AMIP-style global soil simulations with JULES and the Unified Model: The role of soil hydraulics model, pedotransfer function, and basic soil property map

Patrick C. McGuire (*U. Reading, NCAS*), Pier Luigi Vidale (*U. Reading, NCAS*),
Martin J. Best (*Met Office*), David H. Case (*U. Reading, NCAS*), Imtiaz Dharssi (*Bureau of Meteorology, Australia*),
Maria Carolina Duran Rojas (*U. Exeter*), Rosalyn S. Hatcher (*U. Reading, NCAS*), Grenville M.S. Lister (*U. Reading, NCAS*),
Alberto Martinez de la Torre (*CEH*), Carsten Montzka (*Research Centre Jülich, Germany*),
Omar V. Müller (*U. Reading, NCAS, Universidad Nacional del Litoral & CONICET, Argentina*),
Valeriu Predoi (*U. Reading, NCAS*), Eddy Robertson (*Met Office*), Markus Todt (*U. Reading, NCAS*),
Anne Verhoef (*U. Reading*), Simon S. Wilson (*U. Reading, NCAS*)

JULES Annual Meeting, 9/13/2022, v4b

Introduction

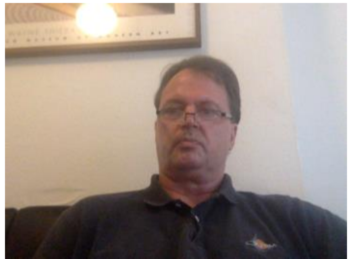
- Soil physical properties affect the flow and drainage of heat and water between the surface and the entire soil column. The soil state, in turn, influences weather/climate, through controls on evapotranspiration and the Bowen ratio, affecting cloud formation and the hydrological and energy cycles. Downstream effects also impact our estimates of floods/droughts, forestry/agriculture, and the water supply.

- The usage of Van Genuchten (1976) model parameters instead of Brooks & Corey (1964) model parameters may more accurately reflect the actual soil hydraulics. With this end, we explored the usage of Van Genuchten model parameters in the JULES (offline) land-surface model as well as with the (coupled) Unified Model.

- We have been using new soil minerals maps, SoilGrids (Hengl et al., 2014), which are suitable for high resolution, with 1-5 km horizontal gridding. Previously, using IGBP/HWSD soil mineral maps was more common.

- We have code working now for comparing different Pedotransfer Functions (PTFs) used to estimate the Van Genuchten soil-hydraulics physical parameters from the soil mineral information in the SoilGrids maps. We have been exploring the use of the PTFs defined by Toth et al. (2014), Weynants et al. (2009), and Zhang & Schaap (2017).

- This is being done for HadGEM3 (JULES).
  - JULES can be run in standalone mode using for example the WFDEI driving data (1979-2012 or 1979-2018, Weedon *et al.* 2018) instead of coupling to the atmosphere and ocean models.
  - **The HadGEM3 coupled model uses JULES as its land model.**



Brooks & Corey model
and Mualem & Van Genuchten model

Brooks and Corey:

Soil Water Retention Relationship

It has been shown that the Brooks and Corey equation (1964) provides a reasonably accurate representation of the water retention-matric potential relationship for tensions greater than 50 cm (Brakensiek et al., 1981). This equation is written as

$S_e = (\psi_b/\psi)^\lambda$

where:

S_e = Effective saturation = $(\theta - \theta_r)/(\theta_s - \theta_r)$

θ = Soil water content, cm^3/cm^3

θ_r = Residual soil water content, cm^3/cm^3

θ_s = Saturated soil water content, cm^3/cm^3

ψ_b = Bubbling pressure, cm of water

ψ = Capillary pressure, cm of water = Capillary head = Matric potential

λ = Pore size distribution index = 1/b

From: Rawls, Brakensiek, & Saxton (USDA), 1982, *Trans. Amer. Soc. Agric. Engineers*

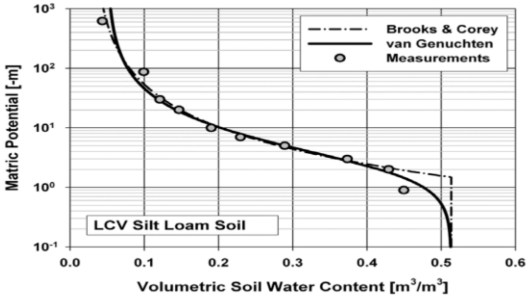


Figure 5: van Genuchten (VG) and Brooks and Corey (BC) parametric models fitted to measured data for silt loam soil.

From: Tuller, M., & Or, D. 2004, *Encyclopedia of Soils in the Environment.*

Mualem and van Genuchten:

The *van Genuchten* [1976] model is widely used for predicting soil water content as a function of pressure head. This model is generally expressed as

$$S_e = \frac{1}{[1 + (\alpha\psi)^n]^m}$$

where:

α, n, m are empirical constants,

and where m is [normally] related to n as follows:

$$m = 1 - \frac{1}{n}$$

Hydraulic conductivity can be represented by:

$$K(S_e) = K_s \cdot S_e^{1/2} \cdot \left[1 - (1 - S_e^{1/m})^m\right]^2$$

where :

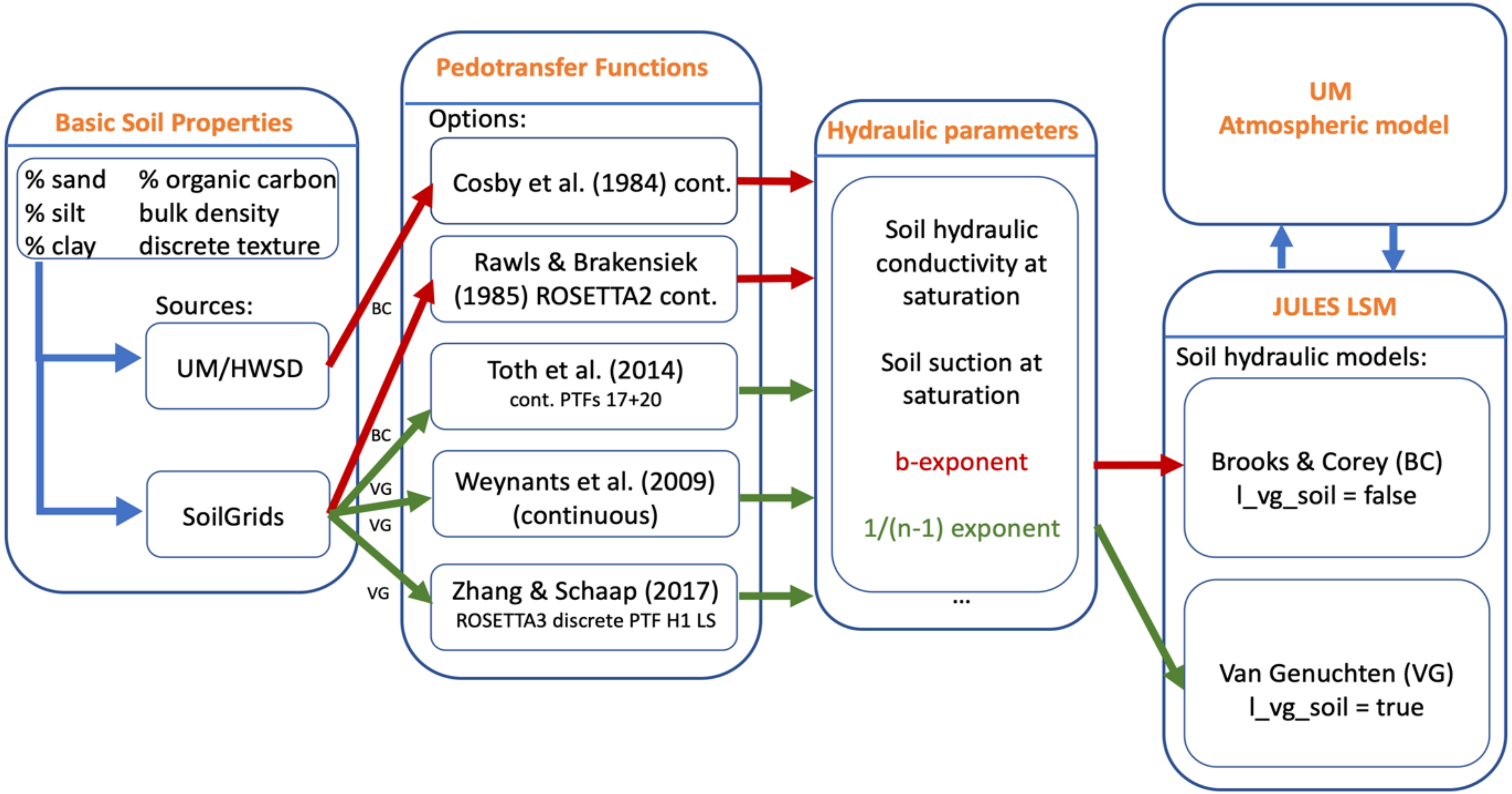
$K_s = K_{sat} = K(S_e = 1)$ is an empirical constant.

