INM RAS-MSU land surface scheme development: physical and computational aspects

V.M.Stepanenko[1], A.I.Medvedev[1], V.Yu.Bogomolov[3,1], A.V.Debolskiy[1,4], E.A.Marchuk[5,1], E.D.Drozdov[1], V.N.Lykosov[2,1]

[1] Lomonosov Moscow State University
[2] G.I.Marchuk Institute of Numerical Mathematics RAS
[3] Insititute of Monitoring of Climatic and Ecological Systems RAS
[4] A.M.Obukhov Insitute of Atmospheric Physics RAS
[5] Hydrometeorological Center of Russia

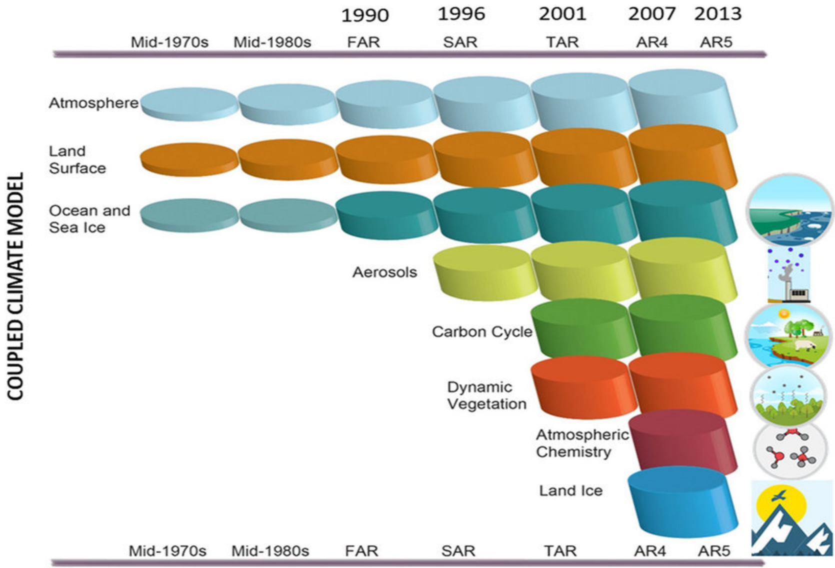
Weather and Climate Modelling Special Interest Group (SIG) seminar

Birchwood Conference Center, Kempton Park, South Africa, 1 December 2019

The plan of talk

- Earth system models, the role of land surface
- Heat and moisture fluxes from the surface
- Heat and moisture transfer in soil
- Snowpack
- Parameterization of lakes
- Parameterization of rivers

Evolution of climate models and Earth system models



The Earth system model by INM RAS

Developed by Russian consortium lead by Institute of Numerical Mathematics

Model includes:

- Atmospheric dynamics
- Soil and vegetation
- Oceanic dynamics, including sea ice
- Carbon cycle
- Aerosol module
- Some electric phenomena

Participated in: CMIP3(2003-2004), CMIP5 (2010-2011)

Participates: CMIP6 (2017-2018)

Current versions:

- INM-CM4-8: Atmosphere 2x1.5 degrees, 30 levels, the uppermost level at 10hPa. Ocean: 1x0.5 degrees, 40 levels
- INM-CM5-0: Atmosphere 2x1.5 degrees, 73 levels, the uppermost level at 0.2 hPa. Ocean: 0.5x0.25 degrees, 40 levels.
- INM-CM5-H: Atmosphere 2x1.5 degrees, 73 levels, the uppermost level at 0.2 hPa. Ocean: 0.5x0.25 degrees, 40 levels.

The role of soil moisture in heat waves

Miralles et al., 2014, *Nature Geoscience*

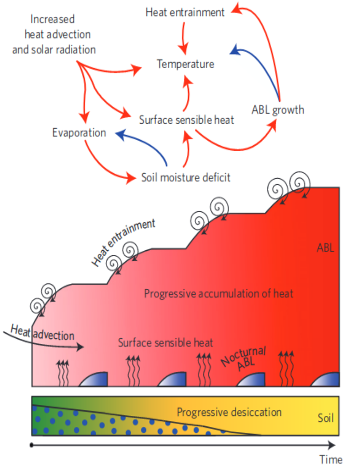
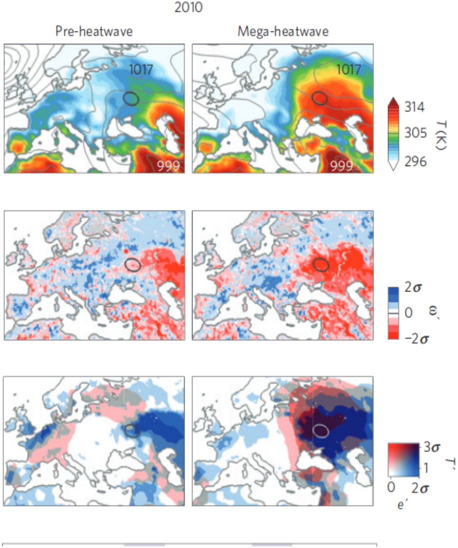
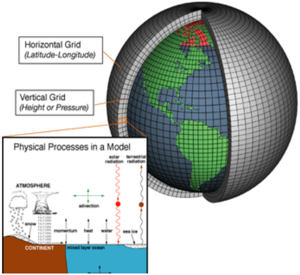


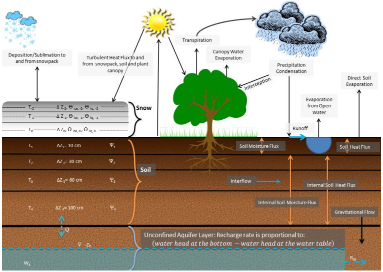
Figure 4 | Land-atmosphere interactions during mega-heatwaves revisited. Representation of the main soil moisture-air temperature interactions in the development of a mega-heatwave. Red and blue arrows represent positive and negative correlations, respectively.



