Soil Parameter Model Intercomparison Project (SP-MIP): Assessing the influence of soil parameters on the variability of Land Surface Models

Coordination

Lukas Gudmundsson (lukas.gudmundsson@env.ethz.ch)

Matthias Cuntz (Matthias.Cuntz@inra.fr)

Scientific Advisory Committee

Sonia I. Seneviratne, Dani Or, Harry Vereecken, Anne Verhoef, Tomislav Hengl, Aaron Boone

Background and Purpose

Land surface models (LSMs) simulate the movement of water and energy through the plant-soil system, amongst other things. There is currently a considerable spread among different land surface models regarding their outputs of water-balance variables such as evapotranspiration, soil moisture or runoff. It is not clear, however, whether this spread is related to model structure (i.e. equations used to describe the underlying processes) or model parameters (i.e. physical properties of the Earth system such as soil porosity).

To approach the question to which degree LSM spread is related to model parameters, controlled multi-model experiments were proposed at the GEWEX-SoilWat workshop held in Leipzig on June 28-30, 2016.

Two steps are necessary to produce soil model parameters such as soil porosity or saturated hydraulic conductivity in each LSM: 1. an input soil map is needed, which may contain soil classes or soil texture information, and 2. the required model parameters must be calculated from the information given by the soil map, for example with look-up tables, given soil classes in the soil map, or via the use of pedotransfer functions given soil textures in the soil map. SP-MIP aims at quantifying the differences between LSM model results that stem from either of the two preparation steps for soil parameters.

There is an intermediate step in the preparation of LSM input data that is not treated within SP-MIP, which is the aggregation of the soil map information or the soil parameters onto the model resolution, instead, all models are run at the same 0.5° resolution with soil information provided through SP-MIP.

Model Experiments

The experiments closely follow the LS3MIP protocol (van den Hurk *et al.* 2016). The models are run globally on 0.5° with GSWP3 forcing (Kim *et al.* in prep.) from 1980-2010 (see below) with the same soil properties throughout the soil column. There will be 4 Tier 1 experiments, leading to 7 model runs (see also Figure 1):

Experiment 1: ***Soil-hydraulic parameters provided by SP-MIP***

Models are run using soil hydraulic parameters that are provided by SP-MIP (Table 2). The *purpose* of this experiment is to establish a baseline of inter-model variability that comes from model components other than the soil parameters, in order to assess to which degree between-model variability can be reduced by enforcing common soil hydraulic properties.

Experiment 2: ***Soil-hydraulic parameters derived from common soil textural properties***

Each modelling group runs their model using relevant soil hydraulic parameters derived based on global maps of soil textural properties provided by SP-MIP (Table 3). The soil hydraulic parameters should be derived using the lookup tables or pedotransfer functions that are commonly used for each individual model. The *purpose* of this experiment is to quantify to which degree between-model variability is related to differences in transferring soil texture information to soil hydraulic properties.

***Experiment 3:* Reference run with all models in their status quo**

All models are run in their default settings**,** with the exception that all soil layers use the same soil properties through the whole soil column. The *purpose* of this experiment is to assess the variability that comes from both the original soil information used by the corresponding model and the model-specific transfer of these soil information into model parameters.

***Experiment 4a, b, c, d:* Spatial uniform soil parameters**

All models are run four times using spatially uniform soil-hydraulic parameters for the whole globe. For this, four "design soils" corresponding to loamy sand (experiment 4a), loam (experiment 4b), clay (experiment 4c), and silt (experiment 4d) (previously considered by Montzka *et al.* 2011) are provided by SP-MIP, together with the relevant soil hydraulic parameters. The *purpose* of this experiment is (i) to quantify the effect of spatial variability of soil parameters (or the lack thereof) on between-model-variability, (ii) to systematically assess the sensitivity of each model to soil hydraulic parameters and (iii) to investigate to which degree between grid-cell variability of key water- and energy balance outputs is controlled by soil-properties in the model world.

