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GEWEX-ISMC SoilWat Project: Taking Stock and Looking Ahead

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H3S Welcomes New Members and Introduces New Initiatives in 2021

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On January 28th, the American Geophysical Union (AGU) Hydrology Section Student Subcommittee (H3S) welcomed 15 new members to the committee, ranging in career stage from undergraduate student to postdoctoral researcher. Since the first meeting, H3S members and subcommittees have been busy brainstorming new initiatives, resources, and opportunities for students and early career researchers. On Friday, March 26th, H3S hosted the first virtual networking event of the year. This event was in the form of a speed networking social with approximately 30 one-minute blocks for early career researchers to meet and share interests. Similar events will be held virtually every month this spring with the hope of strengthening the early career community and building students' and early career researchers' networks. Events with similar goals are also in the planning stage, to be held this summer as well as at the 2021 AGU Fall Meeting.

One year ago, H3S launched its website (*agu-h3s.org*) to provide resources and highlight the research of early career scientists. This spring, H3S members are working hard to expand the website, including absorbing the *WaterPOC* database, created by students from the University of Waterloo. This database is a tool to support efforts of diversity, equity, and inclusion in the field of water research, including:

- Increasing the visibility of these researchers to their peers (both minoritized and not) up and down the career ladder
- Increasing recognition of the excellence of research conducted by these individuals
- Facilitating nominations and recruitment of these individuals for awards, leadership positions, and paid positions

This database also highlights the intersections of identities within water researchers, including race, gender, and career stage. There are currently 180+ entries in the database and it continues to grow. The *WaterPOC* database will soon be accessible through the H3S website for long-term access and maintenance.

Stay tuned for more event announcements in the coming months! Interested in learning more about H3S activities? Follow us on Twitter (*@AGU_H3S*) or Instagram (*agu_hydrology*).

Submit an Article to GEWEX QUARTERLY

Share your GEWEX experiences and activities, including scientific research results and other information associated with global water and energy cycle studies. Articles should be 800–2400 words (1–3 pages) and feature 1–2 figures. If you have an idea for a piece, please contact us at *gewex@gewex.org*.

GEWEX-ISMC SoilWat Project: Taking Stock and Looking Ahead

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The Soil and Water (SoilWat) initiative is a joint activity between the Global Energy and Water Exchanges (GEWEX) project and the International Soil Modelling Consortium (ISMC). SoilWat aims to bring together two research communities to improve the representation of soil and subsurface processes in climate models. The soil modeling community (represented by ISMC) and the climate modeling community (represented by GEWEX) are working together to identify the most pressing challenges and topics related to this effort, in terms of understanding the role of soil properties and parameters, soil physical processes (e.g., infiltration, surface evaporation, water and heat flow), root hydraulics, groundwater dynamics, and their interactions with the vegetation and biogeochemical cycles, deploying a combination of Earth observations (in situ and remote sensing), modeling, and data assimilation.

Soil Properties and Pedotransfer Functions

There is a longstanding tradition in soil science of developing and applying pedotransfer functions (PTFs) for the calculation of hydraulic properties (Clapp and Hornberger, 1978; Cosby et al., 1984; Pachepsky and Rawls, 2004; Vereecken et al., 2010; Van Looy et al., 2017; Dai et al., 2019a). These functions use basic soil properties that are widely available, such as texture, organic matter, and bulk density, to estimate hydraulic, solute transport, thermal, and biogeochemical parameters (Van Looy et al., 2017). The soil hydraulic properties (water retention characteristic and the hydraulic conductivity curve) (Brooks et al., 1964; van Genuchten, 1980; Montzka et al., 2017; Gupta et al., 2020; Gupta et al., 2021) are pivotal in describing the flow and storage of water in soil and its availability for vegetation via root water uptake (Verhoef and Egea, 2014).

Besides applications in soil science, ecology, engineering, and hydrology, soil hydraulic functions and their PTFs are used extensively to derive hydraulic parameters for land surface models (LSMs). LSMs are embedded in global climate and