INM RAS-MSU land surface model

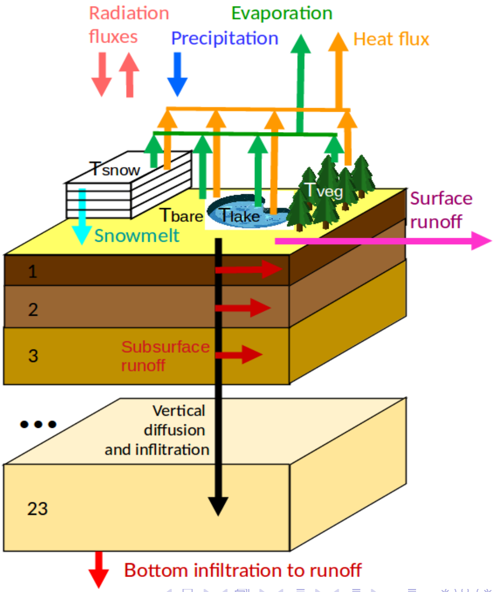
- heat and moisture transfer in soil (23 levels)
- snow pack model (4 уровня)
- effects of vegetation of energy flues through albedo, roughness, stomatal resistance
- carbon cycle parameterizations (photosynthesis, CH_4 emission by wetlands)
- lake model (21 levels)
- river network model (vertically averaged)





Surface tiles and energy balance

- 4 tiles in each cell: bare soil, vegetation, snow and inland waters
- in winter, snow tile occupies entire cell
- each tile has its own surface temperature $T_{s,i}$, all sharing single soil column
- Sensible and latent heat fluxes are aggregated from individual fluxes over each tile, $(\overline{H}, L\overline{E}) = \sum_{i=1}^{4} \alpha_i (H_i, LE_i)$
- Momentum and scalar roughness lengths are taken as single values in each cell



Similarity theory for the surface layer

Surface fluxes are computed from flux-profile relationships:

$$u(z) = \frac{u_*}{\kappa}\left[\ln\left(\frac{z}{z_{0u}}\right) - \Psi_u\left(\frac{z}{L}\right) + \Psi_u\left(\frac{z_{0u}}{L}\right)\right],$$
$$\theta(z) - \theta_s = \frac{\theta_*}{\kappa}\left[\ln\left(\frac{z}{z_{0\theta}}\right) - \Psi_\theta\left(\frac{z}{L}\right) + \Psi_\theta\left(\frac{z_{0\theta}}{L}\right)\right],$$
$$q(z) - q_s = \frac{q_*}{\kappa}\left[\ln\left(\frac{z}{z_{0\theta}}\right) - \Psi_\theta\left(\frac{z}{L}\right) + \Psi_\theta\left(\frac{z_{0\theta}}{L}\right)\right].$$

Scales: L (length), u_* (velocity), θ_* (temperature), q_* (humidity).

Input parameters:

- surface temp. and hum.
- temp., hum. and wind in surface layer

Key uncertainties:

- universal functions Ψ
- roughness lengths: z_{0u}, $z_{0\theta}$

A.S.Monin A.M.Obukhov

Soil and moisture transfer in soil

The **temperature** T is caused by thermal conductance and phase changes:

$$\rho c \frac{\partial T}{\partial t} = \frac{\partial}{\partial z} \lambda_T \frac{\partial T}{\partial z} + \rho_d \left(L_i F_i - L_v F_v \right)$$

The **liquid water** W is transported following potential gradient (Moene and van Dam, 2014; Гельфан, 2007) (Darci law):

$$\frac{\partial W}{\partial t} = -\frac{\partial}{\partial z} \left[-\gamma \left(\frac{\partial \Psi}{\partial z} + 1 \right) \right] + F = \frac{\partial}{\partial z} \left(\lambda_W \frac{\partial W}{\partial z} + \lambda_I \frac{\partial I}{\partial z} \right) + \frac{\partial \gamma}{\partial z} + F$$

The system is closed by semi-empirical links of **water matric potential** Ψ and hydraulic conductivity γ to soil moisture W and ice content I.

Water vapor diffusion V:

$$\frac{\partial V}{\partial t} = \frac{\partial}{\partial z} \lambda_V \frac{\partial V}{\partial z} + F_v$$

Phas changes for **ice** mass fraction I:

$$\frac{\partial I}{\partial t} = F_i$$

Surface water infiltration and runoff

Vertical water flux q at the soil surface:

$$q = P - E - q_s,$$

where P – precipitation, E – evaporation, q_s – surface runoff.

$$q_s = q_{sat} + q_{unsat},$$

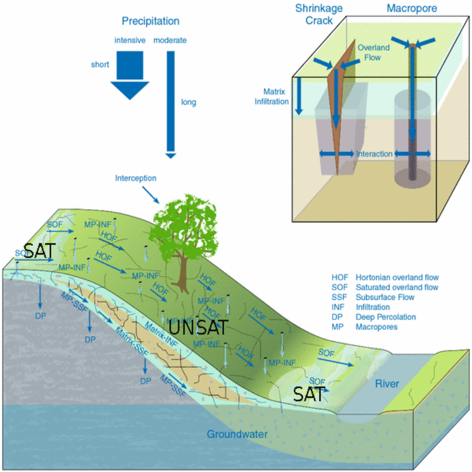
$$q_{sat} = F_{sat} P$$

runoff from saturated soil,

$$q_{unsat} = (1 - F_{sat}) \max(0, P - q_{max})$$

runoff from unsaturated soil

F_{sat} – fraction of cell with saturated soil, q_{max} – maximal surface infiltration flux.



Snowpack model

Snow temperature T equation

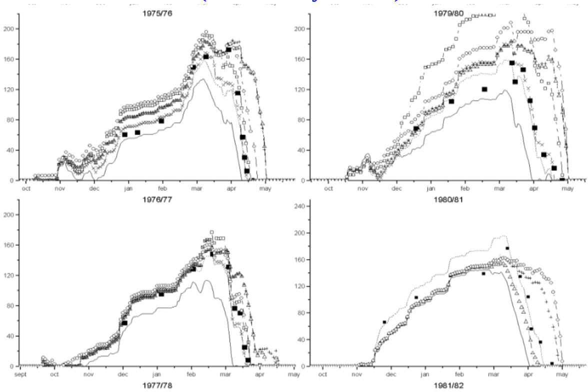
$$c_{sn}\rho_{sn}\frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\lambda_{sn}\frac{\partial T}{\partial z} + \rho_{sn}L_{fr}F_{fr} - \frac{\partial S}{\partial z}$$

Liquid water content in snow W equation:

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

Not taking into account percolation and refreezing of melted water inside snow layer leads to later (by weeks) diseppearance of snow layer.

