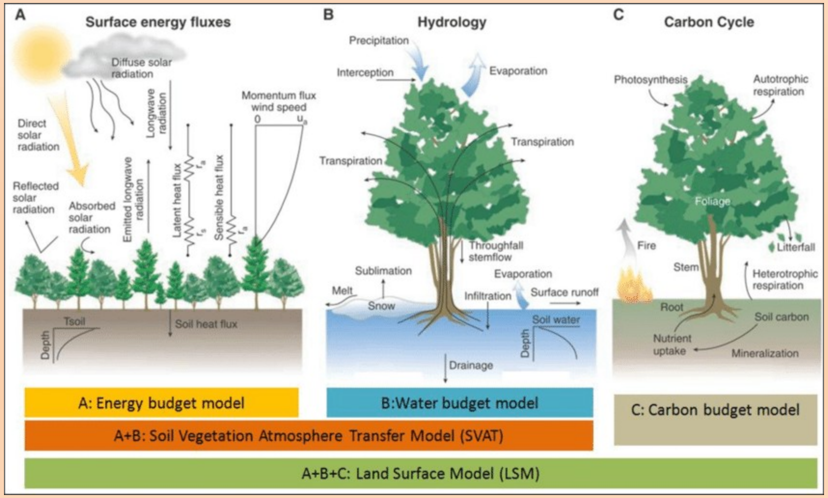
Land surface model TerM: towards an integral flexible tool for predicting ecological and hydrological responses to climate change

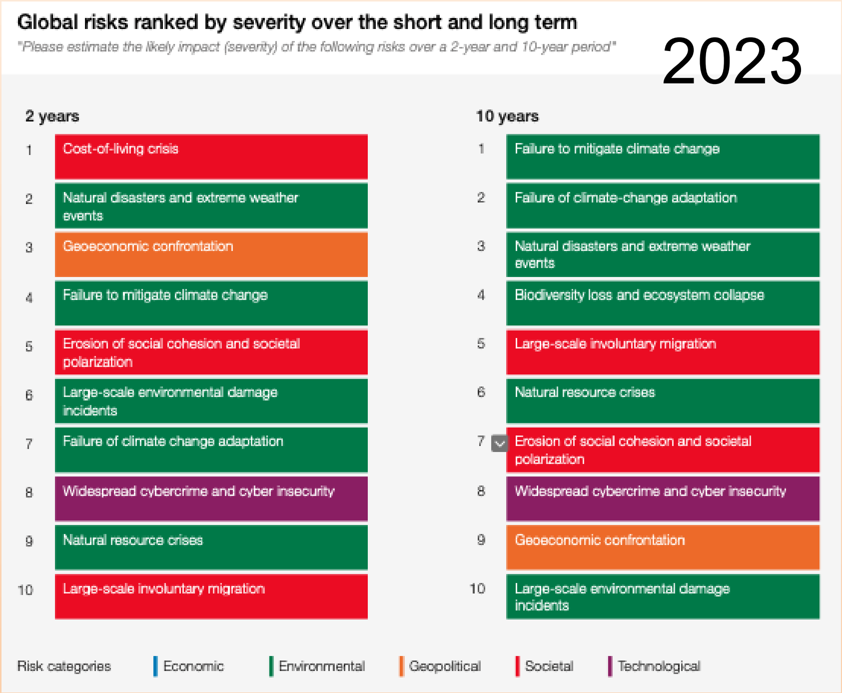
V. Stepanenko, V. Bogomolov, A. Medvedev, A. Ryazanova, I.Ryzhova, G.Faikin, S.Shangareeva, T.Mohomi, M.-J . Bopape

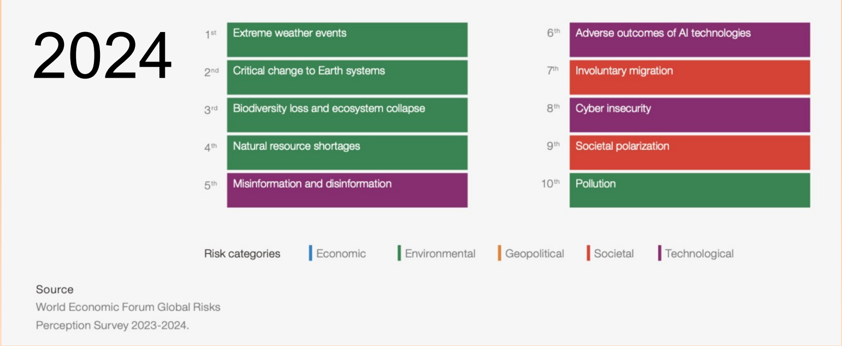


Russian Supercomputing Days, 23 September 2024,
Moscow State University, Moscow, Russia

The need for multisectoral impacts assessment and tools …

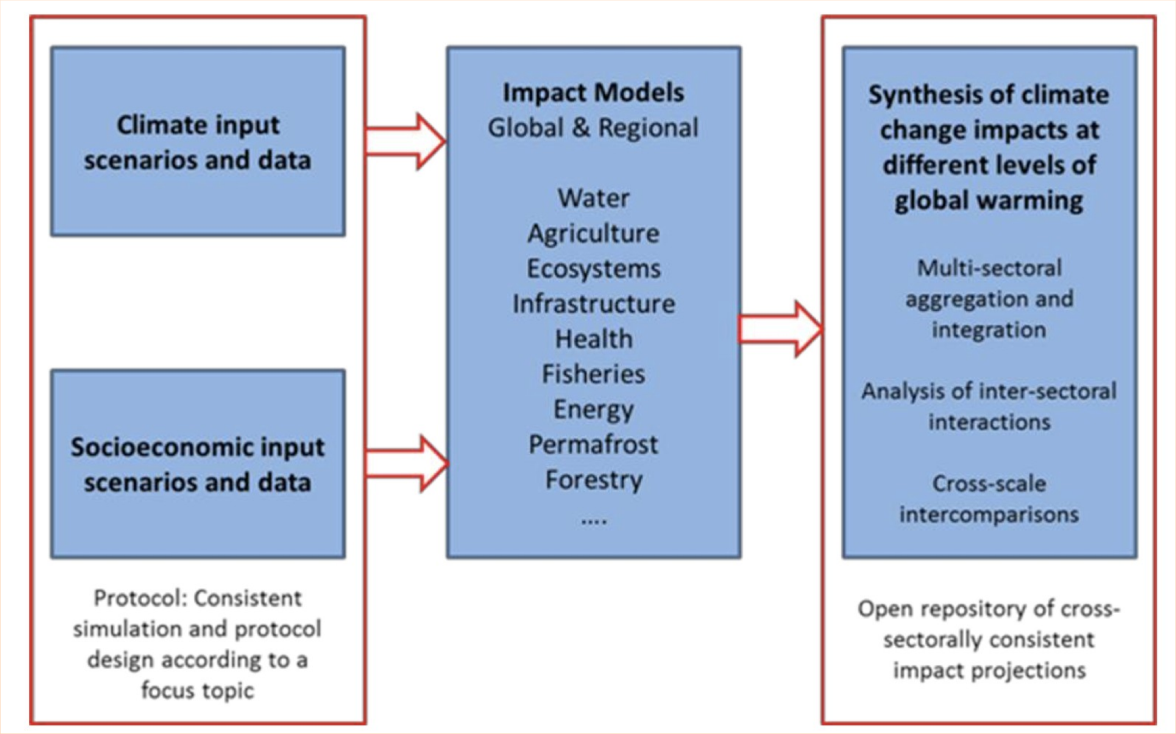
Global Risk Report
(Davos Forum)





ISIMIP project example

ISIMIP
Inter-Sectoral Impact Model Intercomparison Project



https://www.isimip.org

The models for land "sectors" are a major tool …

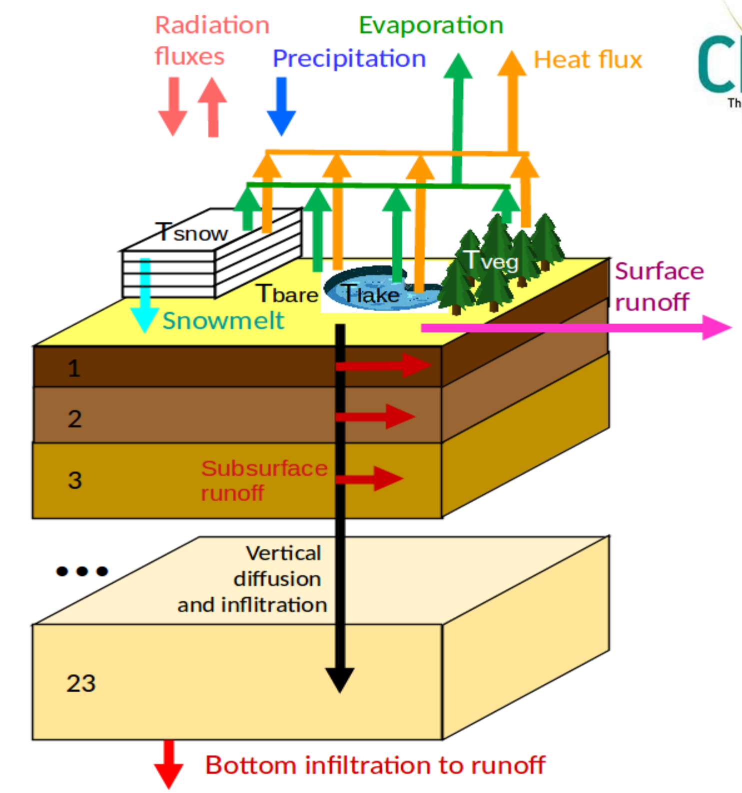
Terrestrial Model (TerM)
(Land surface INM RAS-MSU model)

Corr. member RAS V.N.Lykosov – founder of research direction

INM RAS-MSU land surface scheme

Climate model of Institute of Numerical Mathematics (INMCM)

Global numerical weather prediction SL-AV model



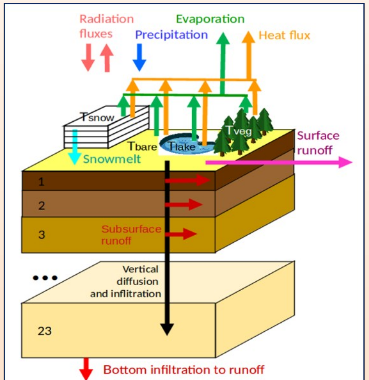
Heat and moisture exchange in a cell of INM RAS-MSU land surface model

- ❑ Heat, moisture, water vapor and ice dynamics in soil (23 lrs)
- ❑ Snow cover with liquid water treatment (4 lrs)
- ❑ Soil and vegetation carb
- ❑ Wetland CH_4 model
- ❑ LAKE model
- ❑ River routing scheme

MPI+OpenMP implementation, CUDA tests

Model implemented in a standalone model (baseline spacing 0.5°x0.5°): (i) global, (ii) regional and (iii) local configurations.