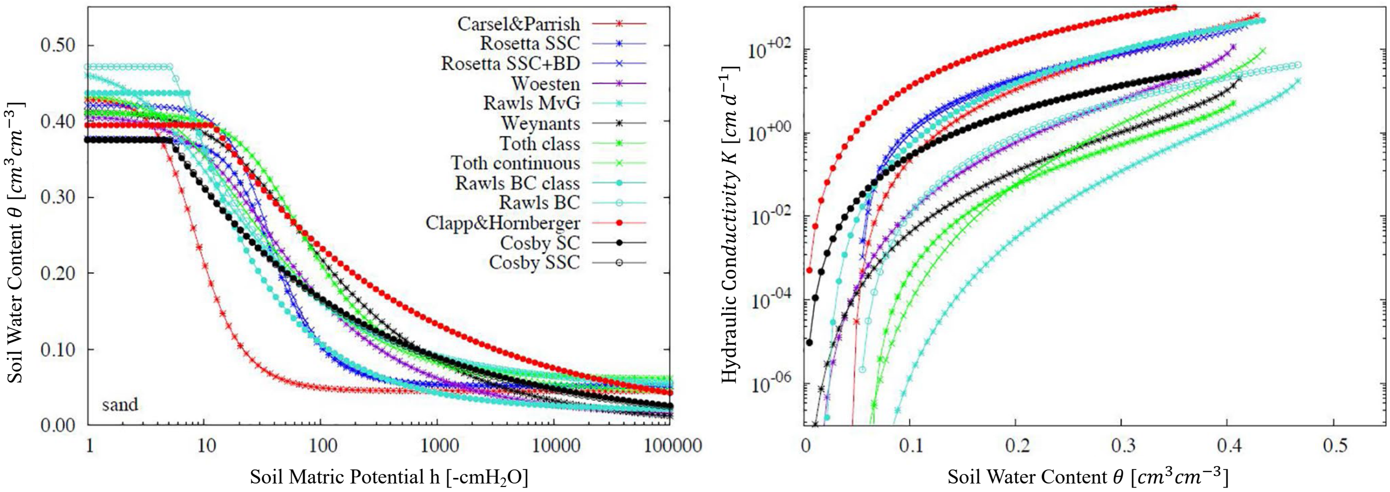

***Figure 1**. Summary of the SP-MIP effort. Comparison between experiments 1 and 2 will show the model diversity caused by the PTFs. Comparison between experiments 2 and 3 will show the model diversity that comes from different soil maps and aggregation schemes. Experiment 4 serves: (i) to quantify the effect of spatial variability of soil parameters on model diversity, (ii) to assess the sensitivity of each model to soil hydraulic parameters, and (iii) to investigate to which degree the spatial variability of key water and energy balance outputs is controlled by soil properties.*

numerical weather prediction (NWP) models to enable regional to global coverage and calculation of soil- and land surface-related processes, pertaining to the water, energy, and carbon balances. Consequently, uncertainty in basic soil properties propagates into the derived soil parameters and can affect fluxes and state variables simulated by LSMs (Weihermüller et al., 2021; Dai et al., 2019b). For example, the evaluation of European Centre for Medium-Range Weather Forecasts (ECMWF) soil moisture and temperature analyses against in situ data collected on the Tibetan Plateau (TP) revealed that the persistent systematic model bias is mainly caused by nonrepresentative values of saturated hydraulic conductivity used in the model and simplifications of certain soil physical processes (e.g., freeze-thaw) (Su et al., 2013; Yu et al., 2018). A further investigation into the five existing soil texture databases over the TP demonstrated a wide uncertainty range across different climate regions of the TP (i.e., arid, semi-arid, and subhumid) (Zhao et al., 2018). The results of these kinds of studies show that the choice of soil information and soil databases matters for LSMs (Dai et al., 2019a; Montzka et al., 2017; Fatichi et al., 2020).

Information on basic soil properties such as soil texture and porosity is also used to derive the parameters required in the equations used to calculate thermal soil properties (thermal conductivity and heat capacity) in LSMs (Dai et al., 2019a; Johansen, 1977; Lu et al., 2007; He et al., 2020; Ghanbarian and Daigle, 2016; Dai et al., 2019c). Hence, the term PTF can also be used in this thermal context. Furthermore, other than considering thermal property equations and their PTFs, SoilWat ultimately aims to develop a unified underlying theory to yield both thermal and hydraulic parameters in a physically-consistent way (Lu and Dong, 2015). This will help facilitate the harmonization of soil hydro-thermal properties and their PTFs as used in LSMs, to avoid artifacts potentially originating from the choice of soil property maps and PTFs (Weihermüller et al., 2021), and confusion with uncertainties stemming from different model structures and physics.