Simulated snow water-equivalent depth using different descriptions of liquid water dynamics (Machulskaya, 2001)



Example of lake effects: cloudiness over the Ladoga Lake

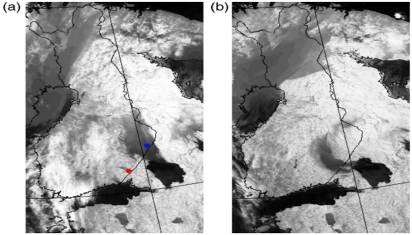
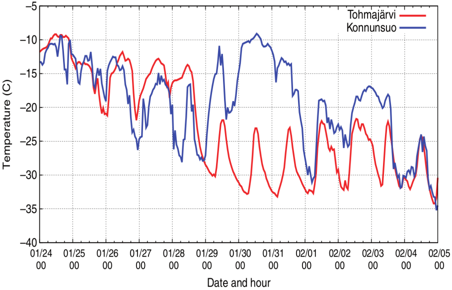


Fig. 3. NOAA AVHRR thermal IR images over Finland and Karelia on 28 January 06 UTC (a) and on 29 January 00 UTC (b) 2012. The low-level cloud cover, shown with dark-grey shades, spreads first northward (a) and later westward (b) from Lake Ladoga. In the single-channel images, the cloud over Lake Ladoga cannot be distinguished from the dark water surfaces. The stations

Ice-free lake evaporates, and resulting stratiform clouds are advected to Finland.

Cloudiness increases the surface net radiation, and 2m-temperature rises by 15-20°C



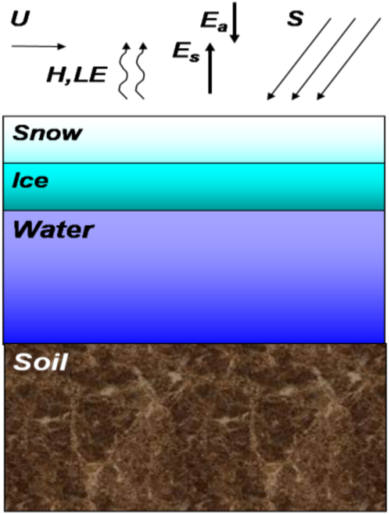
Eerola et al. Tellus A 2014, 66, 23929,
http://dx.doi.org/10.3402/tellusa.v66.23929

1D lake model framework

1D equations result from boundary-layer approximation

- 1D heat and momentum equations
- $k - \epsilon$ turbulence closure
- Monin-Obukhov similarity for surface fluxes
- Beer-Lambert law for shortwave radiation attenuation
- Momentum flux partitioning between wave development and currents (Stepanenko et al., 2014)
- Soil heat and moisture transfer including phase transitions
- Multilayer snow and ice models

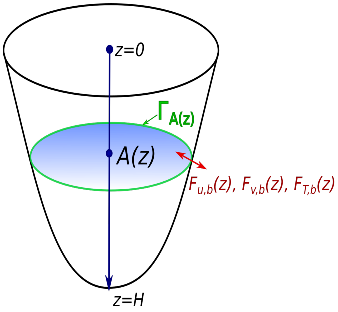
1D concept does not suffice the greenhouse gas modeling task, as it does not take into account differences between CH_4 & CO_2 emissions at deep and shallow sediments



1DV equations for enclosed water basin

Momentum component or a scalar f is governed by equation:

$$c\frac{\partial f}{\partial t} = -c\frac{\partial u_i f}{\partial x_i} - \frac{\partial F_i}{\partial x_i} + R_f(f, ...),$$



Averaging over horizontal cross-section $A(z)$:

$$\overline{f} = \frac{1}{A(z)}\int_{A(z)} f dxdy.$$

Assuming small bottom slopes, $\overline{w} = 0$, yields:

$$c\frac{\partial \overline{f}}{\partial t} = \underbrace{-\frac{c}{A}\int_{\Gamma_{A(z)}} f(\mathbf{u_h}\cdot\mathbf{n})dl}_{\text{Inlets and outlets}} + \underbrace{\frac{1}{A}\frac{\partial}{\partial z}\left(Ak_f\frac{\partial \overline{f}}{\partial z}\right)}_{\text{Vertical diffusion}} \cdot$$

$$\underbrace{-\frac{1}{A}\frac{\partial A\overline{F_{nz}}}{\partial z}}_{\text{Div. of non-diffusive flux}} \underbrace{+\frac{1}{A}\frac{dA}{dz}[F_{nz,b}(z) + F_{tz,b}(z)]}_{\text{Bottom fluxes}} \underbrace{+R_f(\overline{f}, ...)}_{\text{Sources}}.$$

Here, F_{tz} – vert. turb., F_{nz} – vert. non-turb. flux of f.

Validation of LAKE model using site-level data

Lake	Thermodynamics	CH_4	CO_2	Reference
Vendyurskoe (Russia)	+	–	–	(Stepanenko, 2007)
Shuchi (Russia)	–	+	–	(Stepanenko et al., 2010)
Kossenblatter (Germany)	+	–	–	(Stepanenko et al., 2013)
Valkea-Kotinen (Finland)	+	–	–	(Stepanenko et al., 2014)
Kuivajärvi (Finland)	+	+	+	(Heiskanen et al., 2014; Stepanenko et al., 2016)
Kivu (Kongo)	+	–	–	(Thiery et al., 2014)
Seida (Russian)	+	+	–	(Guseva et al., 2016)
Bolshoi Vilyui (Russia)	+	–	–	(Stepanenko et al., 2018)
Uvs (Mongolia)	+	–	–	(Stepanenko et al., 2019)
Alqueva (Portugal)	+	–	+	–
Suva (Japan)	+	+	–	–
Mozhayskoe reserv. (Russia)	+	+	–	–

