Land surface - atmosphere coupling strength in GCMs: the impact of soil physics.

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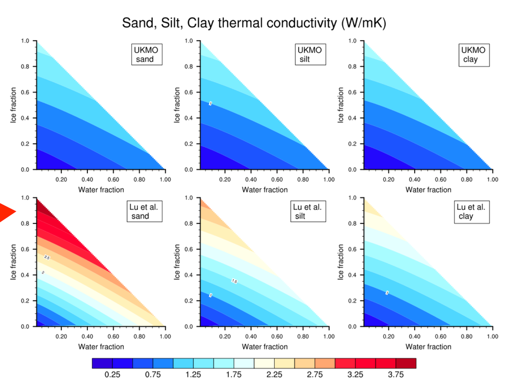
Introduction

Understanding the land surface component of the hydrological cycle has been a high priority for decades. The routing of water through the soil-vegetation system is crucial to our understanding of the water-carbon cycles, as well as for the simulation of floods and droughts. The lack of global, homogeneous data regarding soil moisture amount and variability makes it difficult to close this gap and the use of numerical models is unavoidable. The land-atmosphere coupling strength in GCMs has been under scrutiny in the last few years, due to its role in closing the hydrological cycle at several time scales, which it modulates via memories in the terrestrial water balance. Model intercomparison studies have indicated that there is no consensus on the correct magnitude of the coupling strength and several hypotheses to explain the disagreement have been raised, involving precipitation frequency/intensity characteristics, soil processes (infiltration, runoff generation, root extraction), and boundary layer dynamics. When simulating climate and its variability it is therefore important to assess the impact of the uncertainty in the treatment of soil prognostics (moisture and temperature), which stems from physical parameterizations, numerical discretisation and parameters This study addresses principally the uncertainty in soil hydraulic parameters, as well as the formulation of soil physics, limited to the description of soil thermal conductivity.

1. Changes in the parameterisation of soil physics

Soil hydraulics
A historic error in the parameterisation of the water retention curve in the Met Office land surface models (MOSES and JULES) has been found recently (see also Dharssi et al., 2009). The soil hydraulic parameters that control the vertical flux of soil water had been miscalculated by mis-interpreting a base-10 logarithm for a natural logarithm in Cosby et al.'s (1984) paper. This error affects matric potential (suction), saturated hydraulic conductivity, as well as the soil moisture thresholds that control vegetation activity. The tables and diagrams below illustrate the consequences of this error for FLUXNET sites that span a typical range of soil types.

Soil thermal transfer
The parameterisation of thermal conductivity in the soil has also been updated, using a recent formulation from Lu et al. (2007). The diagram below shows how the new parameterisation produces larger, more realistic, values of thermal conductivity, especially for saturated soils in frozen conditions. This thermal behaviour and **its interplay with soil water dynamics**, profoundly affects plant activity and evaporation.



Soil hydraulic parameters, values in bold concern the corrected hydraulic parameterisation
Ψ_s in m, K_s in mm s^{-1}, all θ in m^3 m^{-3}.
s stands for saturation; c for critical point; w for wilting point.

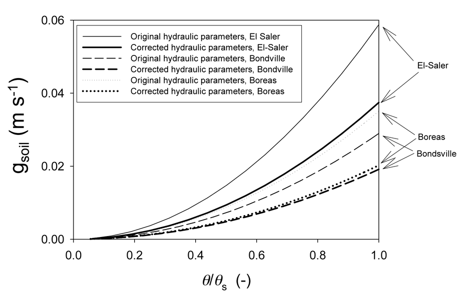
Site	Ψ_s	K_s	θ_c	θ_w	θ_c-θ_w
El Saler	0.026/**0.089**	0.0086/**0.0109**	0.164/**0.206**	0.082/**0.103**	0.083/**0.103**
Boreas_NSA	0.043/**0.288**	0.0052/**0.0034**	0.238/**0.314**	0.137/**0.181**	0.101/**0.133**
Bondville	0.038/**0.217**	0.0051/**0.0033**	0.257/**0.316**	0.163/**0.201**	0.094/**0.115**