For this purpose, SoilWat is conducting a systematic assessment of the quality of resolved soil maps used in climate modeling, and the effect of different soil maps on the prediction of land surface fluxes and state variables. With this endeavor, we seek to improve the quality and resolution of soil maps used in LSMs. Current ongoing efforts include a "Soil Parameter Model Intercomparison Project" (SP-MIP, see Fig. 2); this involves eight LSMs [i.e., the Community Land Model (CLM), the Interaction Sol-Biosphère-Atmosphère (ISBA) model, the Joint UK Land Environment Simulator (JULES), the Jena Scheme for Biosphere Atmosphere Coupling in Hamburg (JSBACH) model, the Organising Carbon and Hydrology In Dynamic Ecosystems (ORCHIDEE) model, the Minimal Advanced Treatments of Surface Interaction and Run Off (MATSIRO) model, MATSIRO with Groundwater (MATSIRO-GW), and the Noah- Multiparameterization (Noah-MP) model] and the ISMC working groups of "Soil Thermal Properties" and "Pedotransfer functions and land surface parameterization" (*https://soil-modeling.org/science-panels/working-groups/pedotransfer-functions*). Analysis of the SP-MIP data is currently ongoing.

The recent paper by Weihermüller et al. (2021) explored the effect of using different PTFs (Clapp and Hornberger, 1978; Cosby et al., 1984; Pachepsky and Rawls, 2004) (see Fig. 1) on key components of the water balance for an area in Germany (using a 30 year set of meteorological driving data). It employed the widely used and tested HYDRUS model (Šimůnek et al., 2016) to avoid confounding effects of choice of PTF and model structure. The effects on the evapotranspiration were considerable, and they varied depending on the choice of soil type, land cover (bare, grass, or crop), and whether groundwater was present. Follow-on studies are currently being conducted to test the effects with other independent soil physical models, as well as the effects on the thermal regime.

Soil Infiltration Processes

Infiltration is a key soil process that partitions precipitation

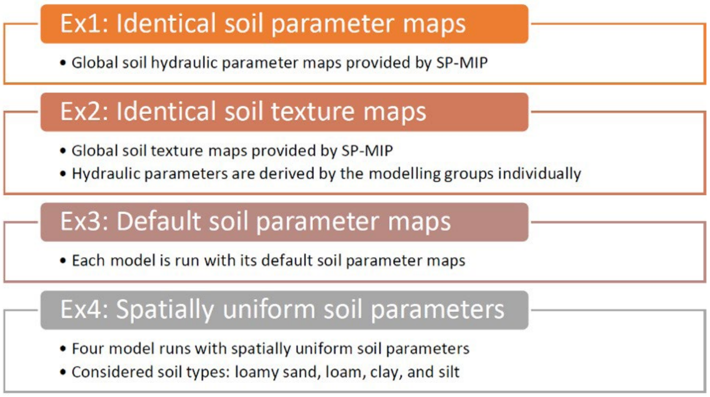

***Figure 2**. Soil water retention curve (left) and hydraulic conductivity curves (right) for the United States Department of Agriculture (USDA) sand class for 13 PTFs (colored curves).*

into surface runoff and water that enters the soil profile. As part of the SoilWat initiative, Vereecken et al. (2019) reviewed the basic principles and current approaches to describe infiltration in LSMs, its numerical implementation, and its sensitivity to model parameters. They found a large variation in infiltration approaches adopted by LSMs, also in relation to upscaling from the local to the grid-scale, in addition to the large variety of approaches used to estimate soil hydraulic properties as mentioned above. They identified several processes not yet considered in LSMs that influence infiltration into soils such as soil structure (Fatichi et al., 2020), water repellency, crusting, freeze-thaw processes, hysteresis, flow instability, and swelling and shrinking. At present, we lack information on how, e.g., vegetation and land use may impact soil structure and thus soil hydraulic properties and the process of infiltration, although efforts by Gupta et al. (2020, 2021) have tried to take this into account.

Soil Surface Evaporation

Soil evaporation is an important component of the hydrological cycle that affects plant available water and the surface energy balance. Knowledge of surface evaporation (defined as evaporation from soil pores and canopy interception, but not transpiration) is important for separation of evapotranspiration to its components (transpiration and evaporation) to better link the water and carbon cycles and for various aspects of water resource management (e.g., irrigation scheduling). The dynamics of soil evaporation and internal drainage following rainfall are sensitive to soil properties; in other words, soil type (as defined by its textural composition) affects the rates by which soil water percolates to deeper layers, and the surface resistance to evaporation. It also affects a characteristic depth below which water cannot be easily extracted by capillarity and related physical processes (of course, plant roots can access and extract soil water down to several meters). These common but often overlooked soil effects on soil evaporation have been formulated in a conceptual model by Or and Lehmann (2019) termed the *Surface Evaporation Capacitor* (SEC), and the model has been applied globally to improve climatic surface evaporation predictions (highlighting shortcomings of some of the common approaches presently used to deduce this important land surface flux). The SEC implements a simple and easy-to-use formulation of evaporation surface resistance (Lehmann et al., 2018) that has been tested using *FLUXNET* data and decadal lysimeter records from arid regions (Lehmann et al., 2019). More recently, the SEC model has been extended to include the competing effects of drainage in an analytical framework (Lehmann and Or, under review). This line of research not only fits into the SoilWat theme of linking soil and climate processes, but it also offers readily useable improvements for global models as has been shown recently (Or and Lehmann, 2019; Decker et al., 2017; Mu et al., 2021).