Land surface model application
for diagnosis and forecast of carbon/water cycles



Heat and moisture exchange in a cell of INM RAS-MSU land surface model

Pools and fluxes of water and carbon

National reports (3-d tier for IPCC, ...)

Land surface model TerM

+ Conservation laws
+ Pools and fluxes
+ Resolution down to 1-10 km
- «Model is model»

Validaiton, calibration

Remote sensing

Land surface observations

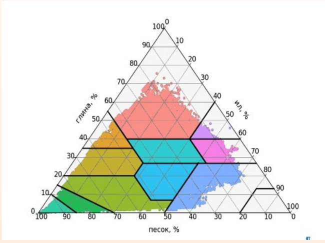
+ Full coverage with resolution down to 10-100 meters
+ High accuracy in obtaining a number of variables
- Limited ability to estimate pools in soils, carbon and water fluxes

Inverse atmospheric modeling for GHGs

+ High accuracy in estimating carbon fluxes and pools
- Low coverage of large (sparse-populated) areas

Architecture of the land surface data preprocessing system TerMPS

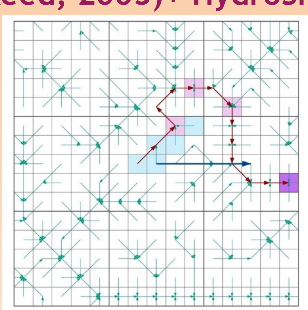
Granulometric composition in the global soil database (Dai et al., JAMES, 2019)



An updated map vegetation of Russia IKI RAS (Egorov et al., 2018)

Maps of urban local climate zones (Demuzere et al., 2021)

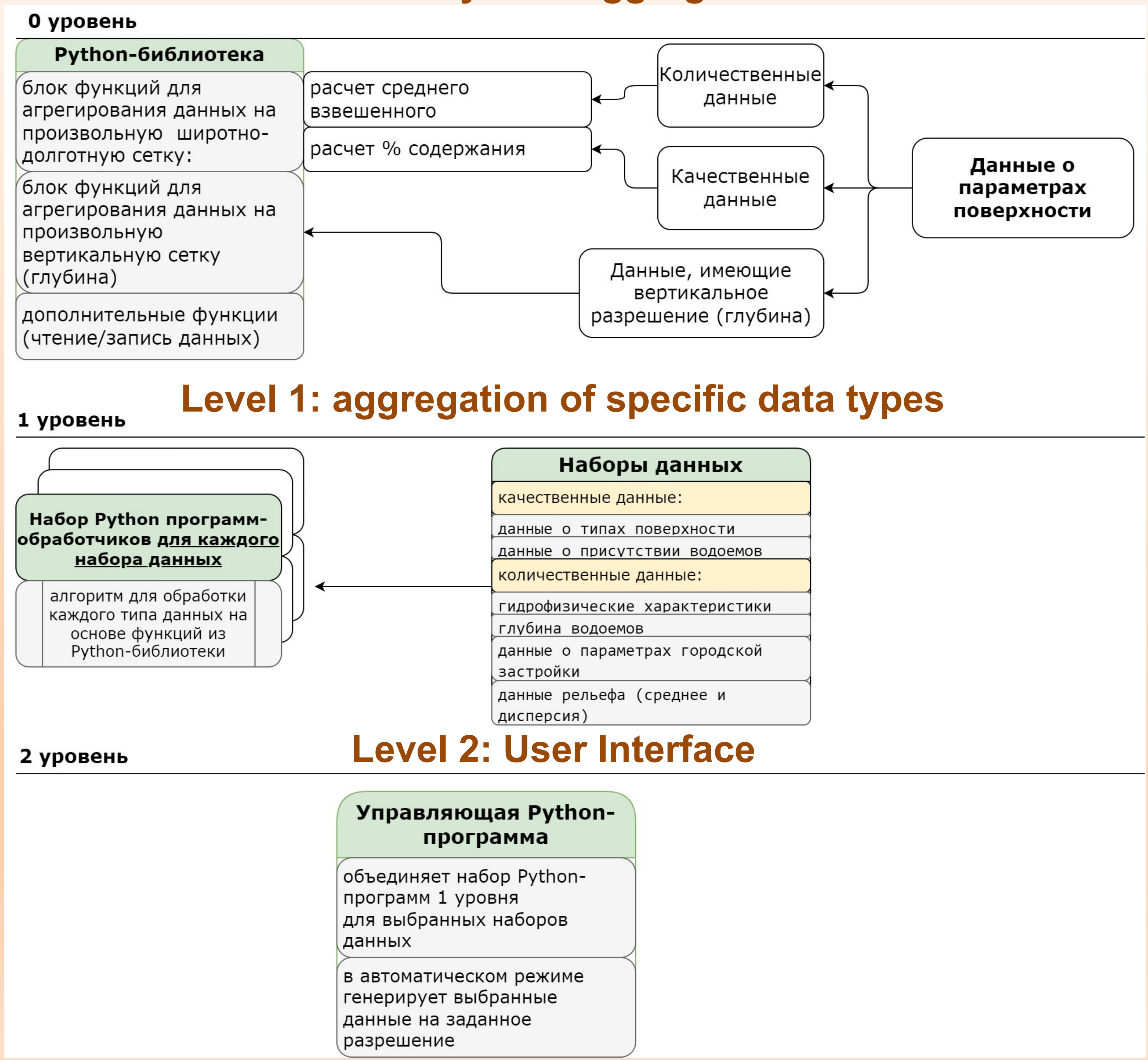
Streamflow tracing (Reed, 2003)+ HydroSheds



Level 0: elementary data aggregation functions

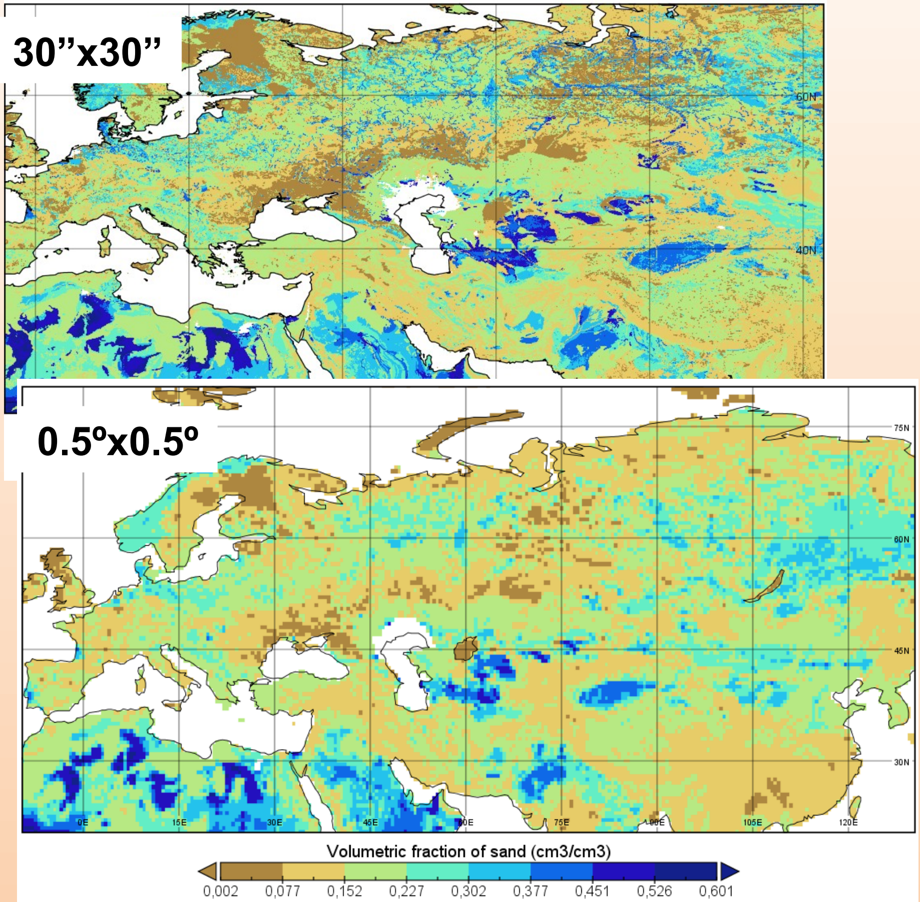
Level 1: aggregation of specific data types

Level 2: User Interface



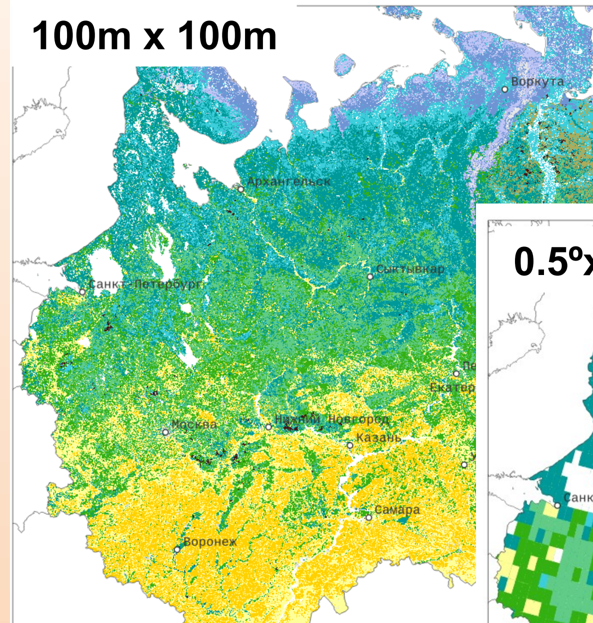
Maps produced by TerMPS

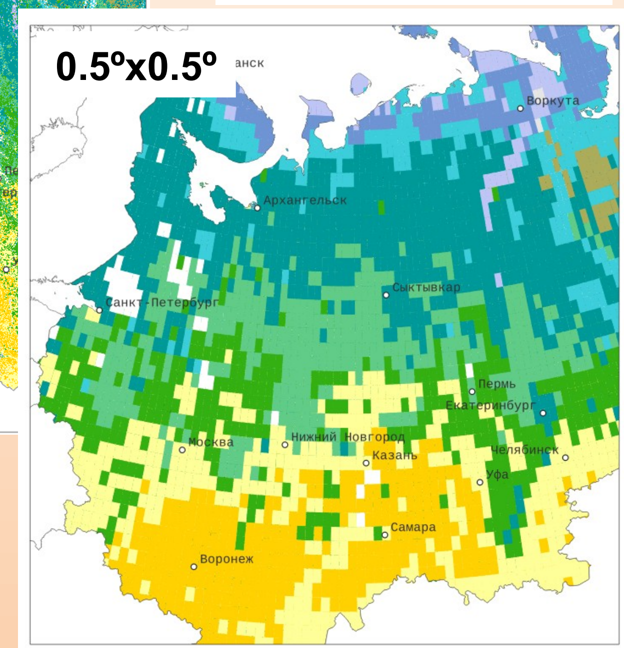
Volumetric clay content



Dai, Y., Xin, Q., Wei, N., Zhang, Y., Shangguan, W., Yuan, H., et al. (2019). A global high-resolution data set of soil hydraulic and thermal properties for land surface modeling. *Journal of Advances in Modeling Earth Systems*, 11, 2996– 3023. https://doi.org/10.1029/2019MS001784

Map of Russia's land cover based on Proba-V satellite data.