From: Carsel & Parrish (US EPA), 1988, *Water Resources Research*

At high values of ψ, the models are equivalent if
b $\equiv 1/\lambda$ is set
= 1/(n-1)

This approximation breaks down at low values of ψ.

Our soil configuration options



Plot from Omar Müller

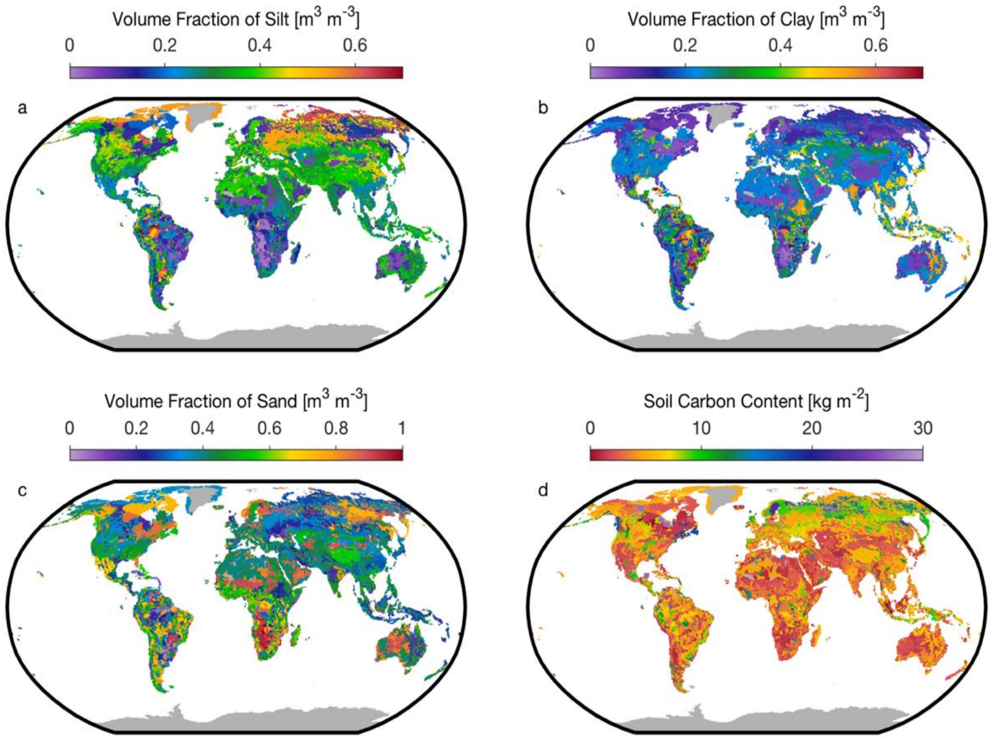
We use the Soilgrids maps instead of the customary UM/HWSD maps as inputs to the VG PTFs.

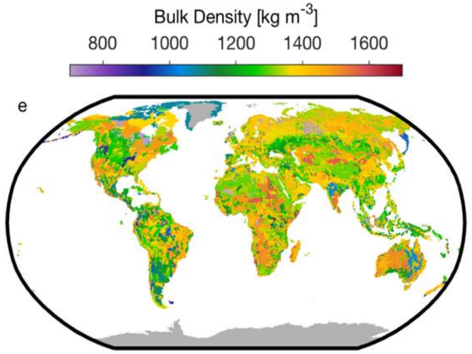
The basic soil properties are normally constant with depth in JULES.

We chose to use the 60cm depth for the Soilgrids maps instead of the 0-30cm depth mainly because we are interested in longer timescales.

UM/HWSD global maps: (0-30cm depth; at N216 resolution)

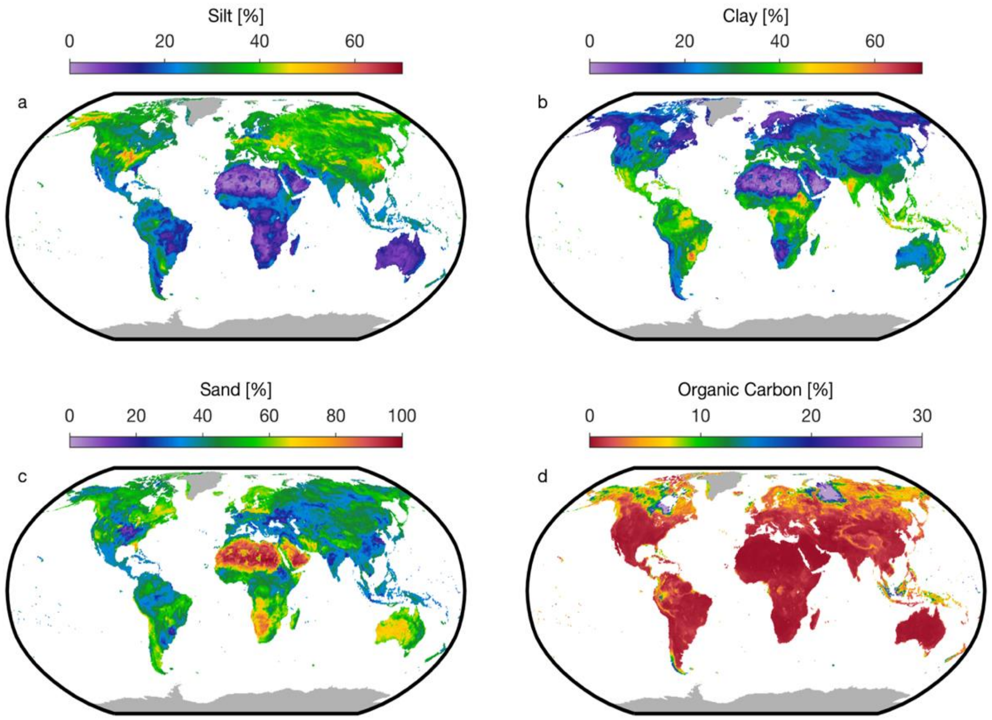
These are the standard UM/JULES input parameters, and they are used here as well, with the Cosby et al. BC pedotransfer function.