$$\psi = \psi_s (\theta / \theta_s)^{-b}$$

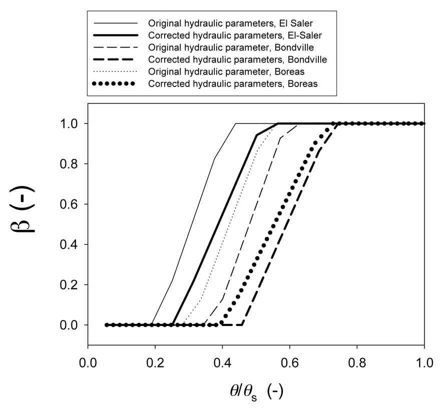
$$K = K_s (\theta / \theta_s)^{2b+3}$$

Affects soil evaporation

$$g_{soil} = \frac{1}{100}\left(\frac{\theta_1}{\theta_c}\right)^2$$



Affects photosynthesis, g_c and transpiration



$$\beta = \begin{cases} 1 \\ \dfrac{\Theta - \Theta_w}{\Theta_c - \Theta_w} \\ 0 \end{cases} \qquad A = A' \beta(\theta)$$

Figure 1: The equations for soil conductance for evaporation, g_{soil}, and the moisture availability function, β, and their dependence on relative saturation, at selected (FLUXNET) sites worldwide: El Saler (Spain), Bondville (USA), Boreas–NSA (Canada).

Table 1. Soil datasets used in this study [a]

Institution	Source	Dataset name	year	nominal resolution
Met Office	Wilson-Henderson Sellers	WHS	1983	1^o
IGBP	Batjes, FAO	IGBP-DIS	1994	5'

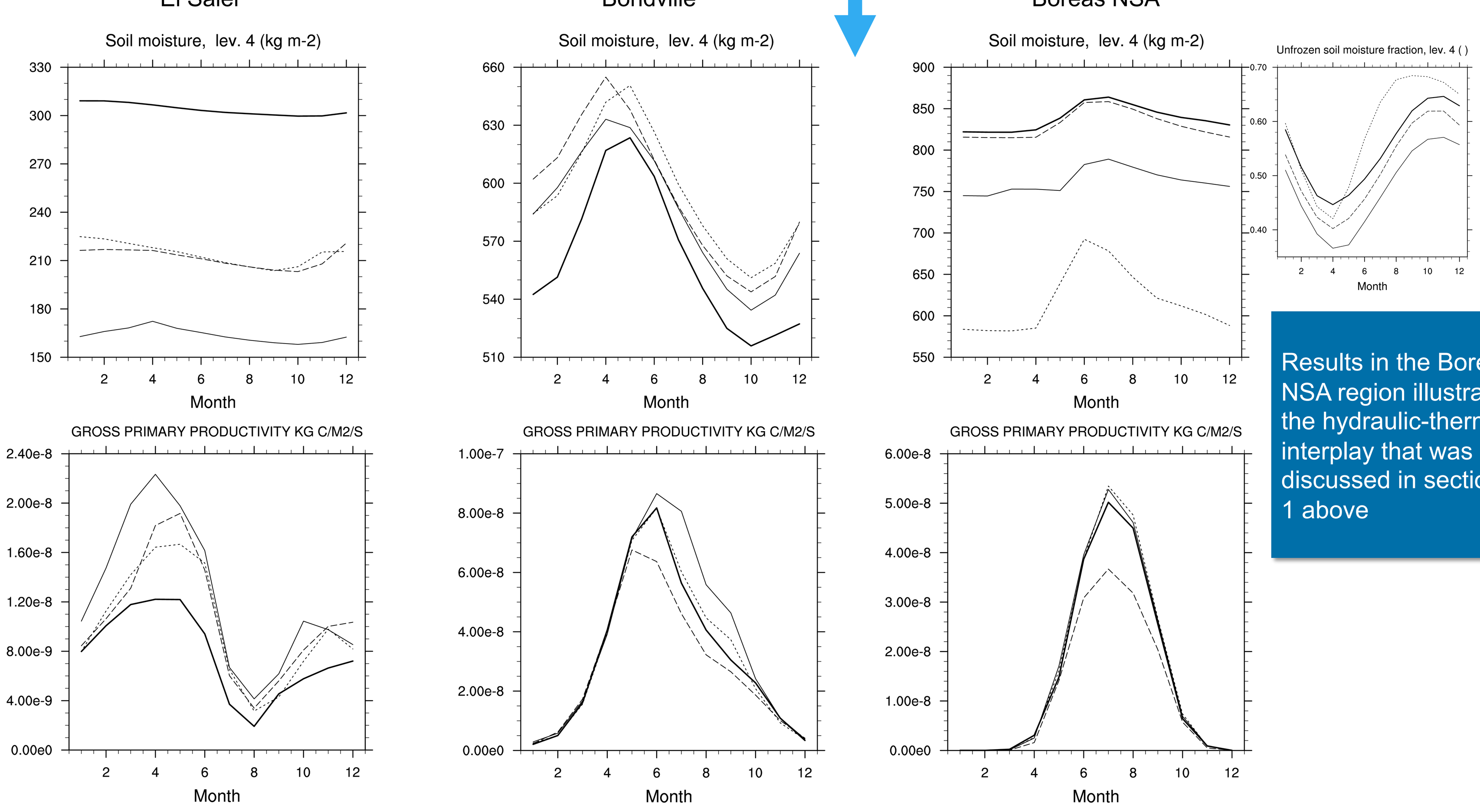
Table 2. Experimental design and experiment names