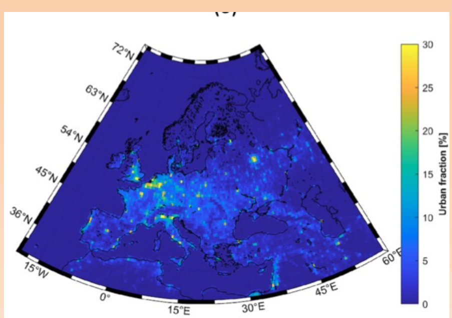




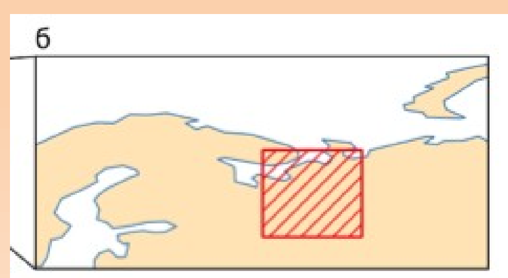
Dominant land cover class over 0.5x0.5 cells

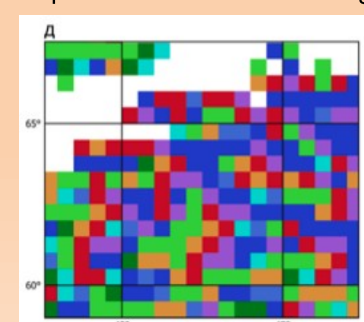
V.A. Egorov, S.A. Bartalev, P.A. Kolbudaev, D.E. Plotnikov, S.A. Khvostikov, Land cover map of Russia derived from Proba-V satellite data, Current problems in remote sensing of the earth from space, 15(2), 2018

Urban surface fraction



Riverflow directions

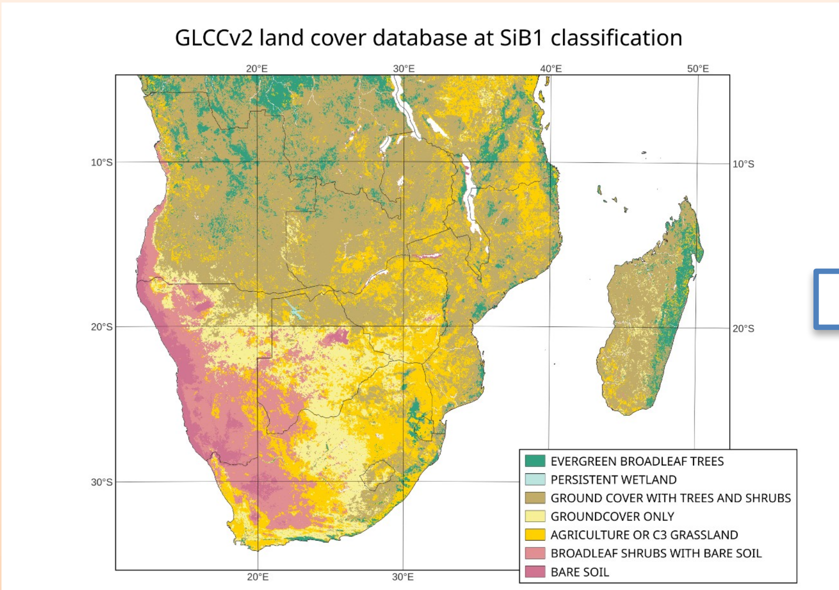


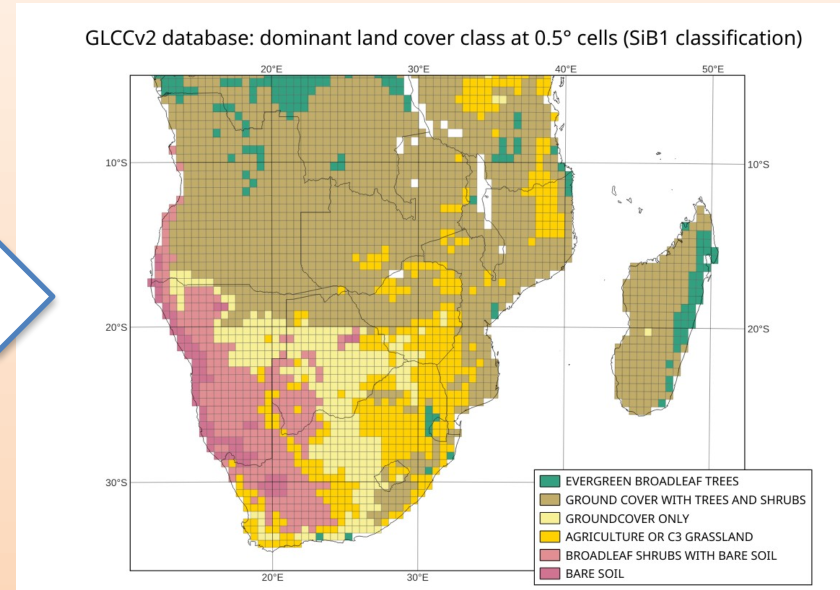


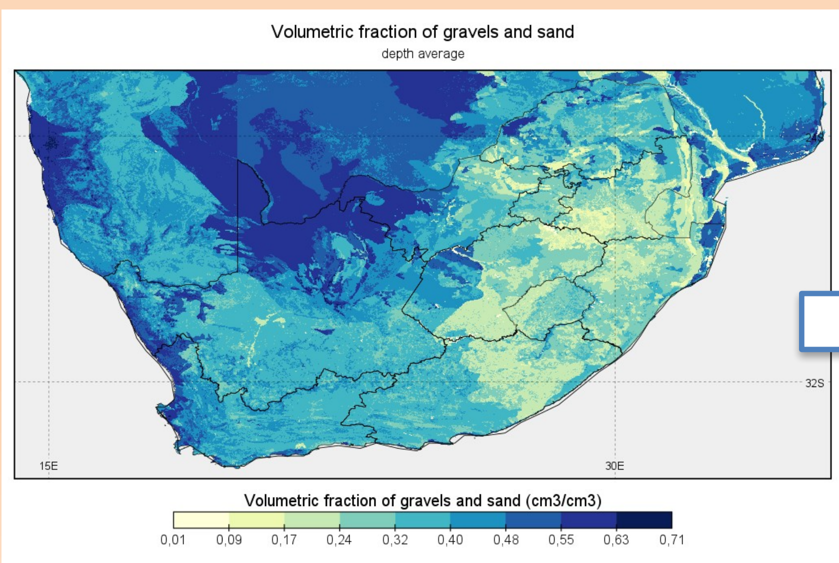
Land cover and soil maps for South Africa (TerMPS)

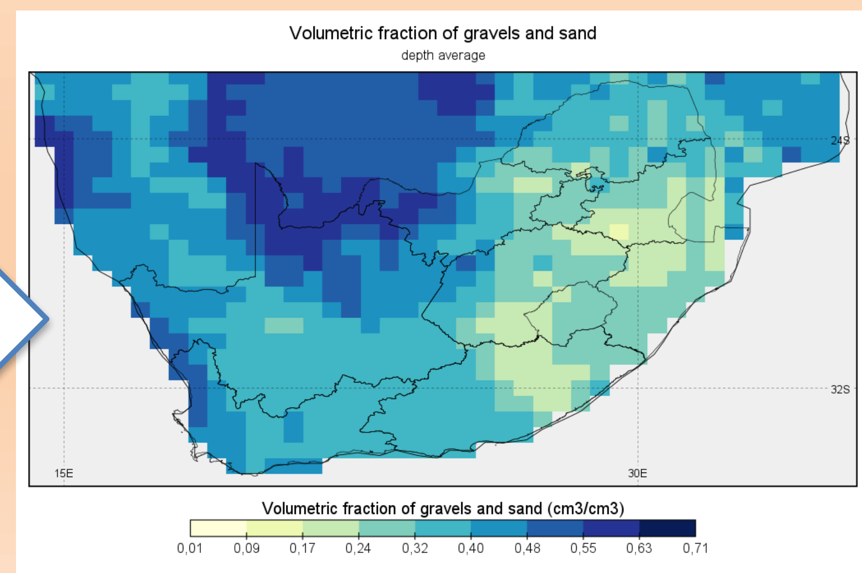
1km-resolution source database GLCCv2

Land cover at 0.5x0.5 model grid









Carbon cycle in TerM

Governing equations:

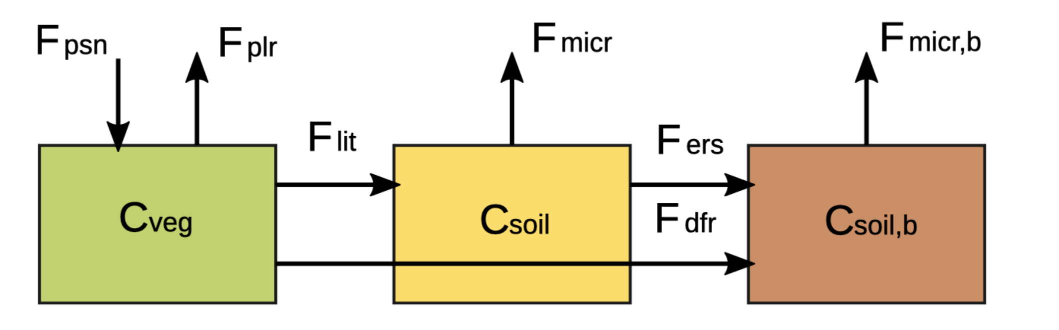
$$\frac{\partial C_{veg}}{\partial t} = F_{psn} - F_{plr} - \frac{C_{veg}}{\tau_{veg}} - F_{dfr,a} - F_{dfr,b}$$

$$\frac{\partial C_{soil}}{\partial t} = \frac{C_{veg}}{\tau_{veg}} - \frac{C_{soil}}{\tau_{soil}} - F_{ers}$$

$$\frac{\partial C_{soil,b}}{\partial t} = F_{dfr,a} + F_{dfr,b} + F_{ers} - \frac{C_{soil,b}}{\tau_{soil,b}}$$

The vegetation and soil carbon pool are simulated in each cell for each vegetation type:

- needleleaf evergreen tree
- needleleaf deciduous tree
- broadleaf evergreen tree
- broadleaf deciduous tree
- tropical seasonal tree
- cool grass (c3)
- evergreen shrub
- deciduous shrub
- arctic deciduous shrub
- arctic grass
- crop
- irrigated crop
- warm grass (c4)
- not vegetated



Pools:
C_{veg} – vegetation carbon
C_{soil} – soil carbon
$C_{soil,b}$ – fast carbon in soil

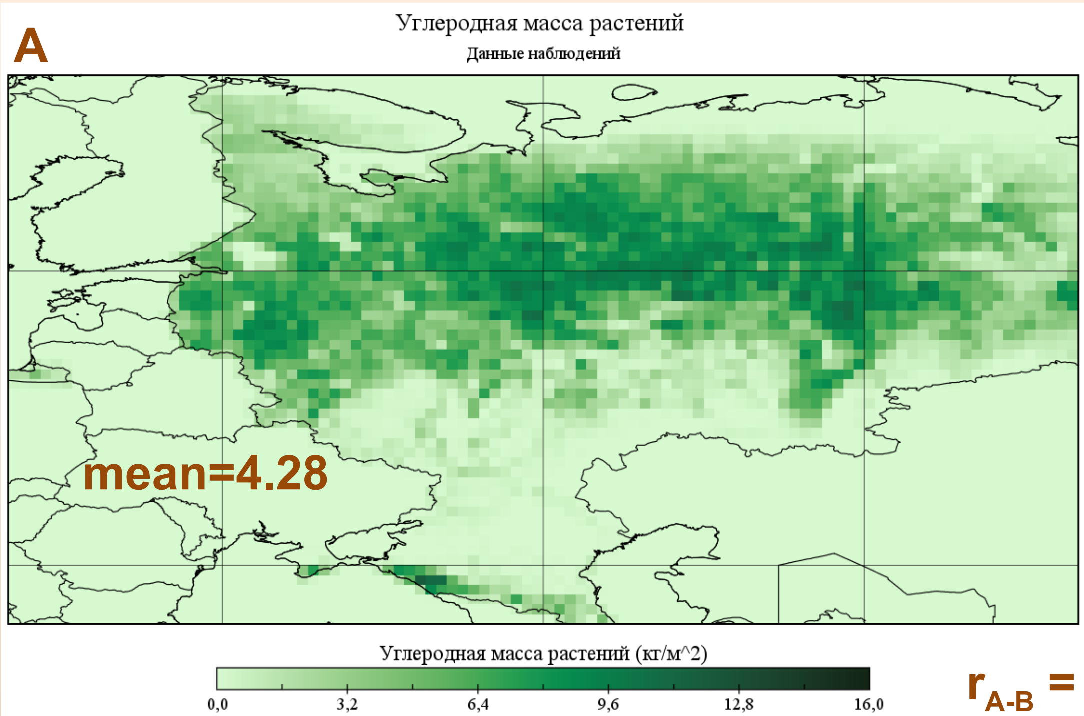
Production:
F_{psn} - photosynthesis

Respiration:
F_{pln} – vegetation respiration
F_{micr} – microbial respiration
$F_{micr,b}$ – microbial respiration of fast carbon

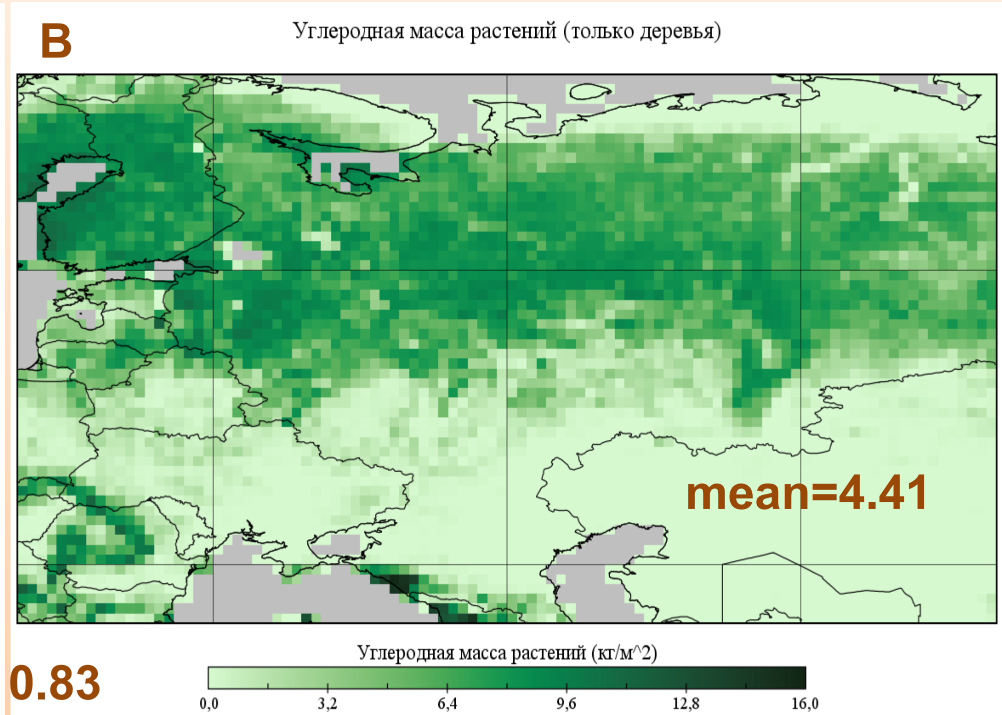
Transfers between pools:
F_{lit} – litterfall
F_{dfr} – deforestation
F_{ers} – soil cultivation

Carbon in forests
(European Russia example)

Remote sensing data of SRI RAS/MODIS on stem wood stock, kg/m²



TerM model, kg/m² : map by 2020



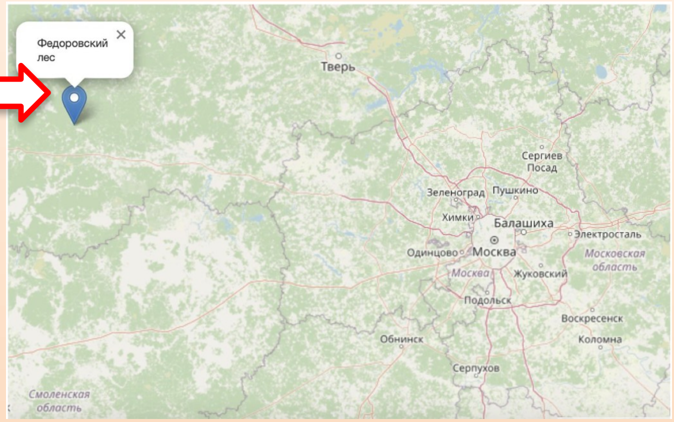
$r_{A\text{-}B} = 0.83$

Simulation parameters:

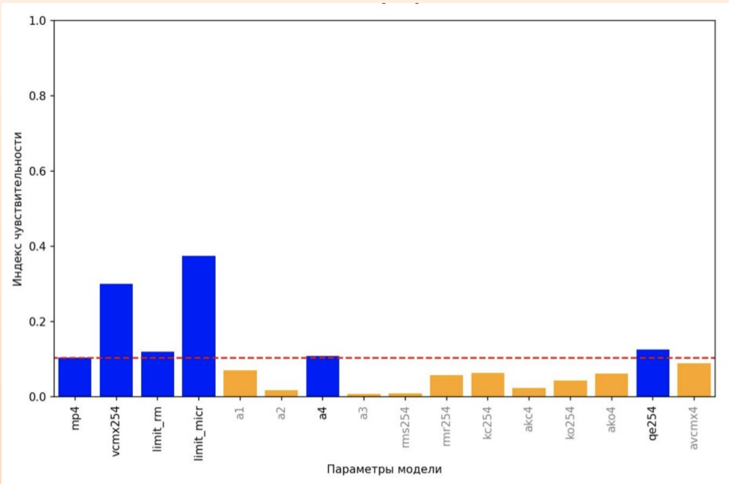
- Simulation period 1991-2020;
- Atmospheric forcing – ERA5;
- Remote sensing data for wood volume were converted to C assuming wood density of 600 kg/m3;
- TerM data are sum of high-vegetation types;

Site-level calibration (Fedorovskoe)

Eddy covariance mast above coniferous forest (Tver region, Russia)