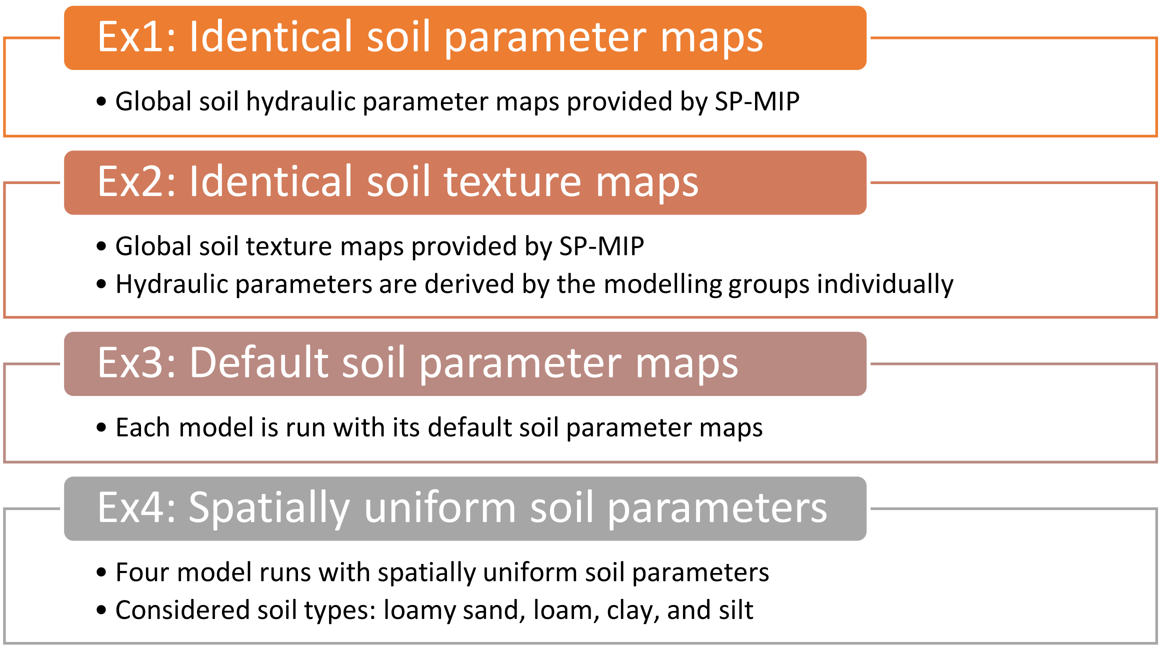

Figure 1: Overview on the four SP-MIP experiments.

Analysis of experiments

Differences between the model experiments will allow the assessment of the inter-model variability that is introduced by the different stages of preparing model parameters.

Comparison of Experiment 1 and Experiment 2 gives the variability between the models that is introduced by the usage of different pedotransfer procedures from soil information to model parameters. Comparison of Experiment 2 and Experiment 3 gives the variability that comes from different soil maps and aggregation schemes used for the different models.

Analysis of variance

An ANOVA-type of analysis is proposed to approach the question to which degree between model variability can be reduced by prescribing common soil hydraulic parameters or soil maps. The between model spread at each grid-cell will first be quantified for experiment 1 and subsequently compared to the spread of the remaining experiments. To assess the impact of soil hydraulic parameters on different dynamical aspects the analysis will be conducted on numerous time scales including daily, monthly and annual resolution as well as climatology's (long-term means).

First order sensitivity analysis

To quantify to which degree errors in soil-hydraulic parameters impact complex LSM simulations, a first-order sensitivity analysis will be conducted using the simulations of Experiment 4. In a first step, the spread among the model runs from Experiment 4 with spatially uniform soil parameters will be quantified at each grid-cell for each model individually. Subsequently, the spread will, for example, be stratified along climatic gradients, biomes or plant functional types (etc.) to determine under which conditions simulation results are most sensitive in soil-hydraulic parameters.