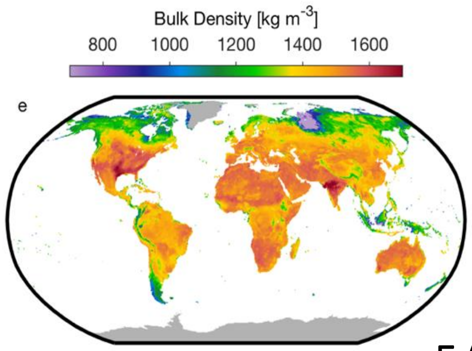




Soilgrids 5km global maps: (60cm depth; at 0.5° resolution)

These are the input parameters we use for the VG pedotransfer functions





The Soilgrids Dataset is from Hengl *et al.* (2014), and is also available at 1km resolution

Plots by Markus Todt

Cosby et al. (BC model) 'continuous' pedotransfer function (PTF)

```
# Clapp Hornberger parameter b .
# Remember, this b might be comparable to 1/(n-1), where n is the parameter used in the MVG model.
# units: dimensionless.
b = 3.10 + 15.70 * Cl - 0.3 * Sa

# Saturated soil water suction (bubbling pressure) ψ_b
# Remember, this ψ_b might be comparable to 1/α, where α is the parameter used in the MVG model.
# units: cm
ψ_b = 10.0 ^ (2.17 - 0.63 * Cl - 1.58 * Sa)

# Saturated hydrological soil conductivity Ksat
# units: kg m^-2 s^-1
K0 = Ksat = 10.0 ^ (-2.75 - 0.64 * Cl + 1.26 * Sa)

# Volumetric soil water concentration at saturation point theta_s
# units: m^3 water per m^3 soil
θ(sat) = 0.505 - 0.037 * Cl - 0.142 * Sa
```

As in the ANTS code

WATER RESOURCES RESEARCH, VOL. 20, NO. 6, PAGES 682–690, JUNE 1984

A Statistical Exploration of the Relationships of Soil Moisture Characteristics to the Physical Properties of Soils

B. J. COSBY, G. M. HORNBERGER, R. B. CLAPP, AND T. R. GINN

Sa = Sand fraction, Cl = Clay fraction, ranging from 0 to 1.

Zhang & Schaap ROSETTA3 H1 LS (MVG model) 'discrete' pedotransfer function (PTF)

USDA Texture-class	θ(res)	θ(sat)	alpha (cm^{-1})	n exp.	m =1-1/n	K0=Ksat (cm/day)	L tortuosity
~~Sa~~	~~0.055~~	~~0.363~~	~~0.0328~~	~~2.895~~	~~0.655~~	~~643.0~~	~~0.5~~
Sa=Lo Sa	0.058	0.383	0.0246	1.697	0.411	108.2	0.5
Lo Sa	0.058	0.383	0.0246	1.697	0.411	108.2	0.5
Sa Lo	0.061	0.381	0.0164	1.457	0.314	37.45	0.5
Lo	0.090	0.402	0.00636	1.421	0.297	13.34	0.5
Si Lo	0.083	0.427	0.00343	1.552	0.356	18.47	0.5
Si	0.065	0.472	0.00604	1.577	0.366	43.75	0.5
Sa Cl Lo	0.093	0.380	0.0124	1.305	0.234	13.23	0.5
Cl Lo	0.107	0.428	0.00995	1.391	0.281	7.06	0.5
Si Cl Lo	0.120	0.470	0.00556	1.434	0.303	11.11	0.5
Sa Cl	0.147	0.382	0.0250	1.237	0.191	11.35	0.5
Si Cl	0.123	0.473	0.0101	1.273	0.215	9.61	0.5
Cl	0.131	0.457	0.00857	1.255	0.203	14.75	0.5
Org	0.000	1.000	0.00690	1.500	0.333	1.00	0.5

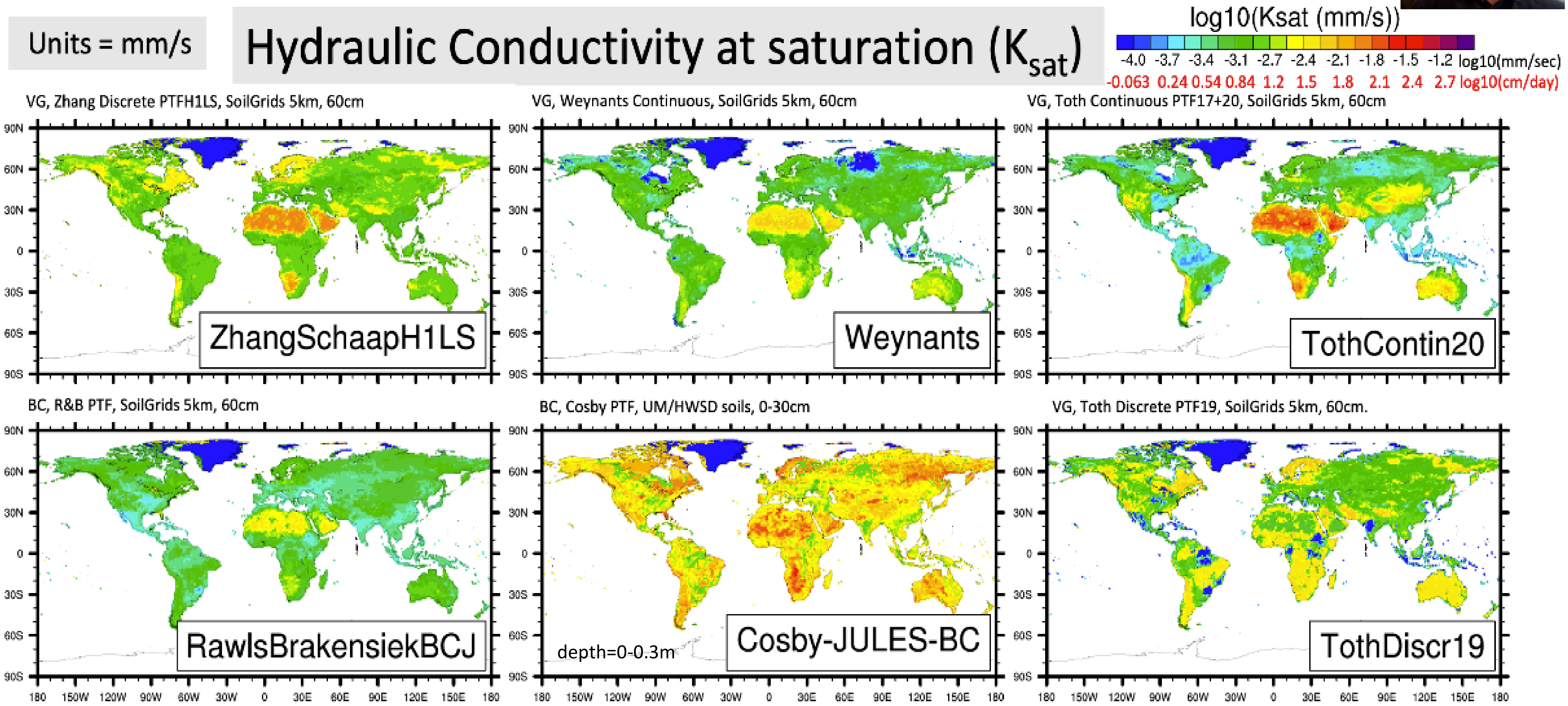
Our current choice/decision:
The K0 & n-exponent values for Sa=Sand are too extreme for JULES to handle
(causing gridded JULES to hang without crashing),
so we replaced the Sa values with the Lo Sa values.
That's why this PTF has LS in its name.