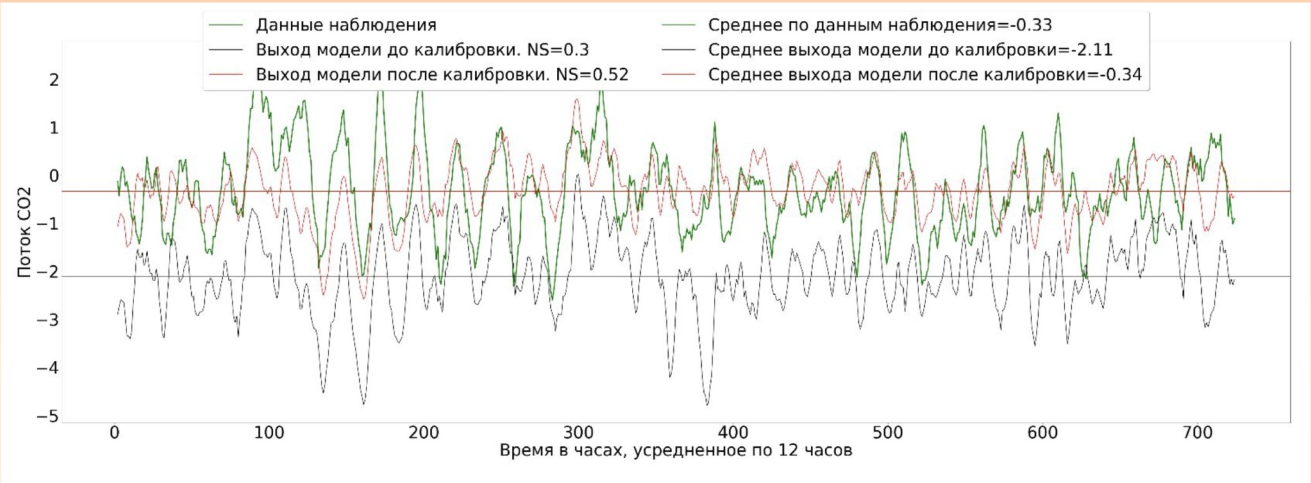
Model sensitivity: FAST *(Saltelli et al., 1999)*



SPOTPY

Model calibration: ROPE *(Bárdossy and Singh, 2008)*

	Mean error	Nash-Satcliffe coeff.
Default params	**-1.78**	**0.30**
Calibrated params	**-0.18**	**0.53**



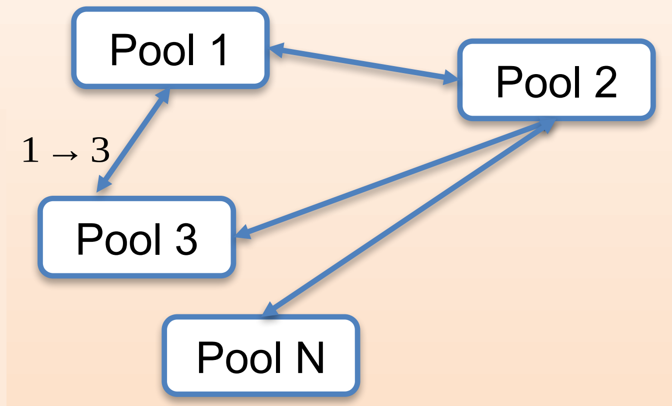
Towards a flexible carbon model structure

$_{1\to 2} = \prod \quad (\quad)$

General equation system of carbon models:

(1)

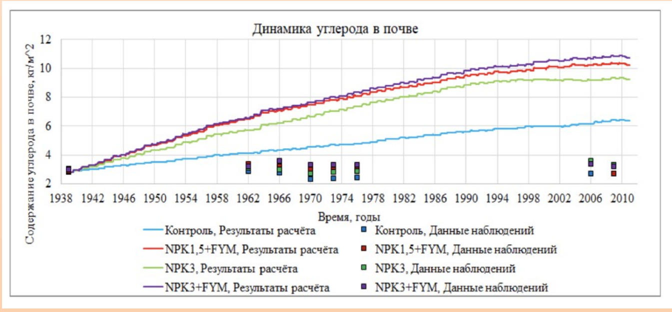
(2)



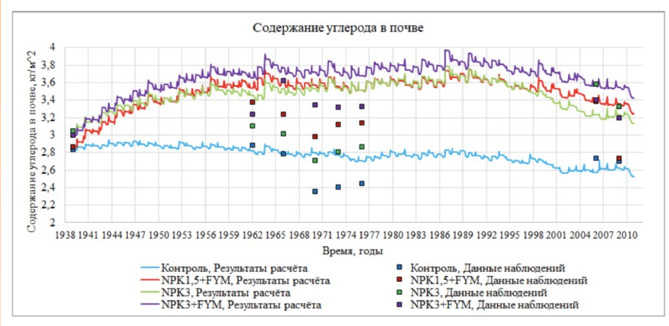
“A carbon model constructor”

A goal is to specify a **desired carbon model structure** in a single code. This allows to choose an optimal model for each ecosystem.

TerM standalone model

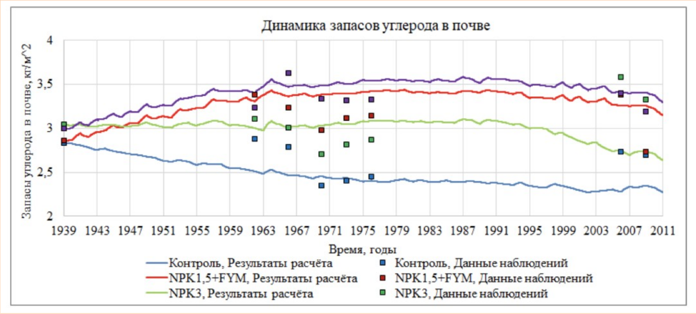


RothC model



SOCS model

(*Ryzhova, 2022*)

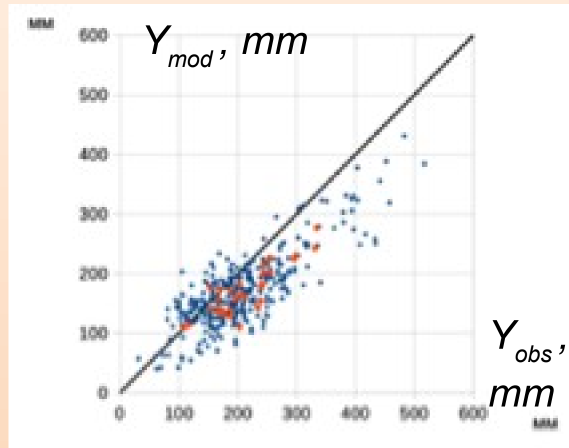


Riverflow simulations

(Northern Dvina and Pechora rivers)

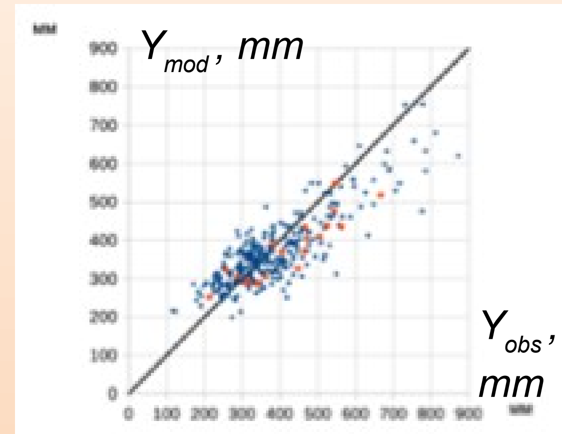
- **liquid moisture content in snow**, its movement along the profile and re-freezing (Machulskaya, 2003)
- imroved gamma distribution dependence of **snow cover fraction** on snow accumulation (Koren, 1991)
- improved dependence of **soil hydrophysical characteristics on ice content** (Kulik, 1978)
- Updating the **database for soil hydrophysical properties** (Wilson & Henderson-Sellers, 1985 -> SoilGrids, 2021)

Average layer of spring flood runoff

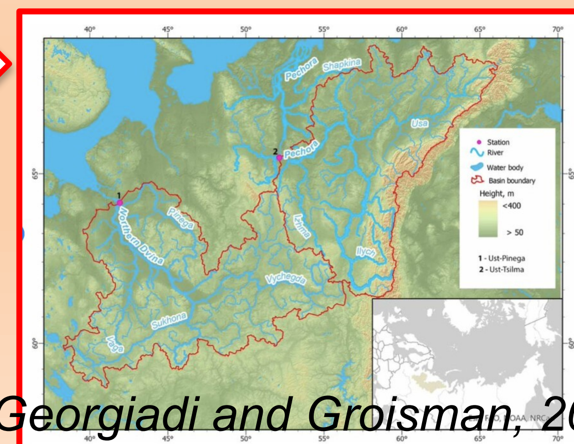


■ Observations
■ model, baseline simulations
■ model, improved

Average layer of annual runoff



■ Observations (route snow measurement surveys)
■ model, baseline simulations
■ model, improved



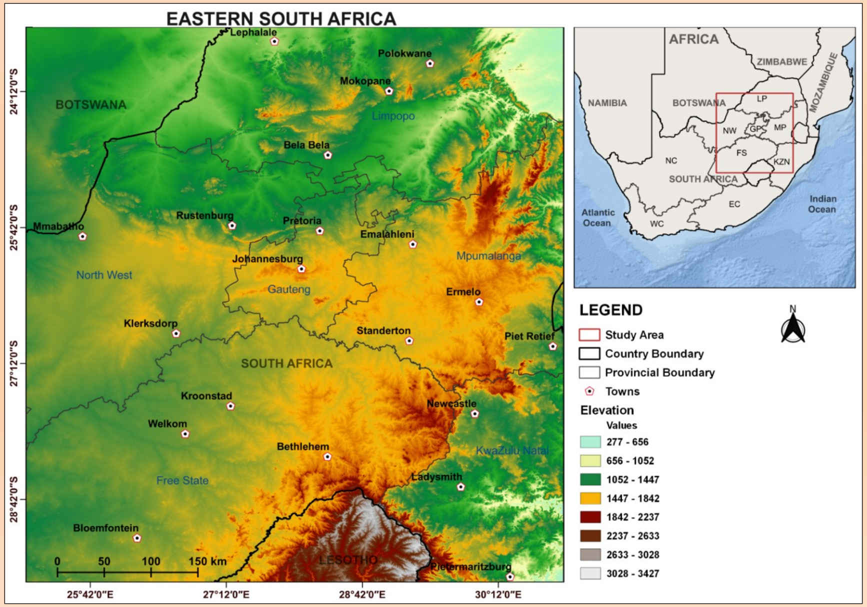
(Georgiadi and Groisman, 2022)

Simulation of South Africa streamflows over natural and urban landscapes using the TerM land surface model

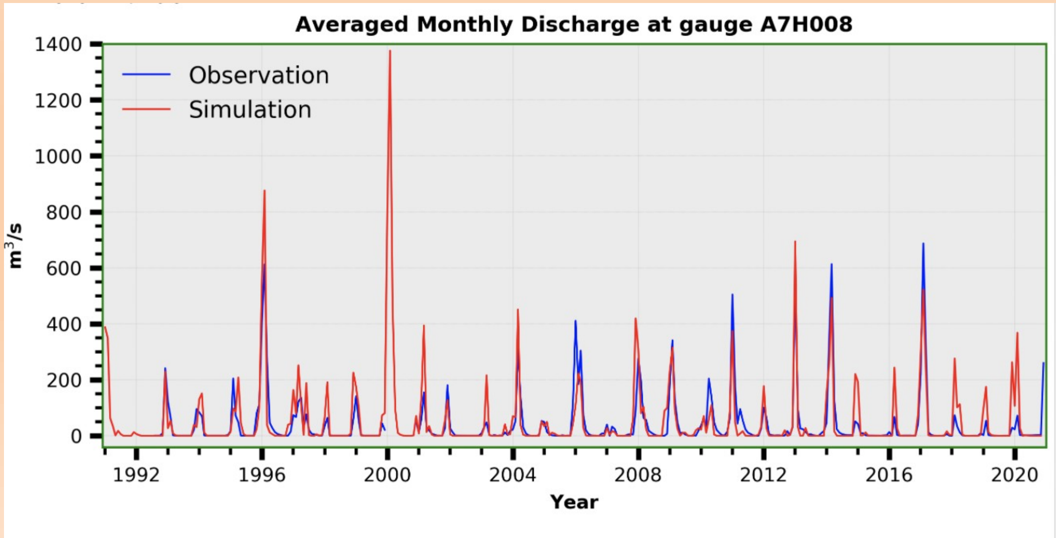
- **Objectives:**
- Evaluation of the TerM performance for South Africa rivers.
- Sensitivity of the TerM to spatial resolution.
- To investigate climate change impacts on future river flows in South Africa.
- **To develop an urban scheme** within the TerM and simulate urban effects on hydrological processes in Gauteng.