Timeline

10-12/2017	Conduct model simulations.
01/2018 onwards	Data analysis; preparation of publication.

Forcing Data

The GSWP3 forcing data (Kim *et al.* in prep) will be used to drive offline LSM simulations. The GSWP3 forcing data is available in NetCDF format and comprises the essential atmospheric variables for modelling land surface processes in 0.5° spatial and 3 h temporal resolutions (Table 1). Although the GSWP3 data is available from the early 20th century onwards, the SP-MIP simulations will be conducted for the period 1980-2010. An atmospheric CO_2 concentration of 380 ppm is assumed.

Note: There are issues with negative precipitation (snow) in some grid-cells of the current version (version 1) of the GSWP3 forcing data. Please set these values to zero.

Table 1: 3 h variables related to the energy and water cycles. The dimension (Dim.) column indicates T: time, Y: latitude, X: longitude.

Name	long_name (netCDF)	Unit	Dim.
LWdown	Downward Longwave Radiation	W m^{-2}	TYX
SWdown	Downward Shortwave Radiation	W m^{-2}	TYX
Tair	Near surface air temperature	K	TYX
PSurf	Surface Pressure	Pa	TYX
Qair	Near surface specific humidity	kg kg^{-1}	TYX
Wind	Near surface wind speed	m s^{-1}	TYX
Rainf	Rainfall	kg m^{-2} s^{-1}	TYX
Snowf	Snowfall	kg m^{-2} s^{-1}	TYX

Soil Properties

Soil parameters for Experiments 1 and soil textures for Experiment 2 at 0.5° resolution were prepared from dominant soil classes of the 0-5 cm layer of SoilGrids (Hengl *et al.* 2014) at 5 km resolution. Brooks and Corey parameters come from Table 2 of Clapp and Hornberger (1978), Mualem-van Genuchten parameters are ROSETTA class average hydraulic parameters (Schaap *et al.* 2001), and soil textures are from Table 2 of Cosby *et al.* (1984). Experiments 4 a-d use the USDA soil classes Loamy sand, Loam, Silt, and Clay, respectively, as in Montzka *et al.* (2011), using the same transfer functions for Brooks and Corey and Mualem-van Genuchten parameters as in Experiment 1.

Parameter filenames have the form: sp-mip_parameter_experiment_#number.nc

Files with information on soil parameters or soil-texture for Experiment 1, Experiment 2 as well as for Experiments 4a,b,c,d are available for **download** at

ftp://sp-mip:sp-mip2017@data.iac.ethz.ch in the sub-directory “soil_input_files”.

Note that no soil-parameter input files are provided for Experiment 2.

Soil Parameters (Experiment 1)

It is currently assumed that all models solve the Richards equation. Soil parameters and textures are provided and it should be assumed that they are uniform throughout the whole soil column.

For experiments 1 and 4, models have to set soil parameters given by SP-MIP (Table 2). For definitions see section "Soil Physics Background" below. Two mathematical descriptions of water retention curves are considered: Brooks and Corey (1964) and Mualem-van Genuchten (van Genuchten 1980). Models that use different forms have to derive their input parameters from the given parameters of Table 2 for the closest match of the soil water retention curves. The file name of the soil parameters for Experiment 1 is: sp-mip_parameter_experiment_1.nc.

Table 2: Soil parameters for the three considered water retention curves provided as input by SP-MIP for experiments 1 and 4a-d. For definitions see section on Soil Physics Background.