Zhang & Schaap (2017)
Zhang (private communication)
Rounded here to a few significant figures.

Sa=Sand, Lo=Loam, Si=Silt, Cl=Clay

Units = mm/s

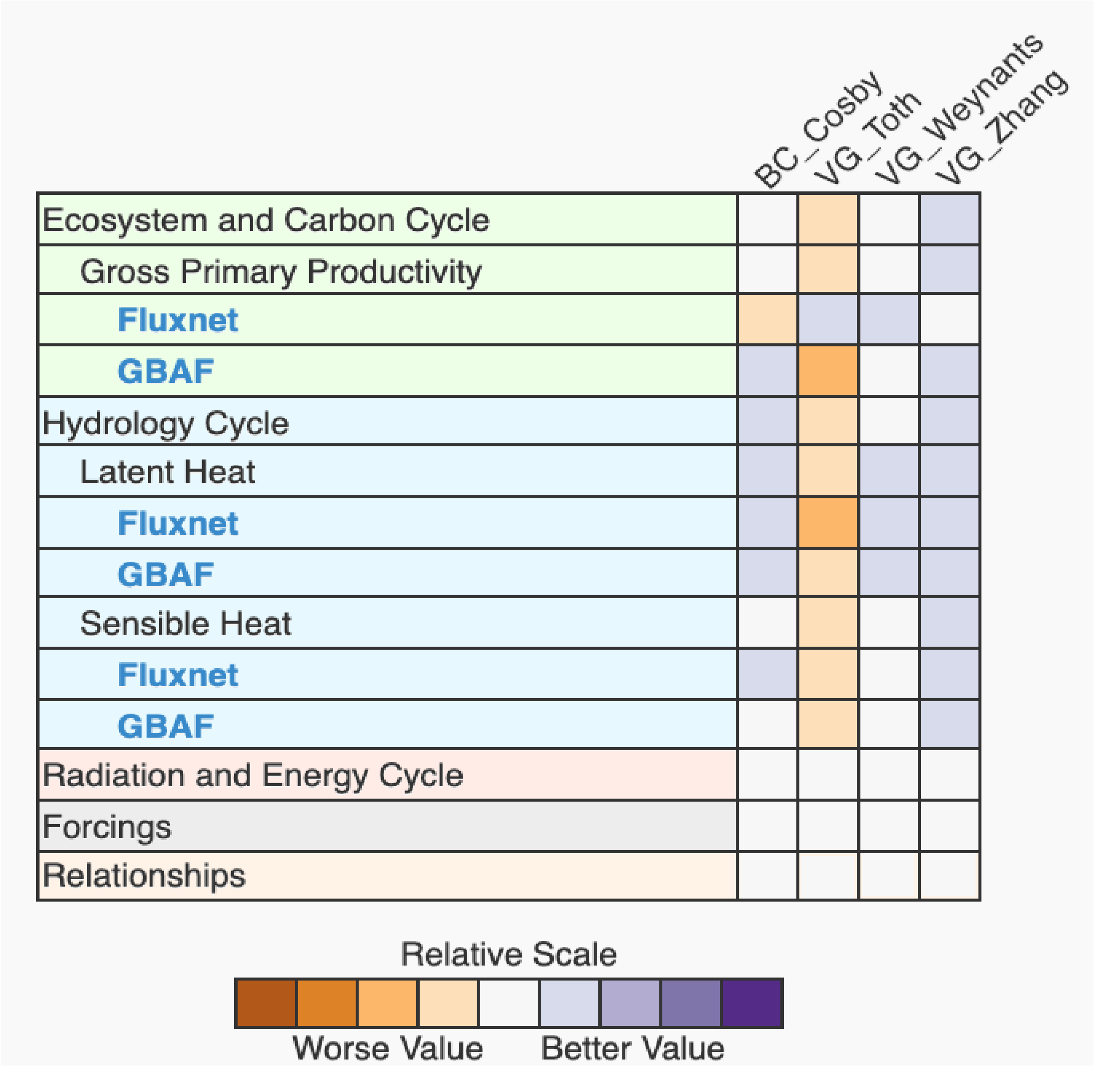
Hydraulic Conductivity at saturation (K_{sat})



Ksat is one of the outputs of the pedotransfer functions, and it is one of the physical soil properties used directly by JULES.

All graphs except Cosby-JULES-BC are at 0.6m depth

ILAMB summary chart, comparing various offline JULES global runs including new run with the Zhang&Schaap H1LS Pedotransfer Function (PTF)