Inter-Sectoral Impact Model Intercomparison Project

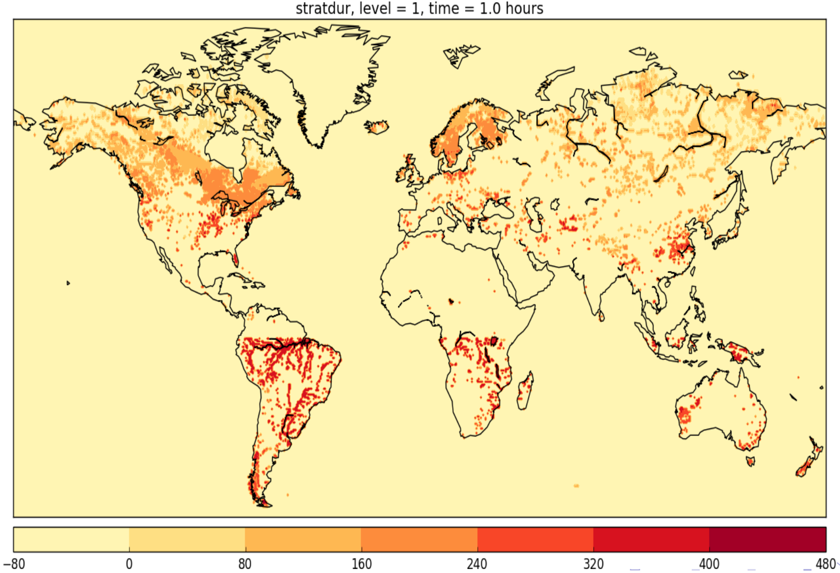
ISIMIP-Lake simulations at Lomonosov-2 supercomputer

- $0.5° \times 0.5°$ lat-lon grid
- lake area database (Choulga et al., 2014)
- lake depth database (Choulga et al., 2014)
- forcing from climate models: GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, MIROC5
- climate scenarios: picontrol, historical, rcp26, rcp60, rcp85 (1661-2099)
- 100 cores per single run
- simulation of 10 years: 5-6 wall-clock hours
- in total $\sim$ 170 000 proc*hours
- input and output data 120 Tb

Lomonosov-2 supercomputer
(4.9 Pflops peak performance)

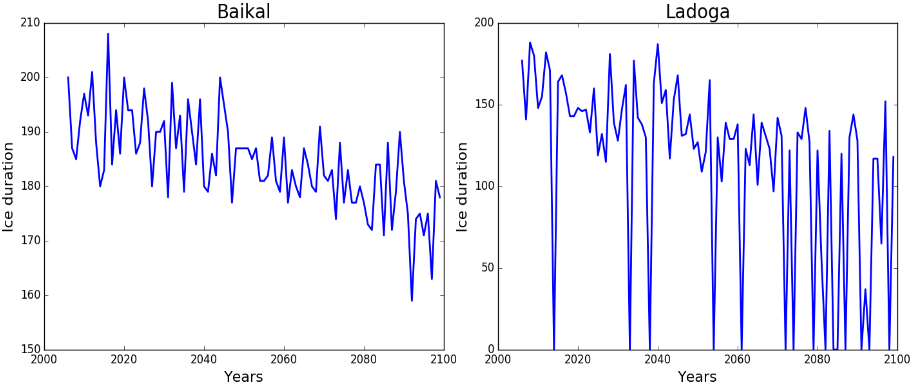
Summer stratification duration in lakes

ISIMIP-Lake simulations, 1670



The change of ice duration on lakes

RCP8.5 climate scenario

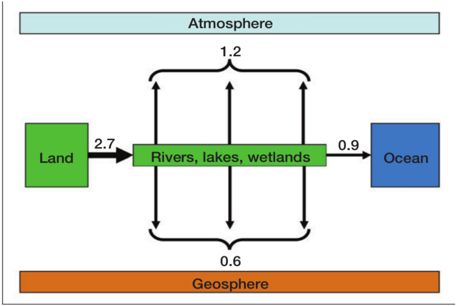


Lake ice changes simulated for XXI century:

- steady decrease of ice duration
- increase of frequency of ice-free winters

The role of rivers in the Earth system

- river runoff affects thermohaline circulation
- river runoff is the most precisely measured component of the land water balance
- rivers are considered as an substantial player in land carbon cycle
- the level and ice regimes of rivers can become the one of the most in-demand output of ESMs



All values are in Pg C yr^{-1} (Battin et al., 2009)

H51E-1538: A global data analysis of sediment and organic carbon yield for modeling riverine biogeochemistry

Conference Paper · December 2016

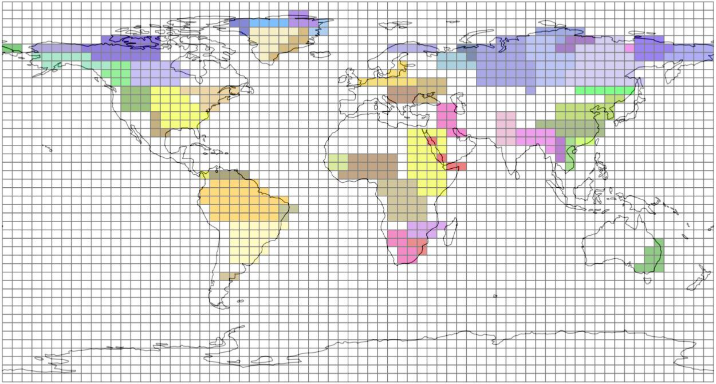
Conference: AGU 2016 Fall Meeting, At San Francisco

1st Zeli Tan
19.17 · Pacific Northwest National Labo...
2nd L. Ruby Leung
45.3 · Pacific Northwest National Labor...
3rd Hongyi Li
30.18 · Montana State University

Abstract

Although soil erosion could have significant impacts on the global carbon cycle and the well being of aquatic and marine ecosystems, few earth system models include process-based representations of the transport of sediments and particulate organic carbon (POC) from land to rivers and streams. Two critical challenges hindering the development of such representations are scale and heterogeneity. More specifically,...

River basins in INM RAS Earth system model ($2^\circ \times 1.5^\circ$)



- 54 major basins
- surface and subsurface runoff are integrated over basins and instantaneously ”added” to oceans in salinity equation
- no river tile in the surface energy balance calculations

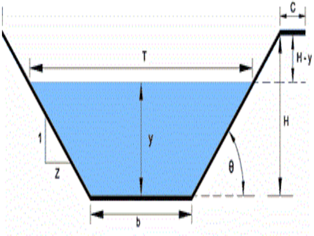
Diffusive wave equations and numerical scheme

Neglecting acceleration provides diffusive wave equations:

$$\frac{\partial S}{\partial t} + \frac{\partial([U_0 + U_*]S)}{\partial x} = E_r + \frac{\partial}{\partial x} k_S \frac{\partial S}{\partial x},$$

$$U_0 = \frac{1}{n} R^{2/3} s^{1/2},$$

$$R = f(S).$$



If S is trapezium, then R is a root of quadratic equation.