Name	long_name (netCDF)	Unit
he	air entry potential	m
mbc	Brooks-Corey m parameter = Clapp-Hornberger b	–
thetar	residual soil moisture	$m^3\ m^{-3}$
thetas	saturated soil moisture, porosity	$m^3\ m^{-3}$
ks	Hydraulic conductivity at saturation or at air entry	$m\ s^{-1}$
lambdac	Corey lambda parameter	–
alphavg	van Genuchten alpha parameter	m^{-1}
nvg	van Genuchten n parameter	–
mvg	van Genuchten m parameter	–
thetafcbc	Brooks-Corey field capacity	$m^3\ m^{-3}$
thetafcvg	van Genuchten field capacity	$m^3\ m^{-3}$
thetapwpbc	Brooks-Corey permanent wilting point	$m^3\ m^{-3}$
thetapwpvg	van Genuchten permanent wilting point	$m^3\ m^{-3}$

Soil Textural Properties (Experiment 2)

For experiment 2, soil textural properties are provided, given in Table 3. The modelling groups have to derive their required parameters in their own usual way from the given texture. The file name of the soil textures for Experiment 2 is: sp-mip_parameter_experiment_2.nc.

Table 3: Soil textural properties provided by SP-MIP for experiment 2.

Name	long_name (netCDF)	Unit
fclay	fraction of clay	–
fsilt	fraction of silt	–
fsand	fraction of sand	–
rhosoil	dry bulk density	$kg\ m^{-3}$
omsoil	organic matter content	$g(C)\ kg^{-1}$

Spatially Uniform Soil Parameters (Experiments 4a, b, c, d)

Global files with spatially uniform soil parameters (same as in Experiment 1) corresponding to loamy sand (experiment 4a), loam (experiment 4b), clay (experiment 4c), and silt (experiment 4d) (cf. Montzka *et al.* 2011) are provided with file names, for example, sp-mip_parameter_experiment_4a.nc, etc.

Spin-up

All modelling groups perform their standard spin-up procedure, making sure that reliable data are available from 1980 onwards.

Model Output Data

Primary target variables are hydrological fluxes and states, i.e. evapotranspiration, surface and sub-surface runoff, soil moisture in soil layers, and root zone soil moisture.

Secondary target variables are related to energy (sensible heat flux, surface and soil temperatures, etc.) but SP-MIP shall focus on hydrology. All target variables are listed in Table 4. Most target variables are a subset of those variables listed as p^* = 1 variables of Tables A1 and A2 of van den Hurk *et al.* (2016). Additionally, hydraulic and thermal conductivities as well as heat capacity in the soil are included.

Daily model outputs should be submitted as NetCDF files with variable names of Table 4. The NetCDF files will have a time (T), a latitude (X) and a longitude (Y) dimension for all variables and a level dimension for soil state variables (Z). All variables should be stored in the same file. To facilitate data handling, model outputs should be saved as annual chunks with the following file naming convention:

<model>_experiment_<number>_<yyyy>.nc

with

<model>: name of the model

<number>: the number of the experiments (i.e. 1, 2, 3 or 4a, 4b, 4c, 4d) see section on experiments

<yyyy>: the year, e.g. 1995

yielding for example: *cable_experiment_1_1995.nc* for experiment 1 (Soil-hydraulic parameters provided by SP-MIP) or *cable_experiment_4a_1995.nc* for experiment 4a (spatially uniform loamy sand).

Table 4 Daily variables related to the energy and water cycles. The dimension (Dim.) column indicates T: time, Y: latitude, X: longitude, and Z: soil or snow layers. "Direction" identifies the direction of positive numbers. Variable names/descriptions are made compatible with CMIP6 definitions (http://clipc-services.ceda.ac.uk/dreq/index.html) were possible.