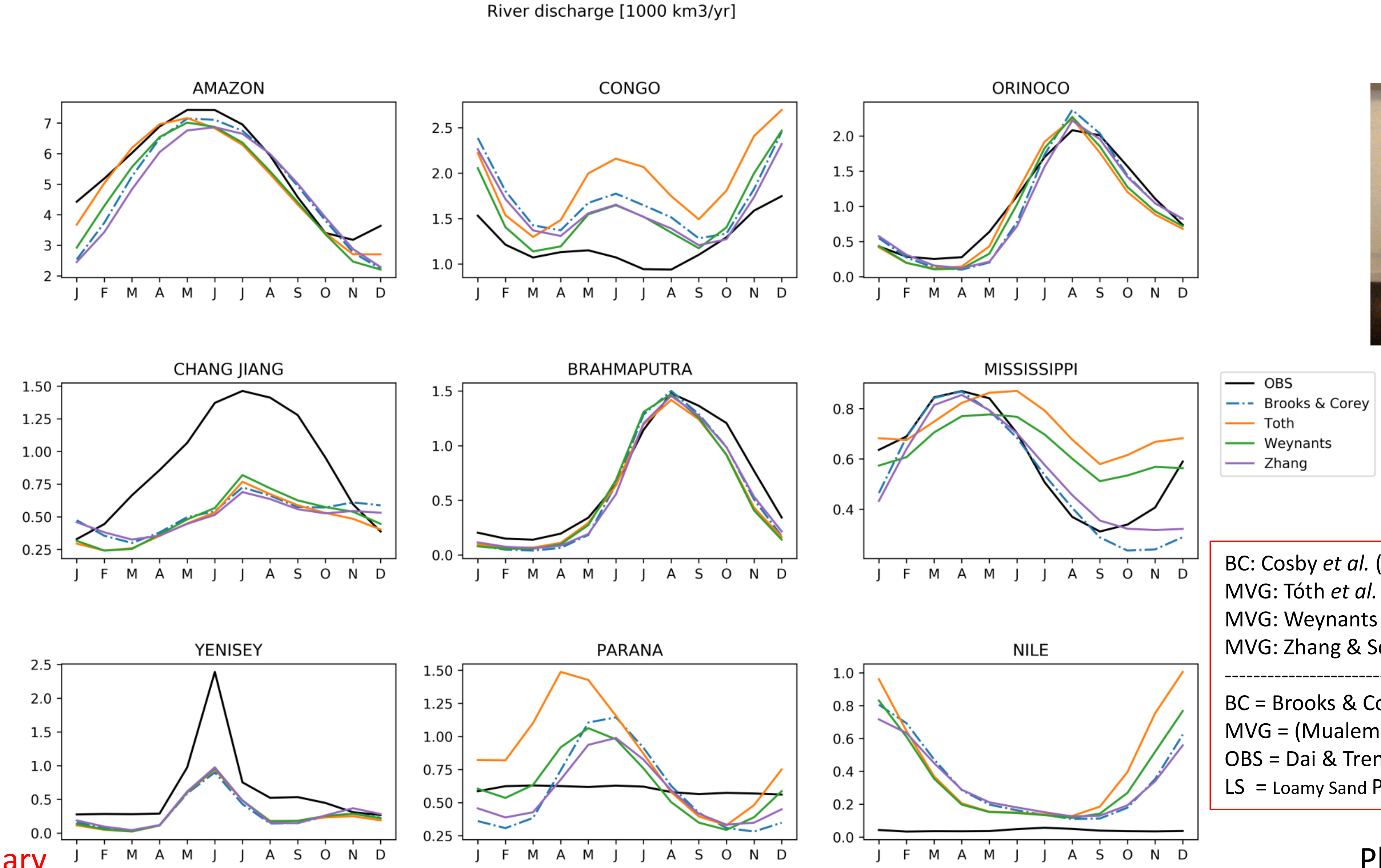
The Zhang&Schaap H1LS VG PTF is the last column.
The Weynants et al. VG PTF is the 2nd to last column.
The Tóth et al. VG PTF is the 3rd to last column.
The comparison control with Brooks & Corey (Cosby *et al.* PTF) is the 1st column.

The Zhang&Schaap PTF has purplish entries for the relative score for Latent Heat Flux, Sensible Heat Flux, and Gross Primary Product.
The Zhang&Schaap PTF is relatively better for more variables than the Weynants et al. PTF and the Tóth et al. PTF, as well as the Cosby et al. BC control,

preliminary

The H1LS PTF uses Loamy Sand H1 PTF values instead of the Sand H1 PTF values

Monthly river-discharges for different basins, comparing various offline JULES global runs, including new run with the VG Zhang&Schaap H1LS Pedotransfer Function (PTF)



BC: Cosby *et al.* (1984) PTF
MVG: Tóth *et al.* (2015) PTF
MVG: Weynants *et al.* (2013) PTF
MVG: Zhang & Schaap (2017) ROSETTA3 H1LS PTF

BC = Brooks & Corey (1964) model;
MVG = (Mualem &) van Genuchten (1976) model
OBS = Dai & Trenberth (2017) river-gauge dataset
LS = Loamy Sand PTF values replacing Sand PTF values

preliminary

Plots from Omar Müller

AutoAssess of 1989-2008 JJA 1.5m air-temperature for AMIP UM run with new soil ancillary

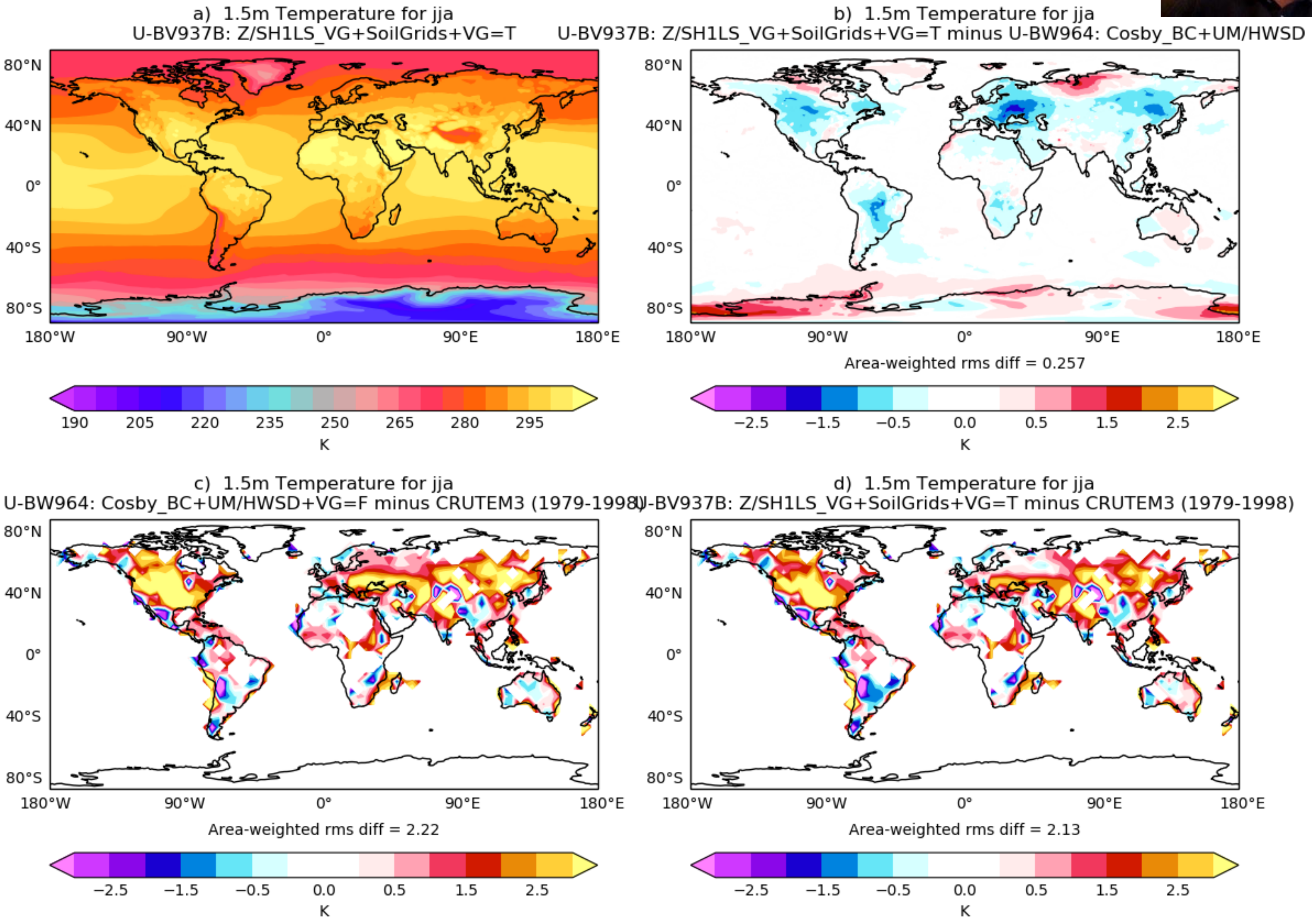
Both control & experiment
used the same standard start-dump,
without extra spinup.
We also did 35-year continuation runs
(1979-2014) using these runs as spinups.
Both control & experiment used
same constant-in-time&space
atmospheric CO2 (348.5ppm = 1988 level)