Second order MacCormack finite-difference scheme:

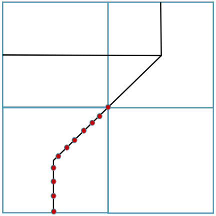
$$\overline{S_i^{j+1}} = S_i^j - \frac{\Delta t}{\Delta x}\left[(SU)_{i+1}^j - (SU)_i^j\right] + \Delta t E_{r,i}^j,$$

$$S_i^{j+1} = \frac{1}{2}\left(\overline{S_i^{j+1}} + S_i^j\right) - \frac{\Delta t}{2\Delta x}\left[\overline{(SU)_i^{j+1}} - \overline{(SU)_{i-1}^{j+1}}\right] + \frac{\Delta t}{2} E_{r,i}^j.$$

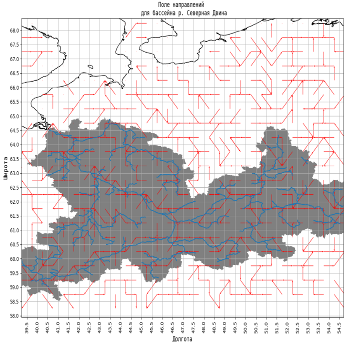
The scheme is conservative in volume. Needs smoothing (Yu and Duan, 2014).

Implementation of rivers in INM RAS-MSU land model

- River data structures are implemented as river-wise.
- Pointer arrays along each river are linked to cell-wise 2D arrays of land surface model
- Such data structures allow for implementation for any 1D river solver



Severnaya Dvina basin

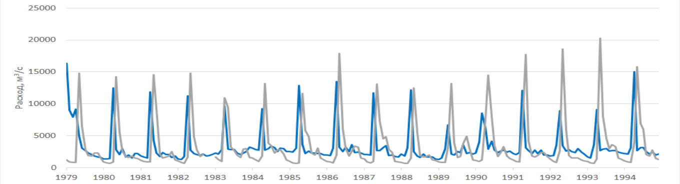


Offline implementation in INM RAS-MSU land surface scheme:

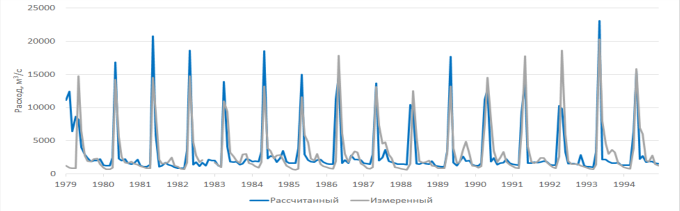
- 0.5 deg. $\times$ 0.5 deg. grid
- ISIMIP dataset on flow directions and slopes
- rivers are coupled to surface and subsurface ru
- ERA-Interim atmospheric forcing

Simulation of water discharge of Severnaya Dvina

Severnaya Dvina discharge in an old runoff scheme



Severnaya Dvina discharge when including: (i) liquid water percolation in snow (ii) river dynamics



Temporal shift of maximal spring water discharge:

- including river dynamics **+1 week**
- including liquid water percolation in snowpack **+1 week**

River temperature simulation

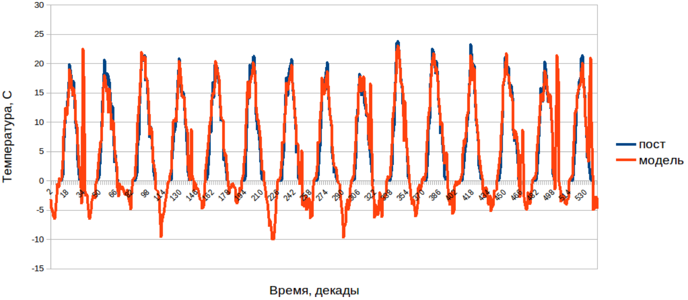
(Stepanenko et al., 2019)

Water temperature equation:

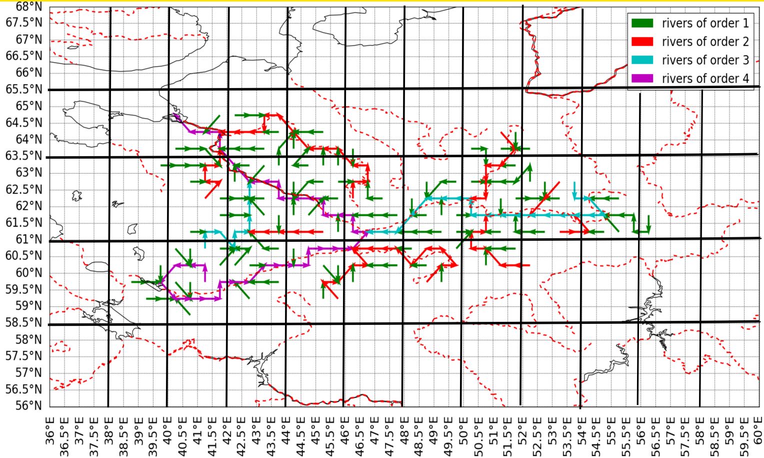
$$\frac{\partial(ST)}{\partial t} + \frac{\partial(U_0 ST)}{\partial x} = h_{tr} u_{tr} T_{tr} + b_s F,$$

where tr denotes values transported by inlets and groundwater, b_s – river surface width, F – the sum of radiation and heat fluxes at the surface. Includes:

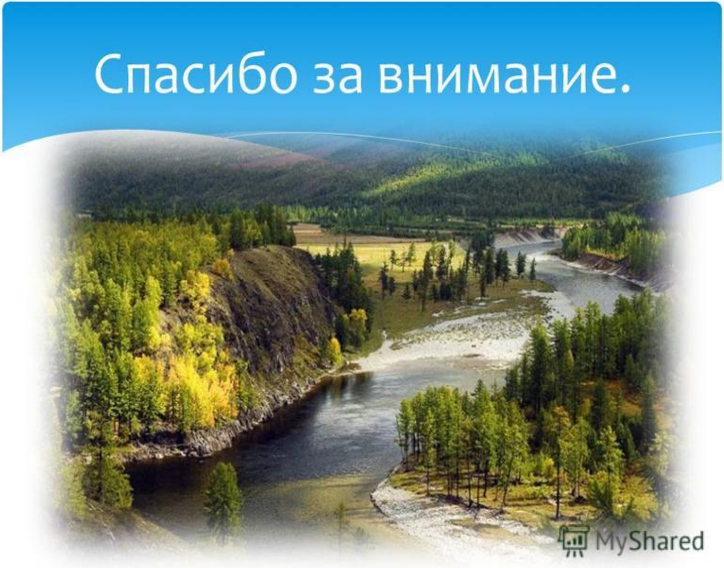
Decadal water temperature measured at Ust-Pinega station (near Severnaya Dvina mouth)