Experiment name	Soil type map	Soil hydraulic parameters	Parameterization of thermal conductivity λ	line pattern	ID
CTL	WHS (1^o)	Cosby (ln)	Cox et al. [1999]	bold	xbxdy
REF (map)	IGBP-DIS	Cosby (ln)	Cox et al. [1999]	black	xcjco
Hyd	IGBP-DIS	Cosby (log10)	Cox et al. [1999]	dashed	xcjcp
λ-Hyd	IGBP-DIS	Cosby (log10)	Lu et al. [2007]	dotted	xcjcw

The JULES land surface model
JULES is the Joint UK Land Environment Simulator. It is based on MOSES (Met Office Surface Exchange System), the land surface model used in the Unified Model of the UK Met Office. MOSES was originally designed to represent the land surface in meteorological and climate models, but both MOSES and JULES are increasingly used for other purposes: predicting river flows, identifying global wetlands, and quantifying water resources.

2. Results from point simulations at FLUXNET sites

Simulations of the impact of soil physics at individual locations around the globe, using FLUXNET or GCM meteorological forcing, reveal the strong interplay between soil dynamics and plant activity, with significant reductions in NPP at locations where water extraction is hindered after correcting for the error in the computation of hydraulic parameters. In cold climates, the impact of increased thermal conductivity is well visible at depth, where more liquid water is available in the growing season. The four lines represent the different simulations detailed in Table 2.



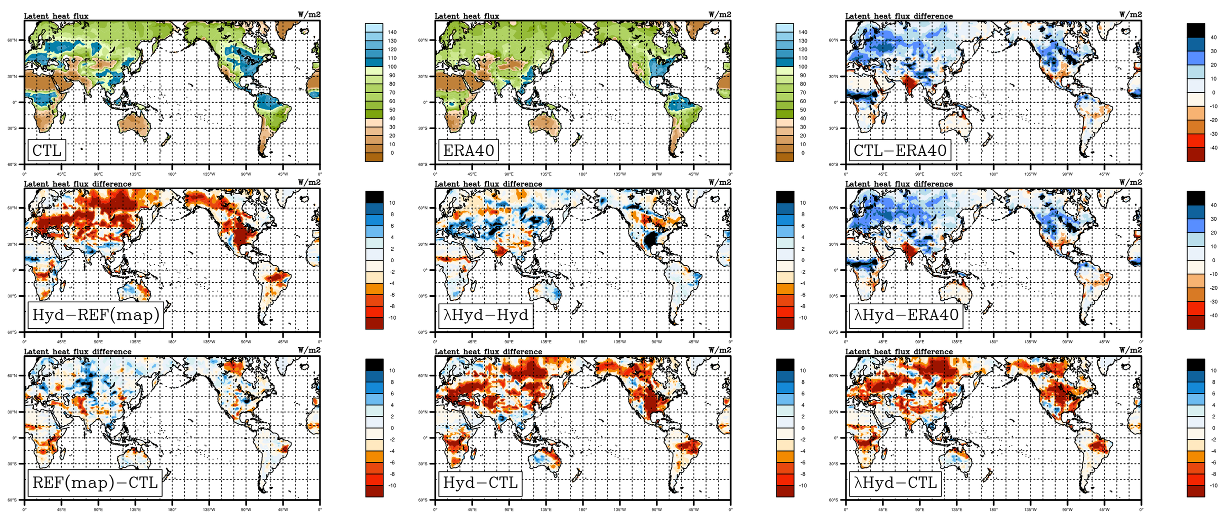
Results in the Boreas NSA region illustrate the hydraulic-thermal interplay that was discussed in section 1 above

