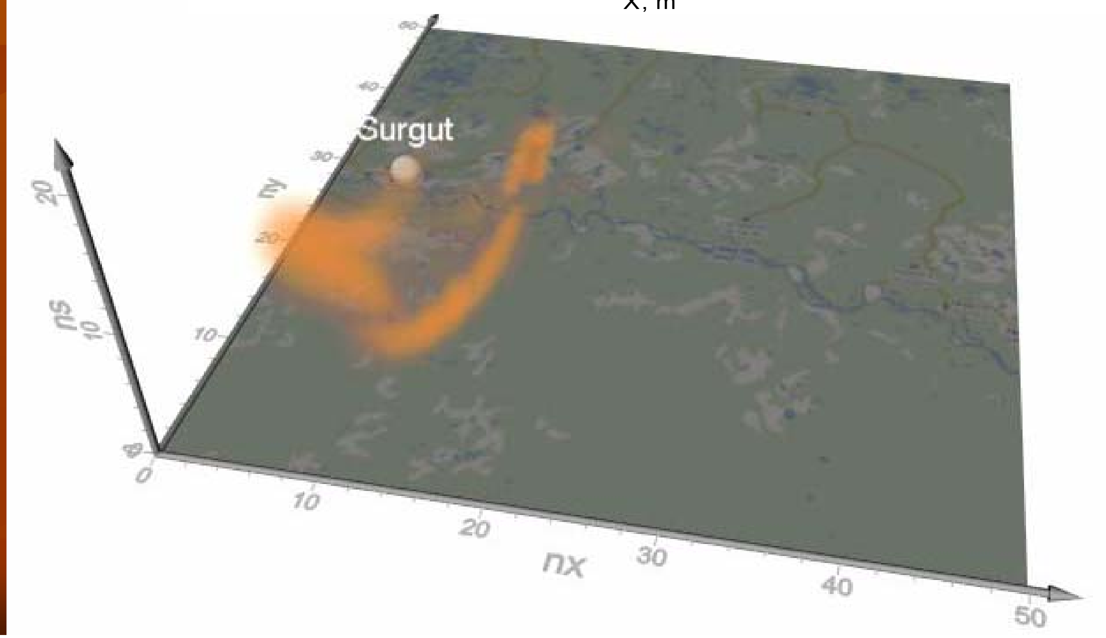
- ❑ $\Delta t = 5$ sec
- ❑ 8 days

Breezes develop over water bodies and transport the tracer far from source even in calm synoptic conditions

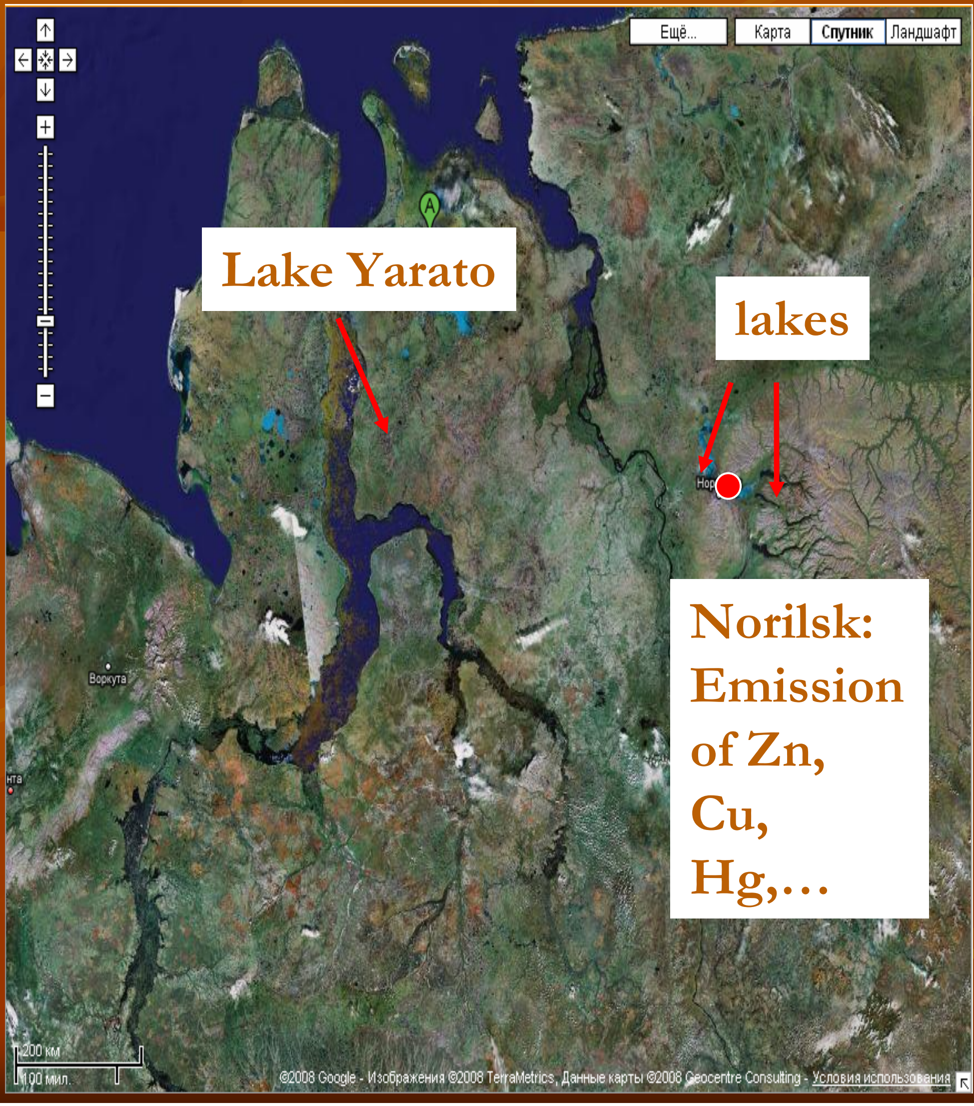
Near surface wind



Aerosol “cloud”



The work underway: aerosol emission and sink at water bodies



Aral Sea

Future development of Lake model

- Insertion the model of methane generation, transport and sink in the soil (lake sediments) – B. Walter and M. Heimann, 2000;
- Introduction of the methane ebullition and bubble convection parameterization in the water body;
- Incorporation of the computationally efficient version of the model into climate model of the Institute for Numerical Mathematics, Moscow;
- …

Acknowledgements

- Dmitrii Mikushin implemented aerosol transport scheme in mesoscale model;
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Thank you!

Your questions are welcome!