Modifications of the TerM runoff scheme:

- dependence of soil infiltration capacity on rainfall duration,
- sub-grid heterogeneity of infiltration capacity,
- evaporation from river surface,
- reduced response of stomatal resistance to soil moisture deficit.

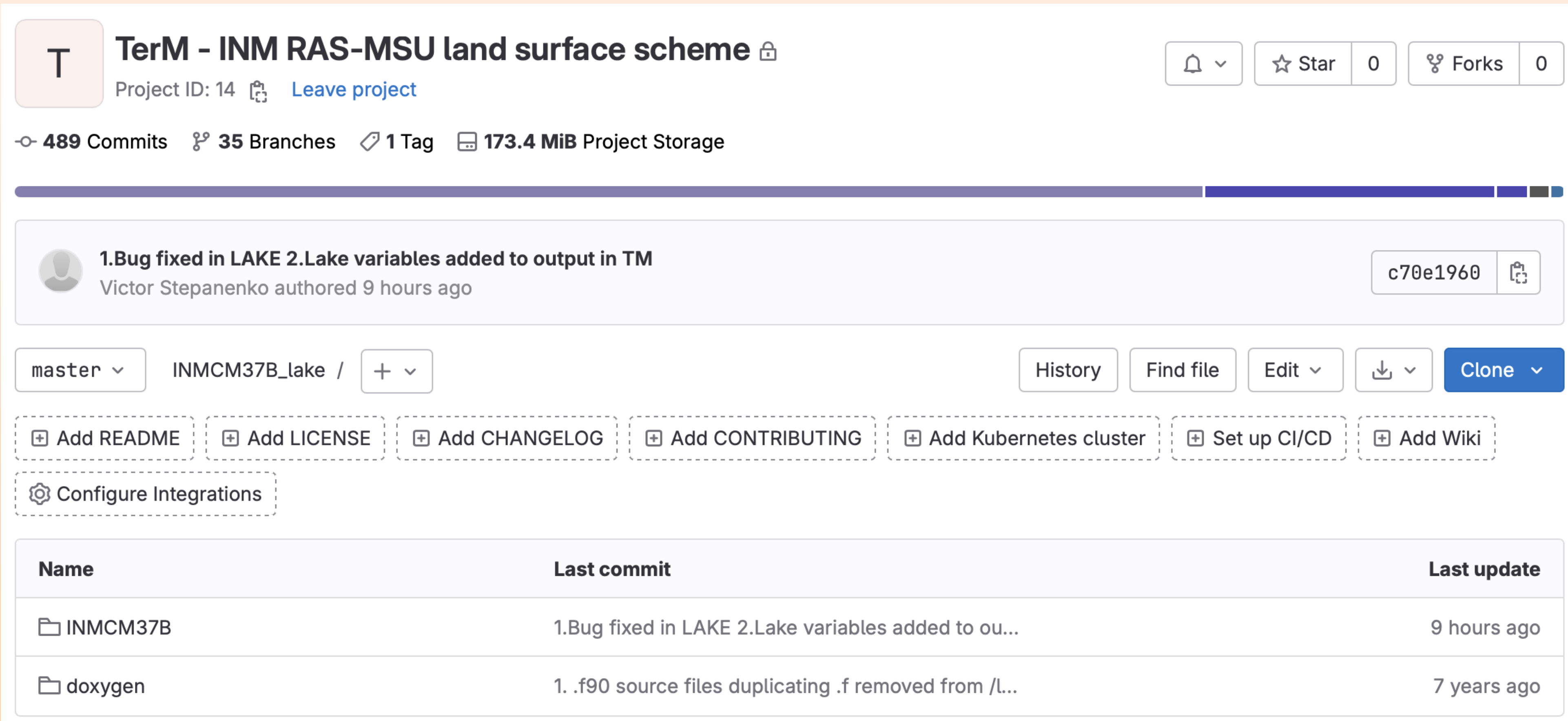


TerM model performance for the Limpopo river



The TerM model repo

http://tesla.parallel.ru/vbogomolov/INMCM37B_lake



Validation and extension of the model for the BRICS use cases

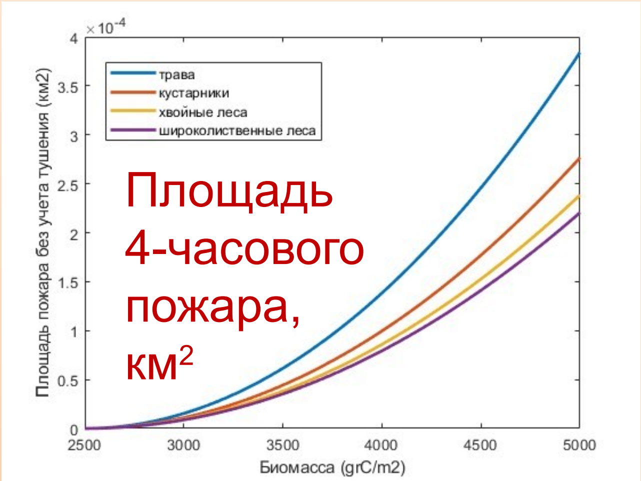
Code / Use case	Use case Russia	Use case South Africa	Use case Brazil	Use case India	Use case China
TerM (water sector)	Config, open code, input/ouput/validation data, tech.docs, and user guides …	In progress …			
TerM (carbon sector)	In progress …				
…					

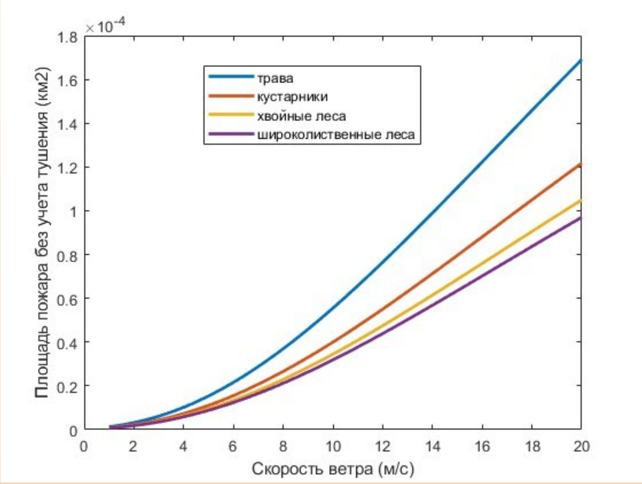

Thank you! ☺

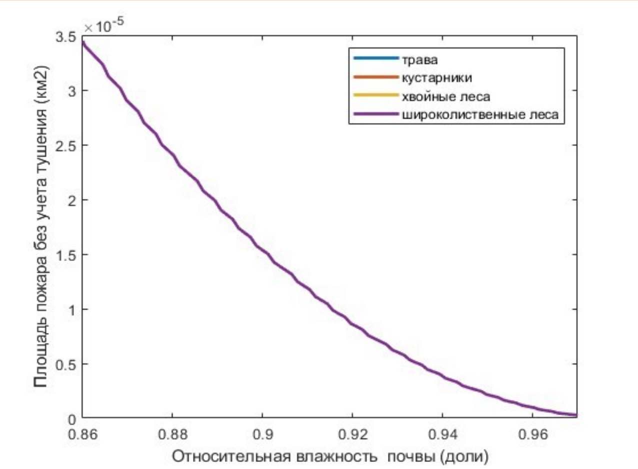
Текущие работы
(до конца 2023 г.)

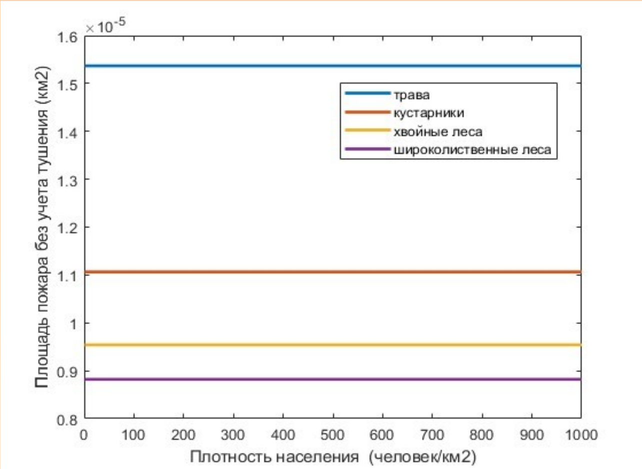
- Модель пожаров (из модели CLM)
- Модель торфонакопления в болотах ИФА РАН
- Рабочий прототип модели азотного цикла

Эксперименты на чувствительность автономной модели пожаров к входным переменным



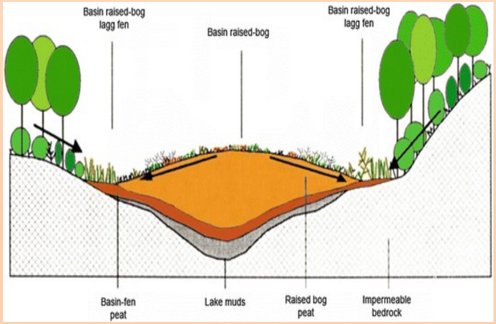


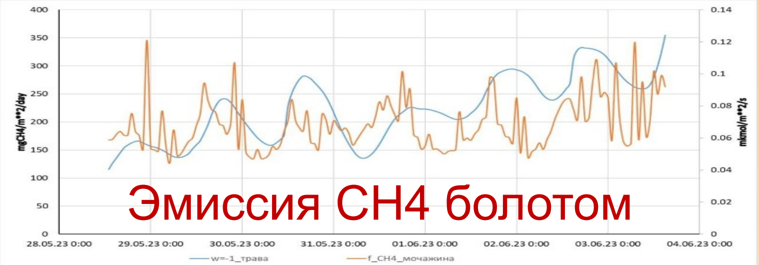




- Использование вырубок по данным Рослесхоза в углеродной модели
- Введение площадей управляемых и резервных лесов

Василий Богомолов и соавт. «Моделирование тепломассообмена и потоков метана в болотных экосистемах». Секция Консорциума 4.