Control =
CosbyEtAl. BC PTF
UM/HWSD (0.0-0.3m) soil mineral maps
JULES flag: l_vg_soil = FALSE

Experiment =
Zhang&Schaap H1 LS ROSETTA3 VG PTF
SoilGrids (0.6m) soil mineral maps
JULES flag: l_vg_soil = TRUE

Much of the model<->model variance is due to l_vg_soil,
but some is due to choice of PTF and mineral maps.

preliminary



The central white ranges from -0.1K to +0.1K

AutoAssess of 1979-2014 JJA 1.5m air-temperature for AMIP UM run with new soil ancillary

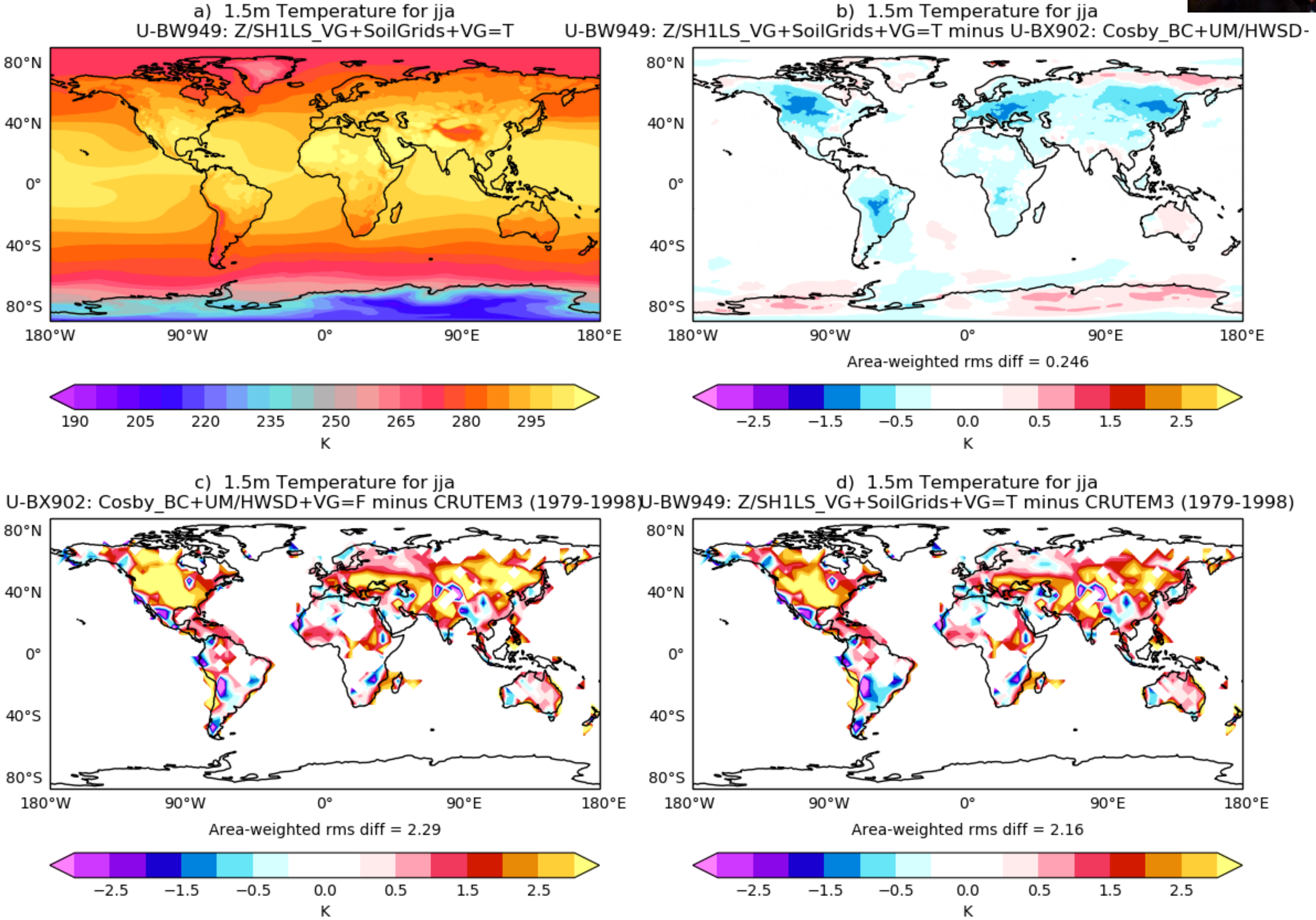
Both control & experiment
  used the same standard start-dump,
  without extra spinup.
These 35-year continuation runs (1979-2014)
  used prior 1989-2008 runs as spinups.
Both control & experiment used
  same constant-in-time&space
  atmospheric CO_2 (348.5ppm = 1988 level)

Control =
CosbyEtAl. BC PTF
UM/HWSD (0.0-0.3m) soil mineral maps
JULES flag: l_vg_soil = FALSE

Experiment =
Zhang&Schaap H1 LS ROSETTA3 VG PTF
SoilGrids (0.6m) soil mineral maps
JULES flag: l_vg_soil = TRUE

Much of the model<->model variance is due to l_vg_soil, but some is due to choice of PTF and mineral maps.

preliminary

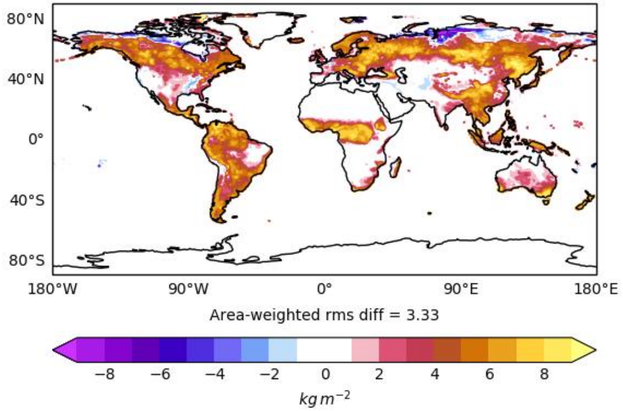


The central white ranges from -0.1K to +0.1K

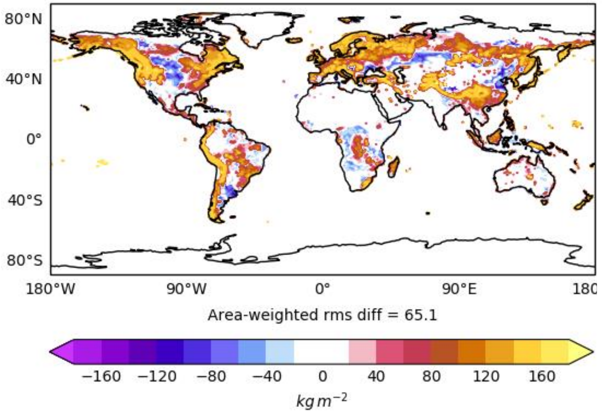
AutoAssess sensitivity of 1989-2008 JJA AMIP runs: New_Soils – Orig_Soils