Soil Water and Heat Flow

Most of the current operational LSMs describe water flow via Richards' equation and heat flow via Fourier's law, and the soil water and heat flow are "softly" coupled via soil heat capacity and thermal conductivity, both of which are dependent on soil water content. Although such model treatments of soil physics can broadly capture the soil water-heat dynamics over humid and subhumid regions, their performance over arid and semi-arid lands (ASALs) (that make up >40% of the globe) are always compromised. Such model deficiency over ASALs is mainly caused by the missing mechanism of vapor transfer, which is key for actively and dynamically coupling soil water and heat flow, since it carries simultaneously mass and energy (Garcia Gonzalez et al., 2012; Zeng et al., 2011a; Zeng et al., 2011b; Shahraeeni and Or, 2010; Shahraeeni and Or, 2012; Shokri et al., 2009).

A study with water vapor transfer incorporated into the JULES model found that the water vapor flux contributes significantly to the water and heat transfer in the upper soil layers over three semi-arid and temperate arid sites (Garcia Gonzalez et al., 2012). The inclusion of vapor transfer has a direct and positive impact on the diurnal evolution of evaporation, soil moisture content, and surface temperature, which will contribute to the improved understanding and prediction of land-air interactions. Furthermore, the consideration of soil vapor flow can further our wider process understanding, including land-atmosphere feedbacks at larger scales. For instance, we might be better able to grasp why afternoon rain is more likely over drier soils (Taylor et al., 2012), or why the semi-arid ecosystem plays a dominant role in the trend and variability of the land CO_2 sink (Ahlström et al., 2015).

Afternoon rain falls preferentially over dry soils, particularly over semi-arid regions, where surface fluxes are sensitive to soil moisture and convective events are frequent (Taylor et al., 2012). Semi-arid ecosystems were found to account for 39% of interannual variability of global Net Biome Production (NBP), which is mainly driven by the local compensatory effects of soil water availability on NBP (Ahlström et al., 2015; Jung et al., 2017). To facilitate understanding the role of soil physical processes within the above context, SoilWat is conducting an in-depth survey on how key soil physical processes (water and heat flow) are represented in Earth System and Land Surface Models.

Soil-Root Hydraulics

Since the root system is the plant organ that is responsible for the acquisition of water and nutrients, its hydraulic properties play a key role in the functioning of the vegetation and in the water, carbon, and nutrient cycles of terrestrial ecosystems. Root hydraulics have been represented in LSMs in different ways: assuming a vertical "big root" (Amenu and Kumar, 2008; Tang et al., 2015) or assuming a network of parallel roots that take up water near the root tips and that are connected at the root collar (Sulis et al., 2019; Kennedy et al., 2019). These hydraulic root models are parameterized in a "top-down" approach by first postulating a simplified root hydraulic structure and then defining its parameters from root distributions and root segment hydraulic properties. Another approach is to start with a 3-D root hydraulic architecture model and solve the corresponding flow equations. This system of equations was scaled up to a 1-D model and general properties of the root system that describe total root water uptake and water uptake distributions as a function of the soil water potential distribution can be derived (Vanderborght et al., 2021).

It was found (Vanderborght et al., 2021) that the upscaled equations can be approximated by a form that is equivalent to the parallel root model. This implies that parameters of the parallel root model can be derived in a bottom-up approach from 3-D root hydraulic architectures, whereas this was not possible for the big-root model, which contains twice the number of parameters as the parallel root model (see Fig. 3, on cover). A parallel root model that was parameterized in a bottom-up approach predicted the root water uptake profiles better than parallel root or big root models that were parameterized in a top-down approach. These results show that simple 1-D root hydraulic models used in LSMs can represent uptake by complex 3-D root hydraulic architectures. Root density profiles could be used to parameterize root architecture models that are subsequently used to parameterize the upscaled root water uptake model. The 3-D root hydraulic architecture is currently being coupled with a soil-root transfer model that describes the water flow from the bulk soil to the root surface and represents non-linearities of soil water flow equations. First results show that upscaling the linear equations of the 3-D root hydraulic architecture, and then coupling the upscaled equations to the non-linear soil equations, results in good predictions of the root water uptake profiles compared to predictions by the full 3-D model coupled with the non-linear soil equations. The upscaling reduces the number of non-linear equations that need to be solved so drastically that this approach may be feasible for use in operational LSMs.