River network model needs new parallelization scheme



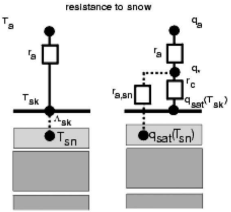
- top level of parallelizm – river basins
- second level – parallel processing or rivers (rivers of the same order are processed independently)
- data exchange between MPI-processes, computing rivers, with MPI-processes of an atmospheric model

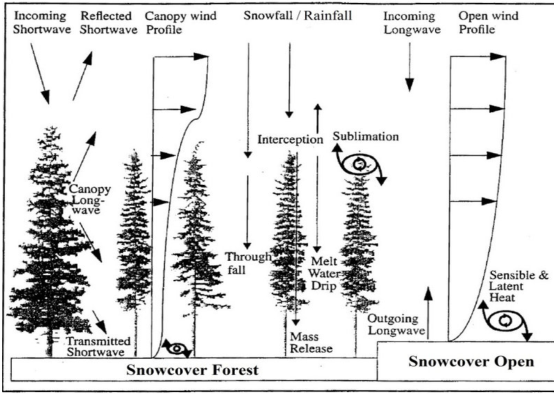

Спасибо за внимание.
MyShared

Снежный покров в высокой растительности

Два резервуара снега:

- снег, перехваченный кронами – интегральная (”балковая”) модель, максимальный объём $\sim$ LAI
- снег на почве – многослойная модель с модификацией расчёта турбулентных потоков





Storck, 2000; Garvelmann, 2014

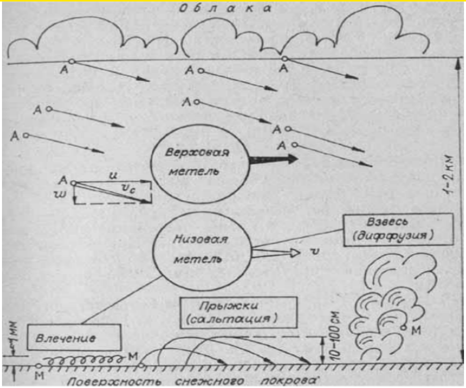
Модификация радиационного баланса в лесу описывается упрощёнными схемами

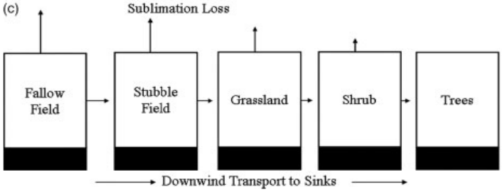
$$LE = \frac{q_a - q_{sat}(T_{sk})}{r_a + r_c\left(1 + \frac{r_a}{r_{a,sn}}\right)} + \frac{q_a - q_{sat}(T_{sn})}{r_a + r_{a,sn}\left(1 + \frac{r_a}{r_c}\right)}$$

(IFS documentation, 2015)

Эффекты метелевого переноса

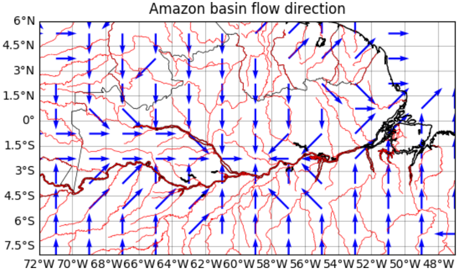
- эффект устойчивой стратификации приземного слоя за счёт наличия частиц (Barenlatt and Golitsyn, 1974; Wamser and Lykossov, 1995)
- трение затраты кинетической энергии потока на отрыв частиц
- испарение метелевых частиц (включено в модель ISBA; Le Moigne et al., 2018)
- перенос снега с возвышенностей в понижения (Fan and Pomeroy, 2009; MacDondald, 2009)
- перенос снега с открытых поверхностей на залесённые (Fan and Pomeroy, 2009; MacDondald, 2009)



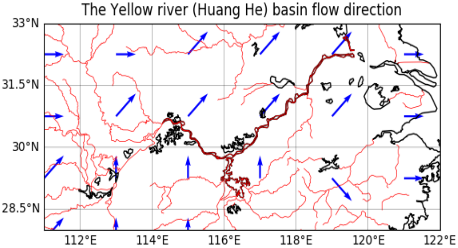


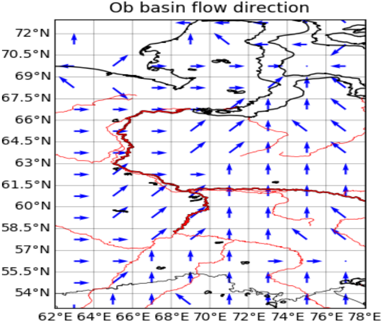
Fang and Pomeroy, 2009

Направления речного стока по методу макс. градиента



At the coarse grid maximal gradient method causes erronous flow directions

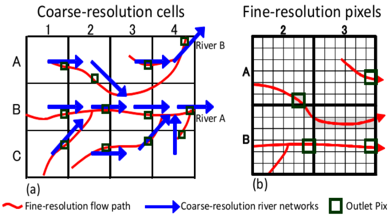




Базы данных по направлению речного стока

Exemplified by (Yamazaki et al., 2009)

Stream upscaling



External parameters for river model:

- flow direction
- riverbed slope
- parameters of cross-section geometry

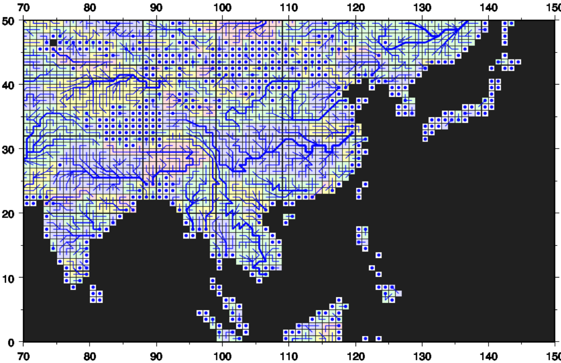


Fig. 6. Illustration of the Monsoon Asian part of an upscaled river network map at the resolution of 1 degree. Bold blue lines indicate riv channels of the upscaled river network map, and circles indicate cells representing a river mouth.