VG_soil=F

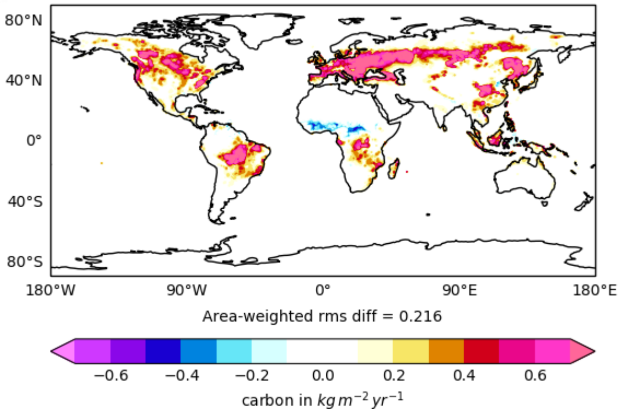
0-10cm Soil Moisture



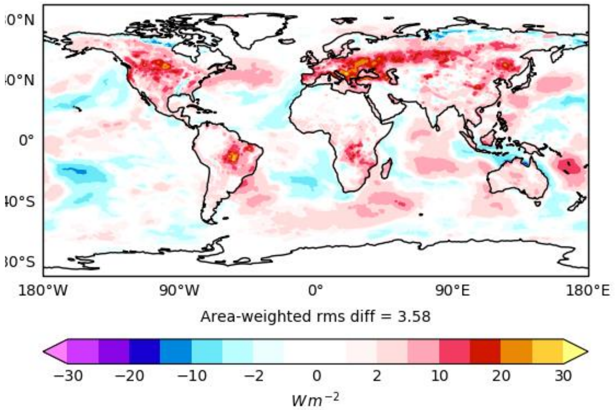
100-300cm Soil Moisture



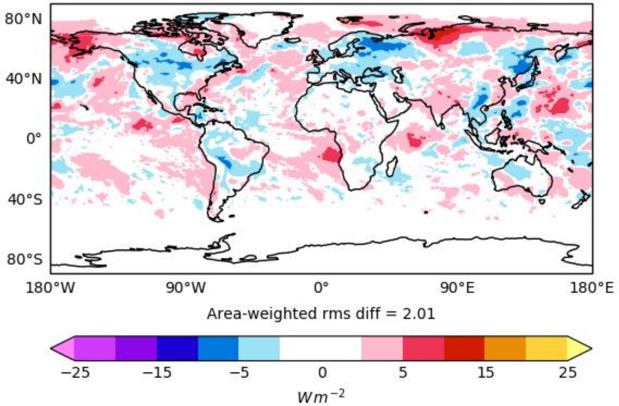
GPP



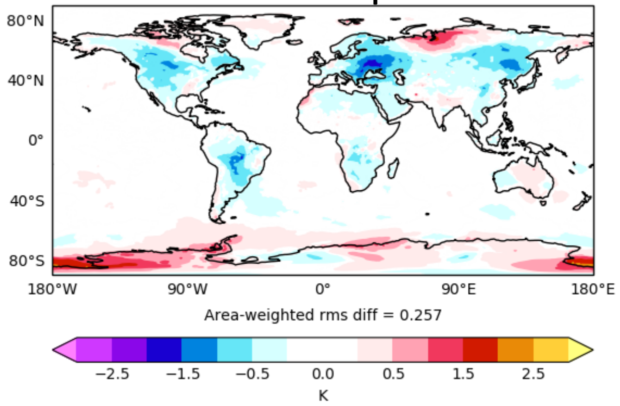
Latent Heat Flux



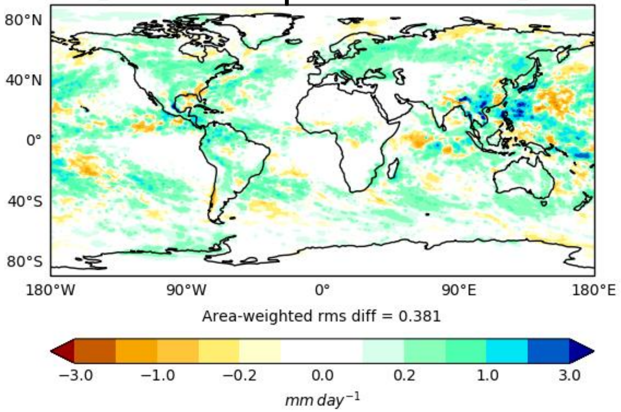
Net Down Surface SW

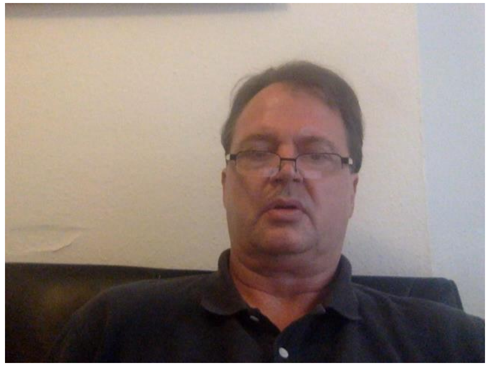


1.5m Air Temperature



Precipitation





‘generalizing’ for JJA (a possible regionally-dominant positive feedback loop):

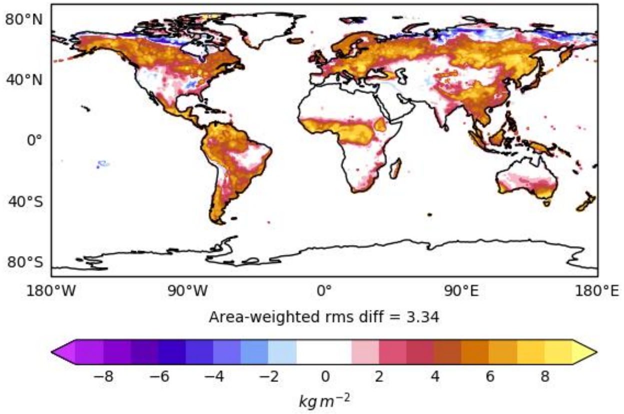
NH land: higher soil moisture, higher GPP, higher latent heat flux, lower surface SW flux, lower 1.5m temps, higher precipitation (more clouds)

preliminary

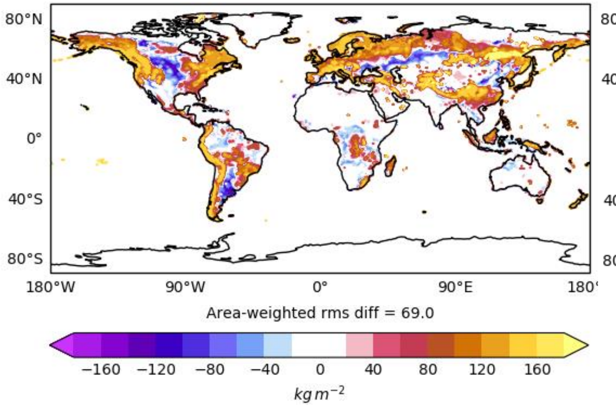
AutoAssess sensitivity of 1979-2014 JJA AMIP runs: New_Soils – Orig_Soils