Name	long_name (netCDF)	Unit	Unit (netCDF)	Direction	Dim.
Energy					
rss	Net Shortwave Surface Radiation	W m^{-2}	W m-2	downward	TYX
rls	Net Longwave Radiation	W m^{-2}	W m-2	downward	TYX
hfls	Surface Upward Latent Heat Flux	W m^{-2}	W m-2	upward	TYX
hfss	Surface Upward Sensible Heat Flux	W m^{-2}	W m-2	upward	TYX
hfdss	Downward Heat Flux in Soil	W m^{-2}		downward	TYX
ts	Surface Temperature	K	K	–	TYX
albsrfc	Surface Albedo	–	1	–	TYX
snc	Snow Area Fraction	–	1	–	TYX
tsl	Soil Temperature	K	K	-	TZYX
Water					
et	Total Evapotranspiration	kg m^{-2} s^{-1}	kg m-2 s-1	upward	TYX
ec	Interception Evaporation	kg m^{-2} s^{-1}	kg m-2 s-1	upward	TYX
tran	Transpiration	kg m^{-2} s^{-1}	kg m-2 s-1	upward	TYX
es	Bare Soil Evaporation	kg m^{-2} s^{-1}	kg m-2 s-1	upward	TYX
mrro	Runoff Flux	kg m^{-2} s^{-1}	kg m-2 s-1	out	TYX
mrrob	Subsurface Runoff Flux	kg m^{-2} s^{-1}	kg m-2 s-1	out	TYX
snm	Surface Snow Melt Flux	kg m^{-2} s^{-1}	kg m-2 s-1	solid to liquid	TYX
rzwc	Root Zone Soil Moisture	kg m^{-2}	kg m-2	–	TYX
cw	Total Canopy Water Storage	kg m^{-2}	kg m-2	–	TYX
snw	Surface Snow Amount	kg m^{-2}	kg m-2	–	TZYX
snwc	SWE intercepted by the vegetation	kg m^{-2}	kg m-2	–	TYX
mrlsl	Water Content per Unit Area of Soil Layers	kg m^{-2}	kg m-2	–	TZYX
tws	Terrestrial Water Storage	kg m^{-2}	kg m-2	–	TYX
mrfsofr	Mass Fraction of Frozen Water in Soil Moisture	–	1	–	TZYX
snd	Surface Snow Thickness	m	m	–	TYX
Additional					
preshead	Soil Pressure Head	kg m^{-2}	kg m-2	–	TZYX
hydcnd	Soil Hydraulic Conductivity	kg m^{-2} s^{-1}	kg m-2 s-1	–	TZYX
thrmcnd	Soil Thermal Conductivity	W m^{-1} K^{-1}	W m-1 K-1	–	TZYX
heatcap	Soil Thermal Capacity	J kg^{-1} K^{-1}	J kg-1 K-1	–	TZYX
lai	Leaf Area Index	-	1	-	TYX
omsoil	Organic Matter Content	g(C) kg^{-1}			TZYX

File Submissions

Data compression

To stay within reasonable disk space only variables listed in Table 4 should be included in the files that are submitted. In addition, all model output will be converted automatically to NetCDF-4 format and compressed 32-bit variables with the following CDO (https://code.mpimet.mpg.de/projects/cdo/) command:

cdo -f nc4 -z zip -b F32 copy netcdf.nc tmp.nc ; mv tmp.nc netcdf.nc

Model groups are encouraged to perform this transformation before uploading results.

File Upload

Model output files, corresponding to the format described above should be uploaded to

ftp://sp-mip-up:sp-mip2017.upload@data.iac.ethz.ch

Files can be removed up to 30 minutes after the upload is completed. Afterwards they cannot be deleted through ftp, to reduce the risk of accidently overwriting or removing files.

Soil Physics Background

The most commonly used soil water retention curves are Brooks and Corey (1964), Clapp and Hornberger (1978) and van Genuchten (1980). We use solely the Mualem (1976) model to link water retention curves with hydraulic conductivity.

Brooks and Corey (1964) defined:

$$h = h_e S^{-m} \tag{1}$$

$$S = \frac{\theta - \theta_r}{\theta_s - \theta_r} \tag{2}$$

$$K = K_s S^{\lambda} \tag{3}$$

with

- h pressure head (m)
- h_e air entry potential/head (m)
- S relative saturation
- m Brooks-Corey m parameter
- θ volumetric soil moisture ($m^3\ m^{-3}$)
- θ_r residual soil moisture ($m^3\ m^{-3}$)
- θ_s porosity = saturated soil moisture ($m^3\ m^{-3}$).
- K hydraulic conductivity ($m\ s^{-1}$)
- K_s hydraulic conductivity at air entry ($m\ s^{-1}$)
- λ Corey lambda parameter

  $\lambda = 5/2 + 2m$ (Mualem).