Soil-Groundwater Interactions

The groundwater system is an essential component of the global hydrological cycle, and is directly connected with the soil profile via the deep drainage at the bottom of the soil profile (groundwater recharge), and root water uptake and capillary rise from the groundwater for relatively shallow groundwater levels. Hence, groundwater can moderate soil water content, and therefore the root water uptake and related transpiration and evaporation processes. It also controls root distribution patterns, together with local climate conditions (i.e., precipitation-infiltration depth) (Fan et al., 2007).

The first generation LSMs did not include simulation of groundwater and simply applied a free drainage boundary condition to the bottom of a fixed soil column. More recently, however, groundwater simulation has been included in a number of LSMs (Yeh and Eltahir, 2005a, 2005b; Maxwell and Miller, 2005), and tested at a range of scales from single basins to the globe, with approaches ranging from lumped to distributed models. Note that lateral groundwater flow is not generally included in the majority of global hydrological models and LSMs, with some exceptions, e.g., Felfelani et al. (2021). Including water table dynamics has been shown to improve river discharge simulations (Yeh and Eltahir, 2005b; Koirala et al., 2014) and including capillary flux from groundwater increases evapotranspiration, with the global mean simulated to rise by up to 16% (Koirala et al., 2014; Niu et al., 2007; Yeh and Famiglietti, 2009; Anyah et al., 2008). Key SoilWat members, together with members of the wider GEWEX hydrological community, are currently in the process of resubmitting a paper on "Global groundwater modeling and monitoring: Opportunities and challenges" (Condon et al., under review) that looks at the complexities of implementing realistic groundwater modeling on the continental to global scale.

Summary and Outlook

There are a number of publications addressing relevant issues linked to SoilWat aims. Ongoing studies include the importance and influence of soil hydraulic and thermal properties, pedotransfer functions accounting for soil structure, soil-plant interactions (via root hydraulics), soil evaporation, coupled soil water and heat flow, as well as soil-groundwater interactions on land surface processes.

Outstanding issues are:

- Critically, how to systematically evaluate added value of improved soil process representation in LSMs (see Bonetti et al., 2021 for some of the challenges of showing improvement)
- How to best consider relevant soil-process-based evaluation metrics in Model Intercomparison Project (MIP) activities, e.g., via incorporation of suitable soil-related indices in the International Land Model Benchmarking Project (ILAMB, *https://www.ilamb.org/*) or *https://modelevaluation.org*
- Soil root hydraulics, and plant hydraulics, depend on the vegetation structure (leaf area index, canopy height, rooting depth, root density). Since roots are hidden, information about root distributions is scarce. Root systems adapt to the soil and environmental conditions. This plasticity has been addressed in LSMs by considering "optimal" distributions. However, in managed systems and when environmental changes occur faster than the

process that optimizes these distributions, optimality cannot be assumed. Describing how vegetation will respond to changing environmental conditions (either by management or due to climate change) will therefore be critical to predict land-surface processes.

- How to better represent preferential (aka bypass) flows in LSMs (Gharari et al., 2019), for example, as caused by macropore flows (Rahman and Rosolem, 2017), fingered flows, and funnel flows (Pales et al., 2018; Demand et al., 2019). This would also require concerted efforts in collaboration with the soil biological and related modeling communities.
- In ASALs, soil water and heat transfer are strongly coupled, and the soil vapor flow dominates (i.e., carrying both mass and energy). Nevertheless, the soil vapor flow is largely ignored in LSMs, and the water flow is only weakly coupled with heat transfer through the heat capacity and thermal conductivity functions (i.e., via soil water content). On the other hand, land surface fluxes and convective events are very sensitive to soil moisture over dry lands, and so is the interannual variability of NBP. Therefore, it is essential to revisit the importance of representing soil vapor flow in LSMs for understanding land-air interactions over ASALs. Related to this issue is the topic of vapor adsorption and how to represent this in LSMs for ASALs (Saaltink et al., 2020; Verhoef et al., 2006). Saaltink et al. show that, on a yearly basis, inward vapor flux (adsorption) into soil can be around a third of the outward vapor flux (evaporation). Detailed soil physical models can reproduce these diurnal evolutions of soil vapor flow, but only if the driest part of the soil water retention curve is represented properly, which brings us back to the importance of choice of hydraulic and thermal properties, and their PTFs.

SoilWat will organize workshops and seminars to facilitate discussions on the above issues, and report back to the community on the outcomes.

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