VG_soil=F

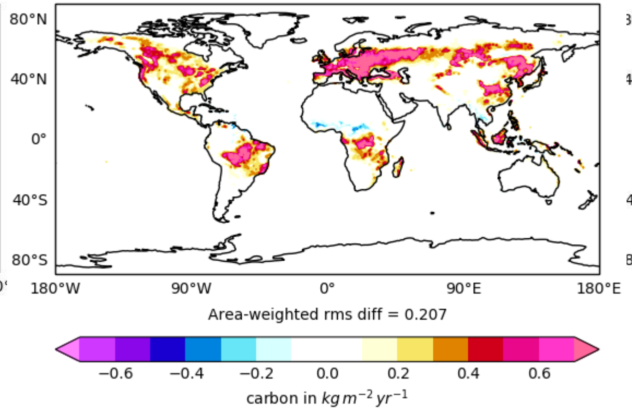
0-10cm Soil Moisture



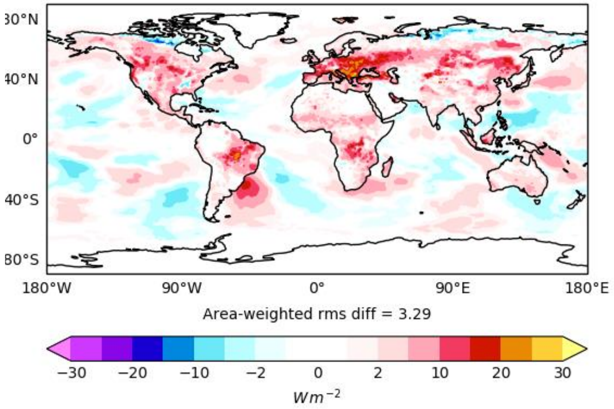
100-300cm Soil Moisture



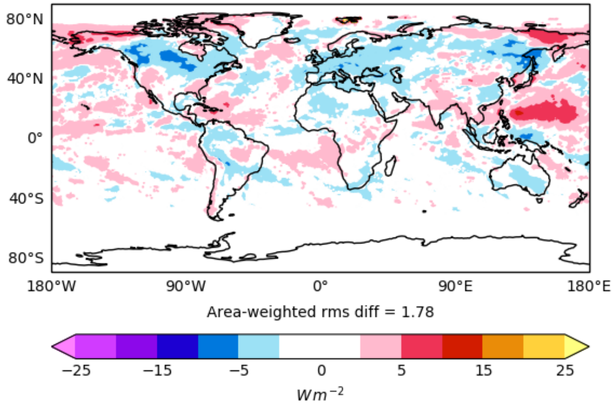
GPP



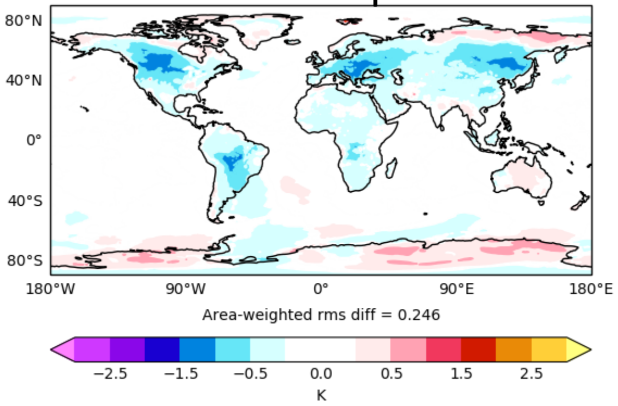
Latent Heat Flux



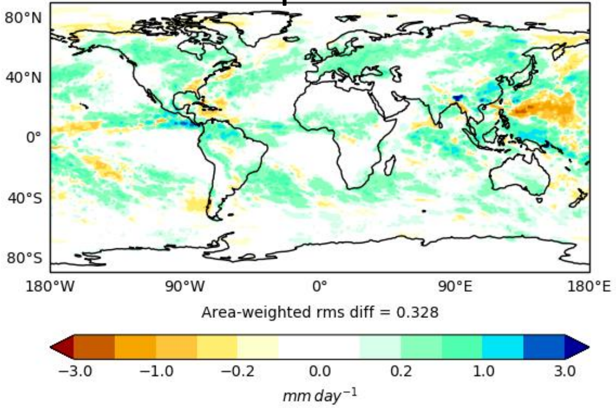
Net Down Surface SW



1.5m Air Temperature



Precipitation



'generalizing' for JJA (a possible regionally-dominant positive feedback loop):

NH land: higher soil moisture, higher GPP, higher latent heat flux, lower surface SW flux, lower 1.5m temps, higher precipitation (more clouds)

preliminary

P.C. McGuire et al.

Overall Progress Report and Conclusions

- We did a comparison of a number of different pedotransfer functions (PTFs) for Mualem-vanGenuchten (MVG) soil properties.
- From this comparison of soil properties, we ran offline JULES with soil ancillaries (constant values with depth, 0.0-3.0m) computed from:

  SoilGrids basic soil properties at 0.6m depth with:
  - Tóth *et al.* 17+20 MVG PTFs, with vg_soil=True
  - Weynants/Vereecken MVG PTF, with vg_soil=True
  - Zhang & Schaap H1 LS MVG PTF, with vg_soil=True

  UM Harmonized World Soil Database (HWSD) basic soil properties at 0-0.3m depth with (the control experiment):
  - Cosby et al. Brooks & Corey (BC) PTF, with vg_soil=False.
- We compared these runs with ILAMB, with Markus Todt's new bias-ratio technique, and with Omar Müller's river discharge comparisons:
  - The ILAMB scores for the Zhang&Schaap ROSETTA3 H1LS PTF are an improvement over the Weynants/Vereecken PTF and the Tóth *et al.* 17+20 PTF.
  - And the river-discharge annual profiles for different river basins in the offline JULES simulations match the Dai & Trenberth (2017) river-gauge measurements much better with the Zhang&Schaap ROSETTA3 H1LS PTF, particularly for the Mississippi.
- We have produced Zhang & Schaap H1LS soil ancillaries in N216 format (with SoilGrids soil inputs), and we have run the (coupled) Unified Model (UM) with this ancillary. AutoAssess has been run, comparing the Zhang & Schaap run with the control experiment.
- The 35-year AMIP UM runs suggest that there is a significant difference between the runs, with lower JJA 1.5m air temperatures, higher soil moisture, higher GPP, and higher precipitation in significant areas of the land, possibly with a positive feedback loop.
- The initial AMIP UM results suggest that we have a viable candidate of a new MVG soil ancillary that will work comparably with the UM N216e runs as with the BC soil ancillary files that were used previously. Even without using new soil ancillaries, much of the improvement seems to be only from switching on the VG parametrization.
- Near future: finish analysis and submit/publish papers on offline runs and on AMIP runs.
- Further in future: study using 4-layer soils with full depth dependence of soil basic & physical properties.