Спасибо за внимание!

Разработка модели TerM
для прогноза климата и углеродного цикла

Сценарные расчёты изменений **глобального климата с учётом обратных связей** в системе атмосфера-океан-криосфера-суша

- **Одноколоночные, региональные, глобальные расчёты**
- **Возможность использования высокого разрешения**
- **Возможность массовых расчётов для тестирования новых блоков/параметризаций**

Модель Земной системы ИВМ РАН

Модель деятельного слоя суши TerM

Передача новых блоков/параметризаций (2024 г. и 2030 г.)

Модель деятельного слоя суши TerM

Реанализ, данные метеонаблюдений или климатических моделей

МГУ НИВЦ

Обеспечение внешних данных о подстилающей поверхности

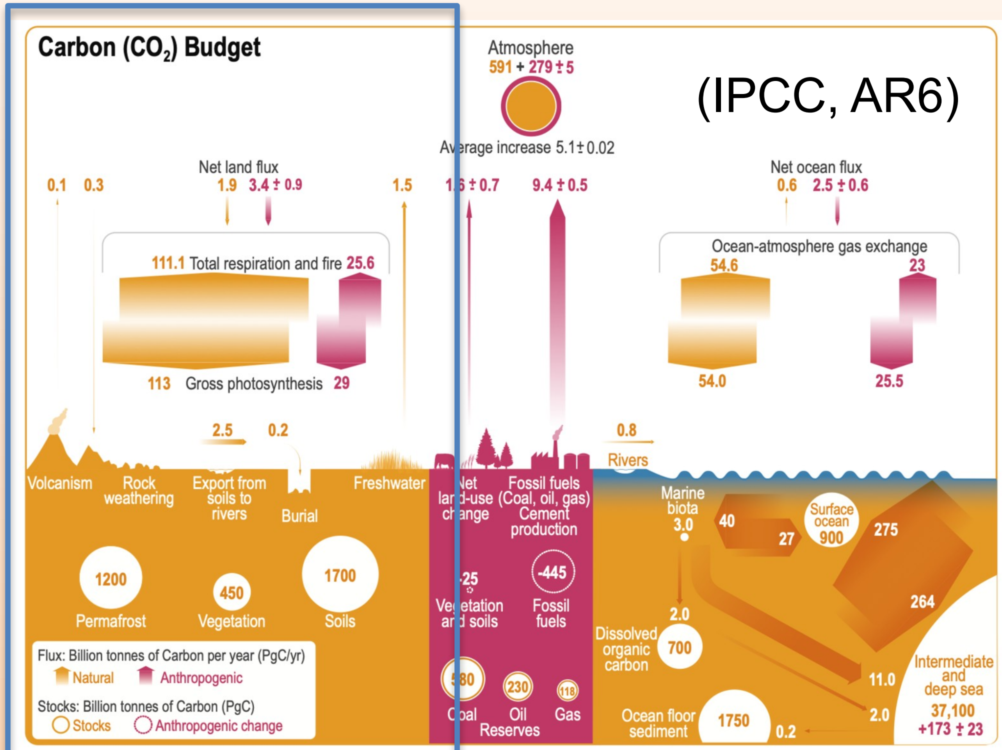
Задача — обеспечение блока деятельного слоя суши и модели климата данными о параметрах подстилающей поверхности.

Технические требования:

- **Интерполяция на произвольную регулярную широтно-долготную сетку с сохранением инвариантов**
- **Скалярные поля-1:** площадь типов поверхности — типы растительности, водоёмы, урбанизированные территории, ледники, маска «океан-суша». …
- **Скалярные поля-2:** параметры растительности (листовой индекс и пр.), параметры почвы, глубина водоёмов, гипсометрические кривые, уклон речного дна, тип городской поверхности, …
- **Векторное поле**: поле направлений речного стока
- **Согласование скалярных и векторных полей на целевой сетке**

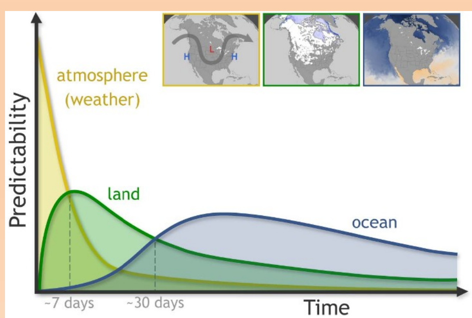
Main foci for land surface processes

- Carbon cycle (impacts on climate change)

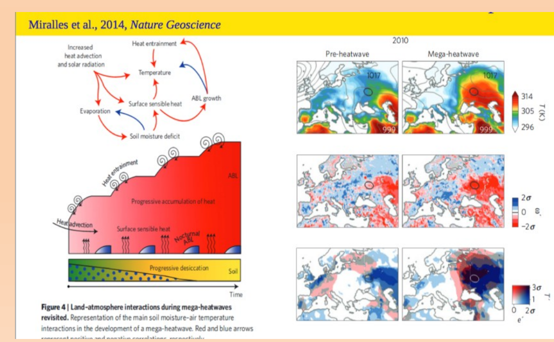


- Water cycle (extreme weather, floods, droughts, …)

Soil moisture is a source of atmosheric predictabily beyond the inner atmospheric predictability timescale



Soil-atmospheric boundary layer feedbacks during heatwaves



Photosynthesis scheme: interpolation between limiting cases (CLM, TerM, JULES, CABLE)

(Clark et al., 2011)

- GPP rate is a minimum of rates of three photosynthesis stages:

Michaelis-Menthen expr.

Rubisco-limitation

$$W_c = \begin{cases} V_{cmax}\left(\dfrac{c_i - \Gamma}{c_i + K_c(1 + O_a/K_o)}\right) & \text{for } C_3 \text{ plants} \\ V_{cmax} & \text{for } C_4 \text{ plants} \end{cases}$$

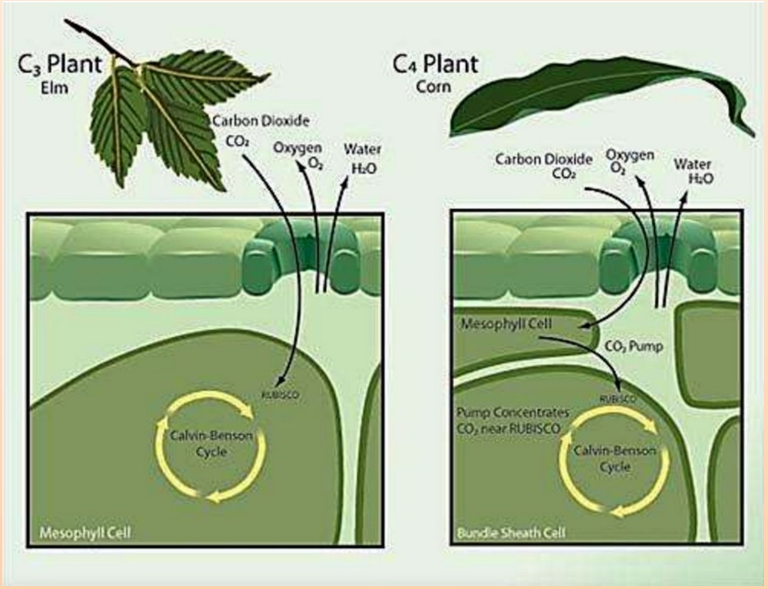
radiation

light-limitation

$$W_l = \begin{cases} \alpha(1-\omega)\, I_{par}\left(\dfrac{c_i - \Gamma}{c_i + 2\Gamma}\right) & \text{for } C_3 \text{ plants} \\ \alpha(1-\omega)\, I_{par} & \text{for } C_4 \text{ plants} \end{cases}$$

transport of photosynthetic products

$$W_e = \begin{cases} 0.5\, V_{cmax} & \text{for } C_3 \text{ plants} \\ 2 \times 10^4\, V_{cmax}\, \dfrac{c_i}{P_*} & \text{for } C_4 \text{ plants} \end{cases}$$



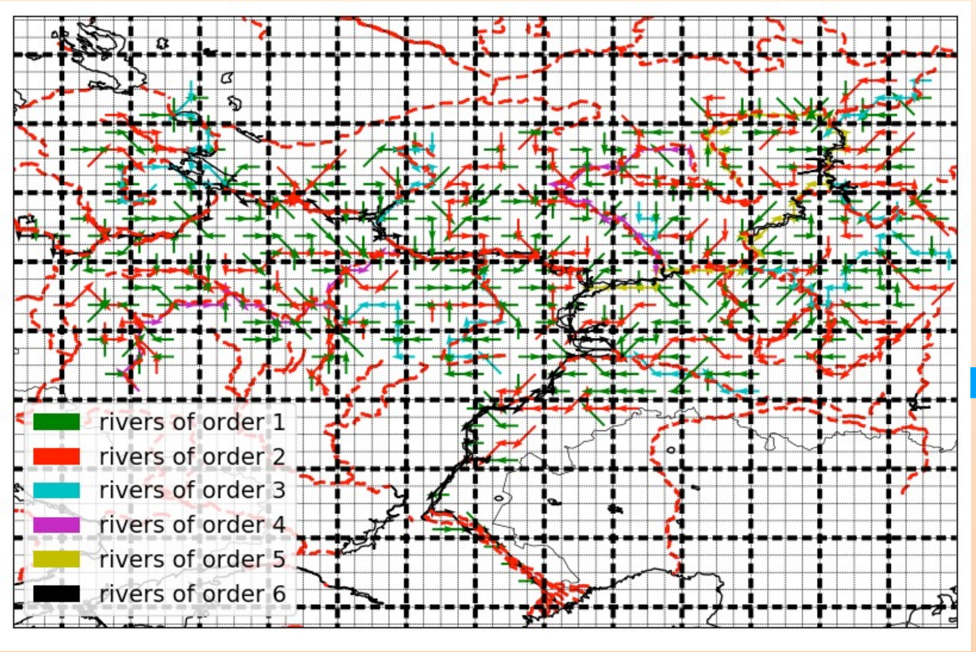
$$= min\,(\quad,\quad,\quad)$$

or smoothed modification of min functio

$$\beta_1 W_p^2 - W_p(W_c + W_l) + W_c W_l = 0$$
$$\beta_2 W^2 - W(W_p + W_e) + W_p W_e = 0$$