Шероховатость поверхности

- Momentum roughness is usually given as constant for each individual surface type (bare soil, high vegetation, low evegtation, snow, etc.):

- In INM RAS model, scalar roughness is calculated, irrespective of a surface type as:

$$\ln\left(\frac{z_0}{z_{0\theta}}\right) = \begin{cases} -2.43, & \mathrm{Re}_{z0} \le 0.111, \\ 0.83\ln(\mathrm{Re}) - 0.6, & 0.111 < \mathrm{Re}_{z0} \le 16.3, \\ 0.49\mathrm{Re}_{z0}^{0.45}, & \mathrm{Re}_{z0} > 16.3, \end{cases}$$

where the Reynolds roughness number is

$$\mathrm{Re}_{z0} = \frac{u_* z_0}{\nu} \tag{1}$$

- For water surface, Zilitinkevich et al. (2001) provide:

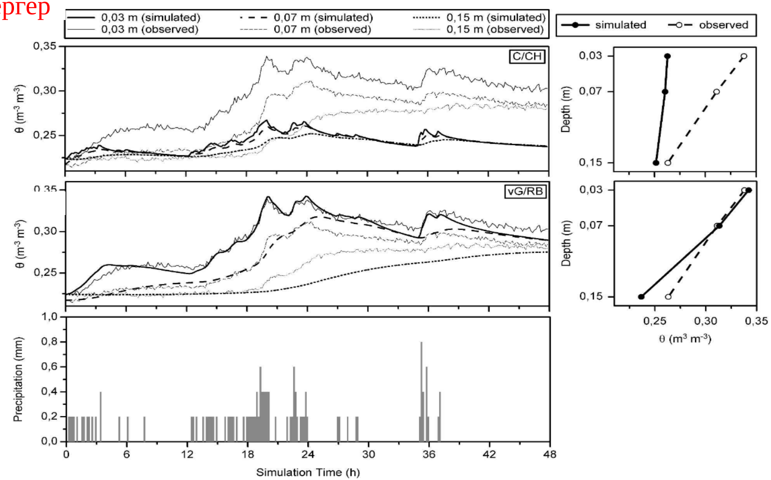
$$\frac{1}{\kappa_T}\ln\left(\frac{z_0}{z_{0\theta}}\right) = \begin{cases} -2, & \mathrm{Re}_{z0} \le 0.1, \\ 4.0\mathrm{Re}_{z0}^{1/2} - 4.2, & \mathrm{Re}_{z0} \ge 0.1 \end{cases}$$

Эффект различной гидравл. характеристики почвы

Braun and Schädler, 2005, *J. Appl. Meteorol.*

Клапп-Хорнбергер

ван Генухтен



Использование потенциала влаги ван Генухтена существенно улучшает качество моделирования влажности почвы по сравнению с моделью Клаппа-Хорнбергера.

Горизонтальный обмен влагой между ячейками

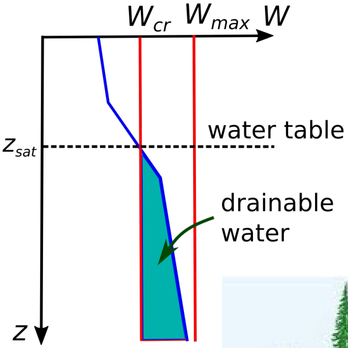
Clark et al., 2015

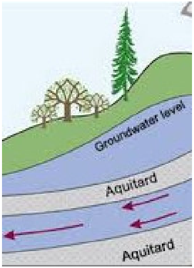
Расход грунтовой воды q_l вниз по склону (закон Дарси) на каждой глубине ниже уровня грунтовых вод z_{sat}:

$$q_{out} = \mathrm{tg}(\beta)\gamma\frac{W - W_{cr}}{W_{max} - W_{cr}},$$

β - средний угол наклона рельефа в ячейке,
γ – гидравлическая проводимость.

- Сток q_{out} добавляется в уравнение переноса влаги.
- Величина q_{out} может добавляться в соседнюю нижележащую ячейку *или* в речной сток.





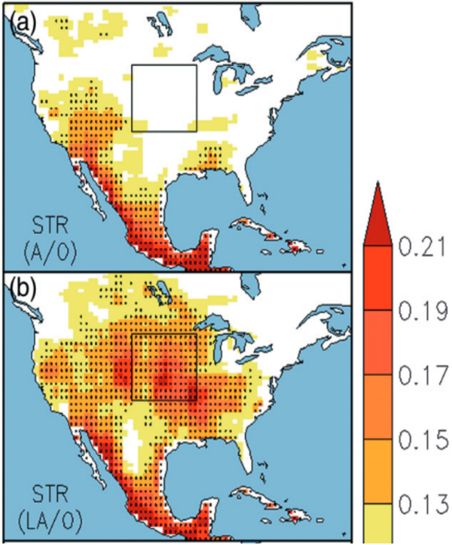
Роль почвы в предсказуемости состояния атмосферы

Мера предсказуемости состояния атмосферы на масштабах времени 40-60 дней:

- со случайным распределением влажности в начальный момент (сверху)
- с реалистичным распределением влажности в начальный момент (снизу)

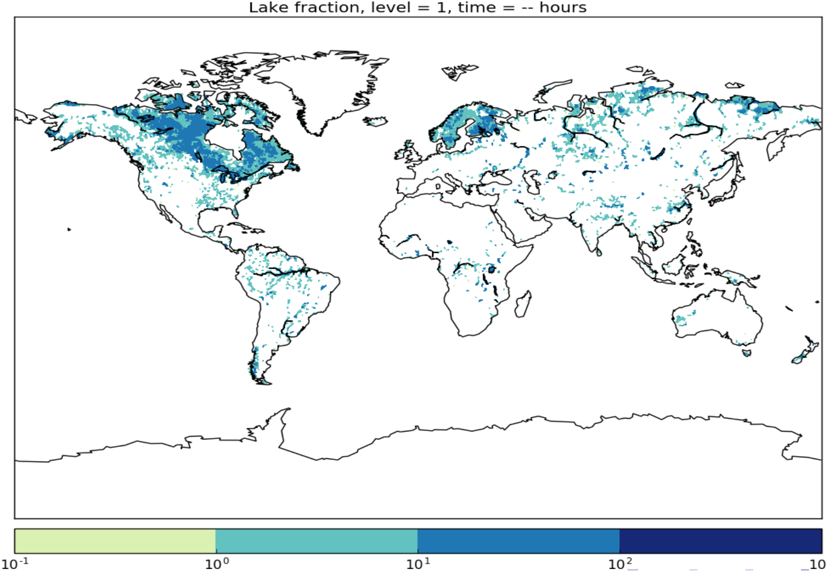
Conil et al., 2007, *Clim. Dyn.*:
*"While in the tropics SST anomalies clearly maintain a potentially predictable variability throughout the annual cycle, in the mid-latitudes the SST forced variability is only dominant in winter and **soil mositure** plays a leading role in summer."*