Figure 2: Soil moisture content and GPP at selected FLUXNET sites worldwide: El Saler (Spain), Bondville (USA), Boreas–NSA (Canada).

The Hadley Centre's HadGEM1 (Johns et al., 2006) – is a state of the art Global Environment Model, building on, but substantially changed from HadCM3. The new climate model includes semi-Lagrangian dynamics and increased horizontal as well as vertical resolution. All the structural changes are combined with an almost completely new suite of physical parameterisations, and include additional processes, such as the sulphur cycle and cloud aerosol effects.

3. Results from GCM simulations

Average jja Latent Heat (W/m2)



Average jja Gross Primary Productivity (kg C/m2/month)

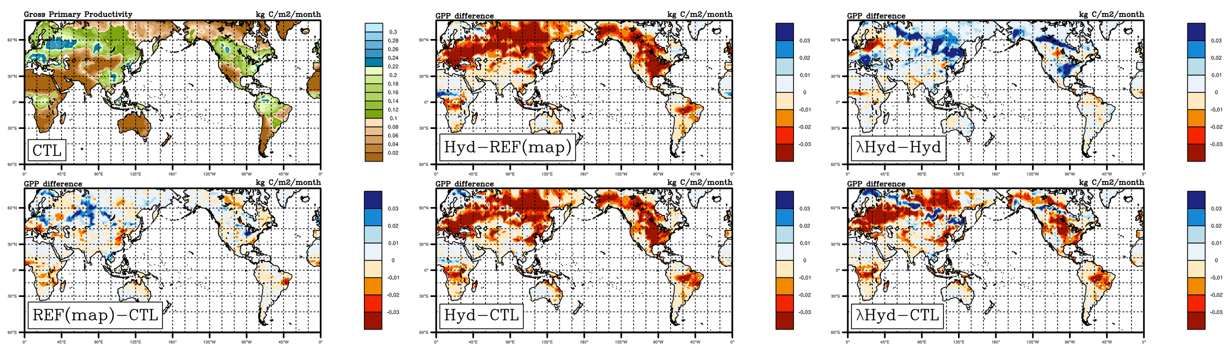


Figure 3: Global maps of latent heat flux (top) and GPP (bottom) from the experiments in Table 2. On the top left of each panel, results from the CTL experiment are shown; the additional plots show the differences introduced by each incremental experiment.

The global maps of latent heat flux and GPP, as well as seasonal cycles of the regional evolution of key surface and sub-surface variables, reveal a chain of mechanisms that is consistent with the results from the single-site simulations: a change in the definition of mineral composition (see Table 1) has mostly a minor impact, except locally over small areas in which a large change in mineral content is imposed. Correcting the soil hydraulic parameters to the log-10 formulation depresses latent heat fluxes from the surface during the growing seasons, as well as vegetation production. Updating the parameterisation of soil thermal conductivity makes it possible to increase soil heat flux, e.g. to melt deep soil water at high latitudes, enhancing deep drainage, but also partially restoring the deficit in plant photosynthetic activity, through increased liquid water ratio in the soil.