Module for greenhouse gas emissions and uptake by reservoirs

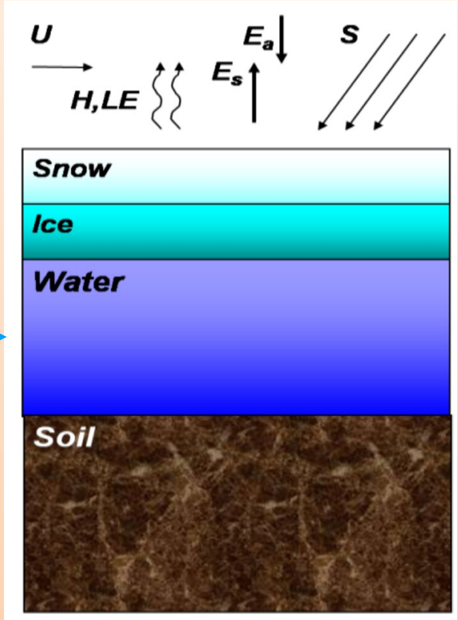
Model of thermohydrodynamics of rivers



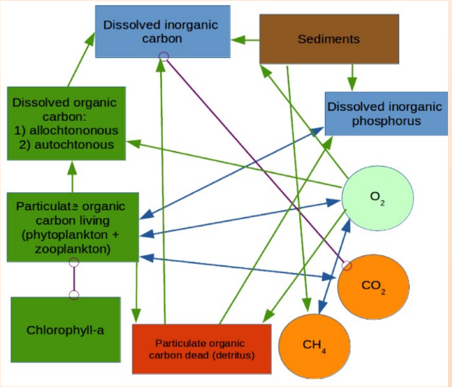
- Diffusion wave model for fluid dynamics
- Simulation of thermal regime

Lake model LAKE3.x

Thermo-, and hydrodynamics

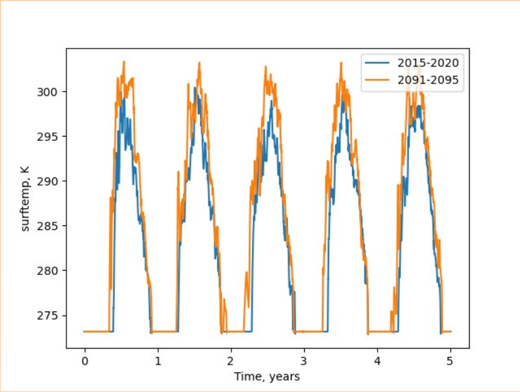


Biogeochemistry

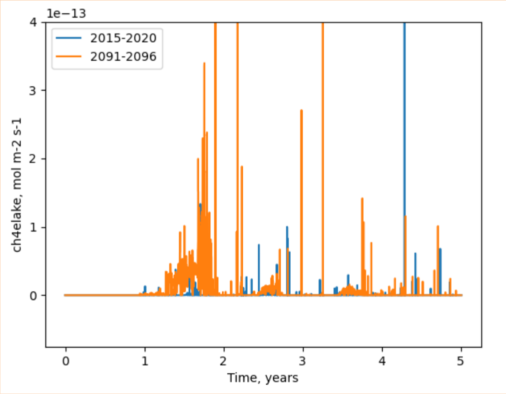


- O_2, CH_4, CO_2 — концентрации и потоки
- Продукция, дыхание, разложение …

Surface temperature of Kuibyshev reservoir



CH4 flux, Kuibyshev reservoir



Model calibration

SPOTPY

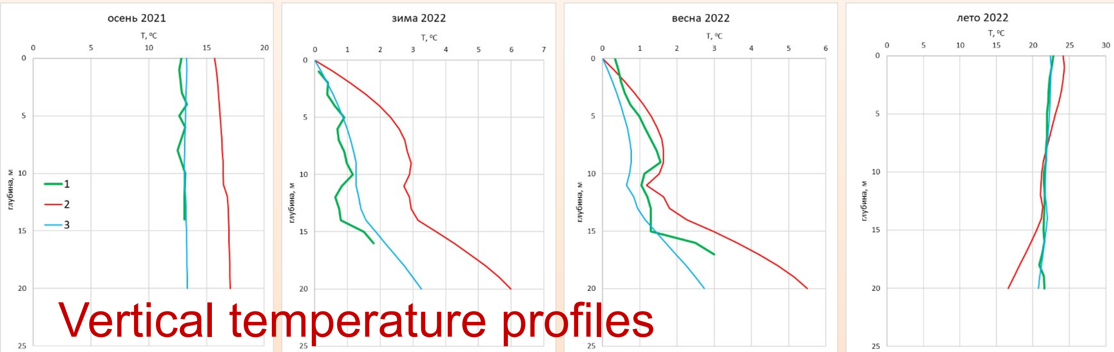
(Optimization methods Monte-Carlo, ROPE, …)

LAKE

CH4 measurement data collected at Russian reservoirs

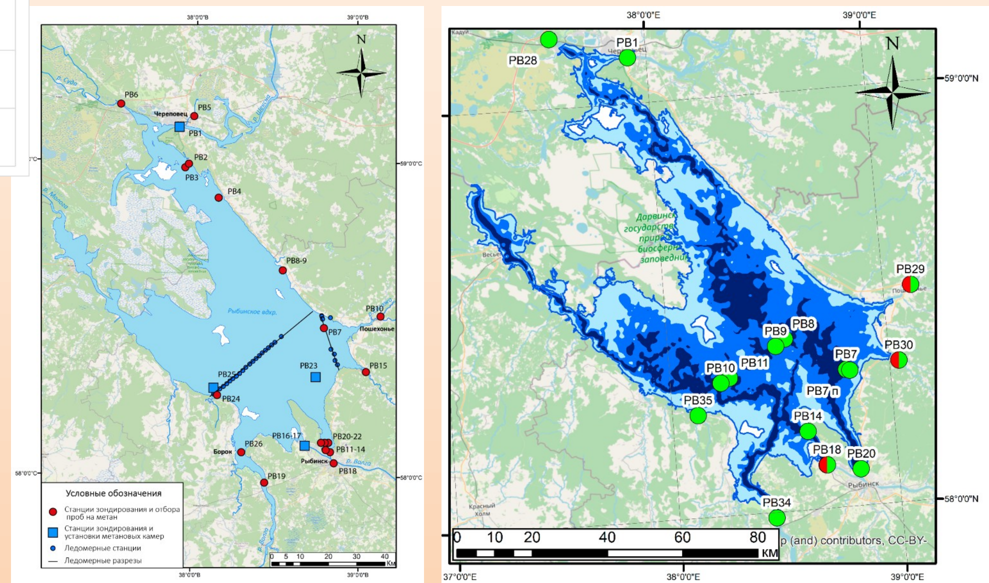
Calibration of the reservoir model

<u>Stages:</u> 1. Optimization of temperature 2. Oxygen optimization 3.Methane optimization

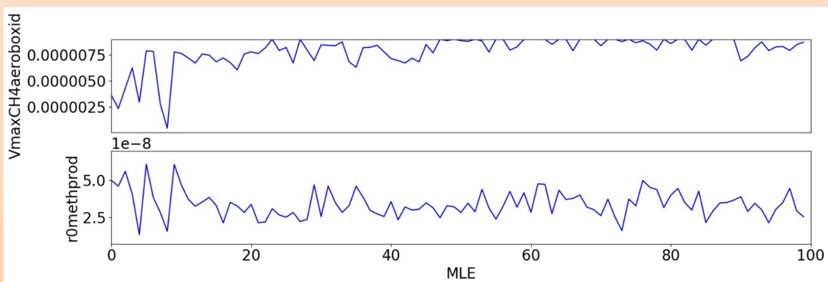


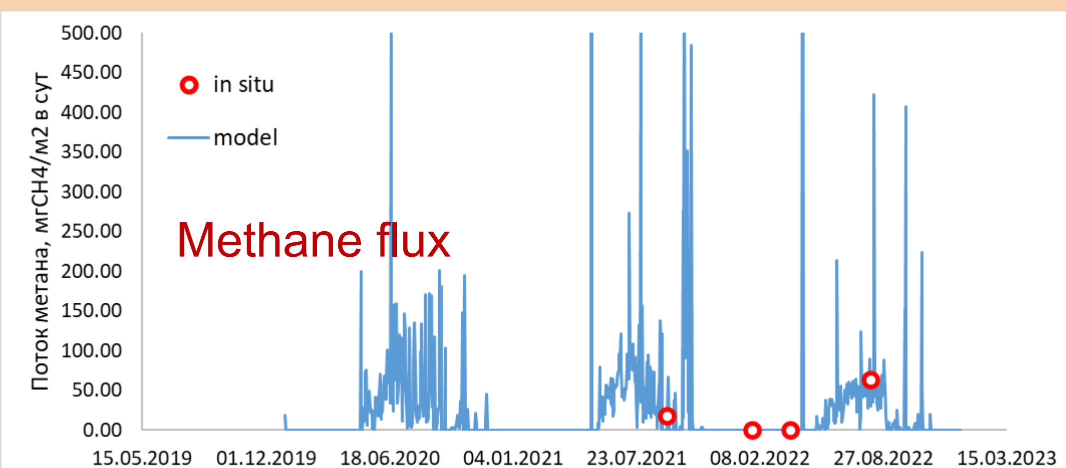
1 - observations ---
2 - before calibration and selection of the correct forcing ---
3 - after calibration ---

Examples of distribution of field observation stations in different seasons on the Rybinsk Reservoir (Russia)



Tracking parameters calibration in methane model





Calibration based on data from 9 reservoirs (2024)