Guo et al., 2012, *J. Climate*



Доля площади суши, занятая озёрами

База данных Choulga et al., 2014



Потенциал почвенной влаги

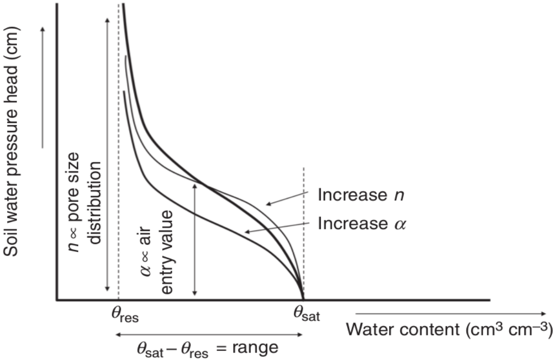
Clapp and Hornberger (1978):

$$\Psi = \Psi_{sat} \left(\frac{\theta}{\theta_s} \right)^{-b}$$

van Genuchten (1980):

$$\Psi = -\frac{\left(S^{-1/m} - 1\right)^{1/n}}{\alpha_g},$$

$$S = \frac{\theta - \theta_{res}}{\theta_{sat} - \theta_{res}}$$



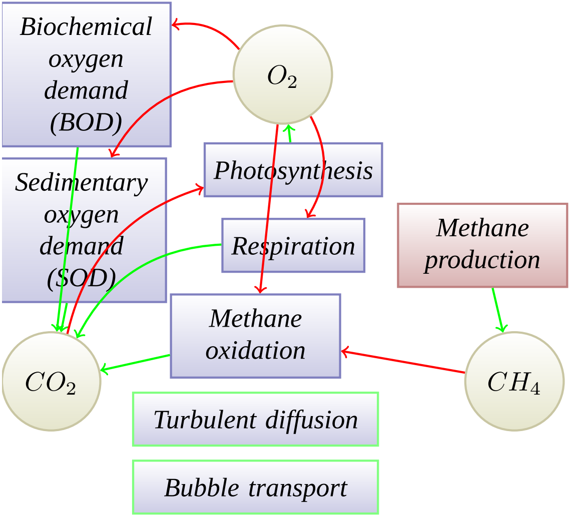
Преимущества vG1980
(Кучмент и др., 1983; Глобус, 1987; Гельфан, 2007):

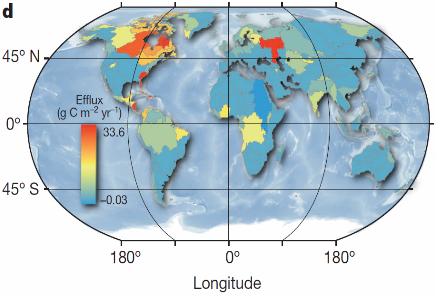
- лучшее соответствие качественным особенностям эмпирических зависимостей
- параметры α_g и n имеют физический смысл
- в физике почв по параметрам α_g и n накоплен большой массив данных

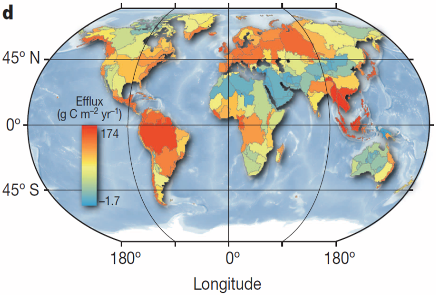
Biogeochemical processes in the model

- Photosynthesis, respiration and BOD are empirical functions of temperature and Chl-a (Stefan and Fang, 1994)
- Oxygen uptake by sediments (SOD) is controlled by O_2 concentration and temperature (Walker and Snodrgass, 1986)
- Methane production $\propto P_0 q_{10}^{T-T_0}$, P_0 is calibrated (Stepanenko et al., 2011)
- Methane oxidation follows Michaelis-Menthen equation

Sinks and sources of gases in a lake



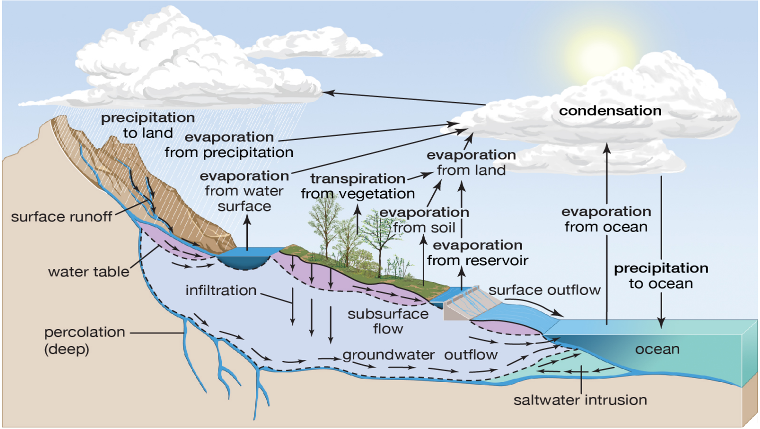




Lakes   Rivers

- global emission of CO_2 by freshwaters is 2.1 Pg C yr^{-1}
- lake emission is 0.3 Pg C yr^{-1}, river emissions is 1.8 Pg C yr^{-1}
- significant contribution of Volga hydropower reservoirs

Влагооборот в климатической системе



Water bodies occupy $\approx 1.8\%$ of land surface. Soil moisture is the key factor of surface evaporation and energy cycle. Soil moisture is the most variable component of land.