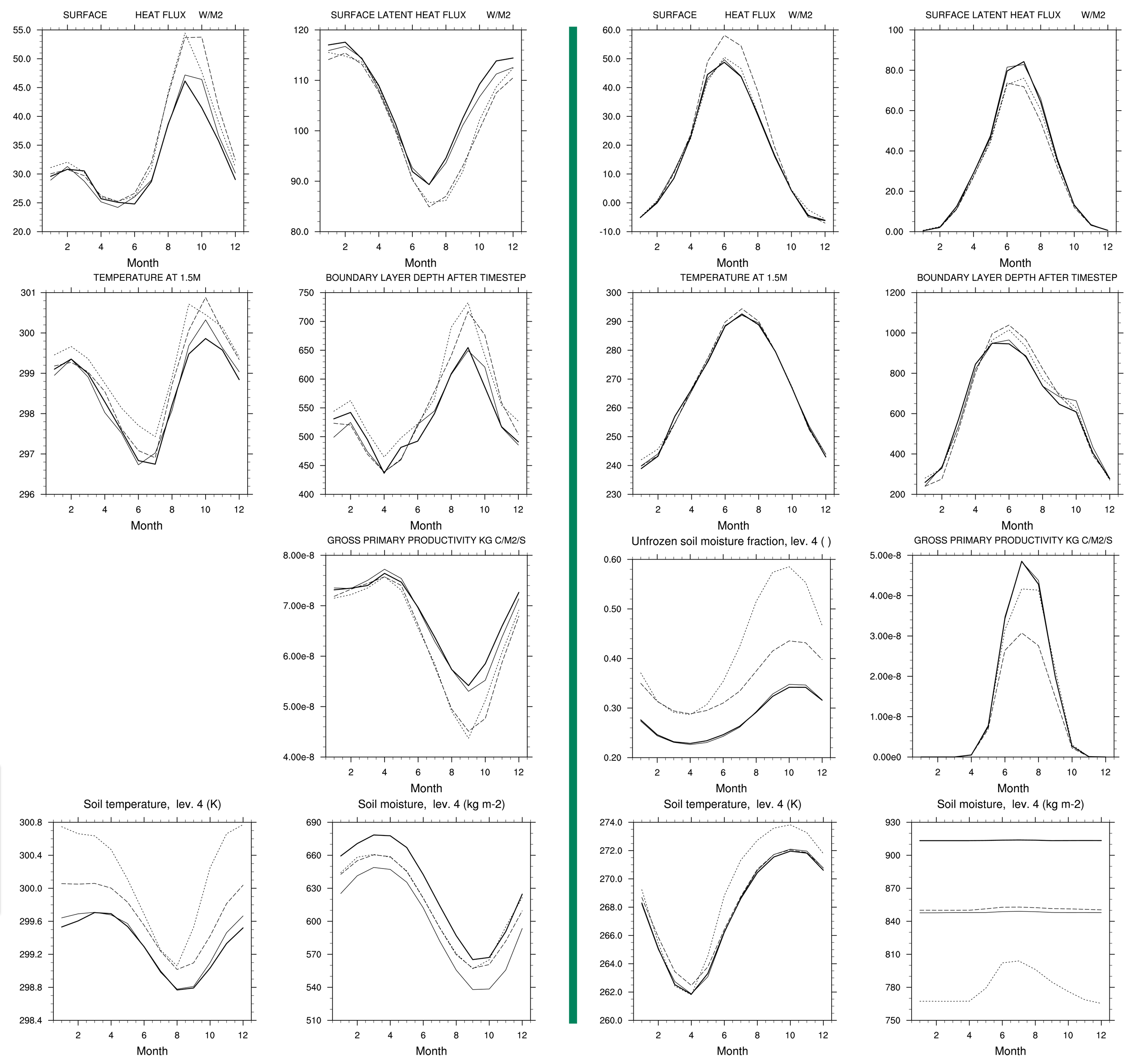
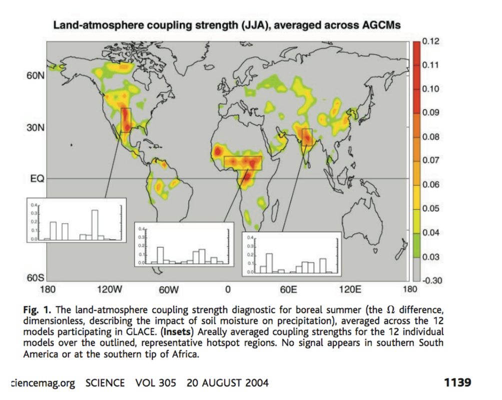


Figure 4: Seasonal variation in key surface (top two panels) and soil (bottom) variables for the GCM simulation runs presented in Table 2. Plots are for regional domains over Amazonia on the left-hand panel; for North East Asia on the right-hand panel.