Clapp and Hornberger (1978) simplified Brooks and Corey (1964) by using

$$S = \frac{\theta}{\theta_s}, \tag{4}$$

all else equal but the Brooks-Corey *m* parameter is often called Clapp-Hornberger *b*.

van Genuchten (1980) defined:

$$h = \frac{1}{\alpha}\left(S^{-\frac{1}{m}} - 1\right)^{\frac{1}{n}} \tag{5}$$

$$S = \frac{\theta - \theta_r}{\theta_s - \theta_r} \tag{6}$$

$$K = K_s\sqrt{S}\left(1 - \left(1 - S^{\frac{1}{m}}\right)^{m}\right)^{2} \tag{8}$$

if

$$m = 1 - 1/n \tag{8}$$

with

- h pressure head (m)

S relative saturation

n van Genuchten n parameter

m van Genuchten m parameter

$m = 1 - 1/n$ (Mualem)

θ volumetric soil moisture ($m^3\ m^{-3}$)

θ_r residual soil moisture ($m^3\ m^{-3}$)

θ_s porosity = saturated soil moisture ($m^3\ m^{-3}$)

K hydraulic conductivity ($m\ s^{-1}$)

K_s hydraulic conductivity at saturation ($m\ s^{-1}$).

Soil water limitation functions for plants often use (pressure heads at) field capacity and permanent wilting point. The former can be defined as the volumetric soil moisture at a pressure head of 3.3 m. The latter can be defined (in soil science) as the volumetric soil moisture at a pressure head of 150 m:

$\theta_{fc}(h_{fc} = 3.3\ m)$ field capacity ($m^3\ m^{-3}$)

$\theta_{pwp}(h_{pwp} = 150\ m)$ permanent wilting point ($m^3\ m^{-3}$).

References

Brooks RH and AT Corey (1964) Hydraulic properties of porous media, *Hydrology Papers* 3, Colorado State University, Fort Collins, CO, pp. 37.

Clapp RB and GM Hornberger (1978) Empirical equations for some soil hydraulic-properties, *Water Resources Research*, 14(4), 601–604.

Cosby BJ *et al.* (1984) A statistical exploration of the relationships of soil-moisture characteristics to the physical-properties of soils, *Water Resources Research*, *20*(6), 682–690.

van Genuchten MT (1980) A closed-form equation for predicting the hydraulic conductivity of unsaturated soils, *Soil Science Society of America Journal*, 44(5), 892–898.

Hengl T *et al.* (2014) SoilGrids1km - Global soil information based on automated mapping, edited by B. Bond-Lamberty, *PLoS ONE*, *9*(8), e105992.

van den Hurk B *et al.* (2016) LS3MIP (v1.0) contribution to CMIP6: the Land Surface, Snow and Soil moisture Model Intercomparison Project – aims, setup and expected outcome, *Geoscientific Model Development*, 9(8), 2809–2832.

Kim H *et al.* (in prep.) A century-long global surface meteorology for offline terrestrial simulations.

Montzka C *et al.* (2011) Hydraulic parameter estimation by remotely-sensed top soil moisture observations with the particle filter, *Journal of Hydrology*, 399, 410–421.

Mualem Y (1976) A new model for predicting the hydraulic conductivity of unsaturated porous media, *Water Resources Research*, 12(3), 513–522.

Schaap MG *et al.* (2001) ROSETTA: a computer program for estimating soil hydraulic parameters with hierarchical pedotransfer functions, *Journal of Hydrology*, *251*, 163–176.