4. Implications for land surface – atmosphere coupling

GCMs disagree on the dynamics of the hydrological cycle, its land surface branch in particular, as well as on the land-atmosphere coupling strength:

- Hadley Centre GCMs have the lowest land-atmosphere coupling strength, due to a number of model errors in the formulation of the atmosphere, surface, soils;
- Soil physics improvements and research on land surface processes promise to increase the level of coupling in HC GCMs, enabling a larger role in the hydrological cycle for plant transpiration, with longer memory; however, the entire carbon cycle may need to be re-tuned;
- Can monthly anomalies provide indication of changes in the coupling strength for the HadGEM-MOSES coupled model?



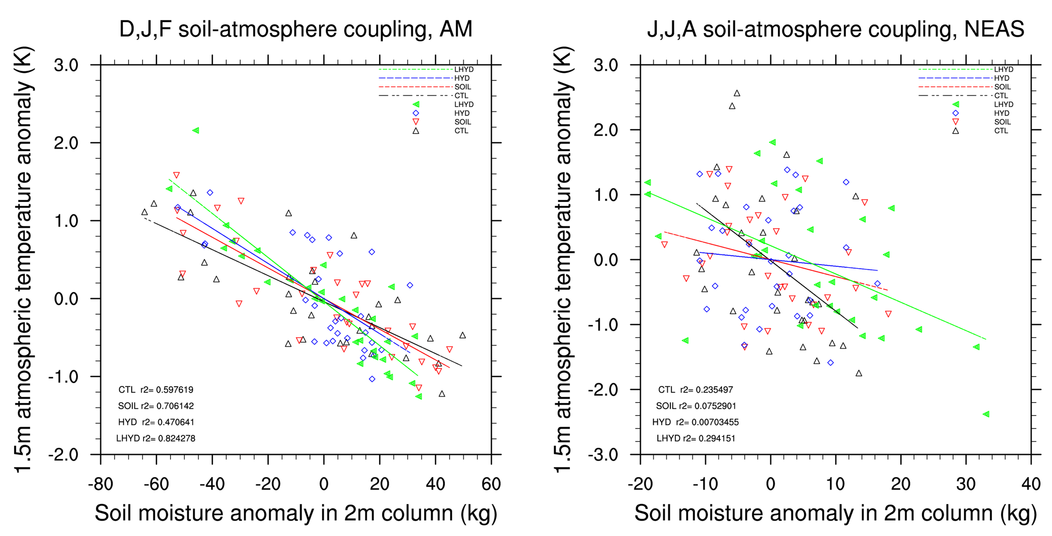


Figure 5: Soil water and surface temperature anomalies over selected regional domains: Amazonia and NE Asia. Monthly deviations for the Amazonian rain season (December, January and February), as well as for the boreal summer in NEAS (June, July and August). 10 years are shown, comprising a total of 30 pairs.

We computed monthly anomalies, as deviations from monthly means, for several regional domains worldwide (for a total of 19), targeting the "hot-spot" regions above. Two locations are shown, one in the Amazonian forest and the other in the Boreal forest of NE Asia.
The results in the Amazon indicate a strengthening of the land surface – atmosphere coupling with the new soil formulation, which is also confirmed in West Equatorial Africa and in Central Africa (from map above).
Results in the Boreal forest of NE Asia indicate that improved thermal exchanges with deeper portions of the soil strengthen the coupling.
This investigation will be expanded into soil moisture – precipitation relations.

References

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Summary

We find that the introduction of a more realistic treatment of soil physics profoundly affects soil water and thermal dynamics, as well as plant activity at the surface. These changes are particularly noteworthy at high latitudes, where the enhanced heat transfer in the soil alters the fraction of unfrozen water, which is made available to plant roots and activates GPP, enabling longer-lasting growing seasons and enhanced seasonal to interannual variability.