Weak sensitivity of the terrestrial water budget to global soil texture maps in the ORCHIDEE land surface model

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Reply to anonymous Referee #3

General

C1: This paper explores the impact of soil texture on the simulated water budget by the ORCHIDEE LSM at the global scale at 0.5 degree resolution. The authors conclude that the use of three different soil texture maps result in very similar terrestrial water budgets, and that the choice of the input soil texture map is not crucial for large scale modelling. While the study topic is very relevant and deserves publication, the manuscript needs to be revised.
We would like to thank the reviewer for taking the time to go through the paper, and for the relevant comments. According to all the three reviews that we received, we decided to make some substantial changes to the paper, in particular, the scientific question of the paper will be more clarified and new sub-sections will be added. A detailed presentation of the new structure of the paper is presented in the answer to Referee #1. In the following, we will provide a response to every point raised by Referee #3, these points are numbered from C1 to C21 for convenience.

C2: First, I think the authors should make in the Introduction their research question(s) clearer, in my opinion lines 52-53 are not sufficient, and it is also not quite clear why this research is different from earlier studies.
This comment was already raised by Referee #1, and we agree that the scientific question of the paper was too briefly stated in the introduction of the submitted paper. In the revised version of our paper, this will be clarified by expanding the last line of the introduction to a more classical paragraph detailing the specific research question of the paper and the structure of the paper: "*Here, we aim at exploring more systematically the impact of soil texture on the water budget from point to global scale, using a state-of-the-art LSM with physically-based soil hydrology, and multiple input soil texture maps. After presenting the model and soil texture maps used in this work, the results are presented as follows. We first provide an analysis of the similarities and differences between the different soil maps, then, we evaluate the point-scale response of the model to different soil textures to make sure it displays a reliable behavior. This point-scale response is then analyzed from a geographic point of view, with a comparison to a distributed observation-based ET product, and a focus is made on areas with a large sensitivity to the soil texture maps. We finally explore how the magnitude and significance of the simulated ET changes with the scale of analysis up to the land scale, defining the terrestrial water budget. The closing section summarizes the main conclusions of the study, and discusses its limitations and perspectives.*"

C3: The authors mention the use a physically based soil hydrological modelling component (including Richards equation) in these lines (line 53), but do not follow up in the Discussion and conclusions section.
This is a good point, and we propose to add the following sentences in the closing section, at the end of L210, after discussing the SP-MIP project: "*As mentioned in Introduction, much stronger responses to soil properties have been reported from bucket-type LSMs. It must be underlined, however, that these papers considered much larger changes of soil properties, which reduces in bucket-type models to available water holding capacity (AWC), combining information on porosity, soil depth, and the difference between field capacity and wilting point. As an example, the main changes discussed in Stamm et al. (1994), Ducharne & Laval (2000), de Rosnay & Polcher (1998), and Milly & Dunne (1994), correspond respectively to AWC changes of +75%, +110%, +200%, and +1400%, while the AWC changes when switching among the three soil texture maps used in the present paper range between +1 and +7%.*" These percentages will be supported by citing the updated Figure 8, to be moved to the new section 3.1, cf response to comment C22 Referee#1.

C4: Furthermore, I believe the manuscript could benefit from a more detailed analysis and description on the differences between hydrological variables from different soil texture inputs (and PTFs), also focused on a regional/local scale.
We agree with the reviewer, and as detailed in the answer to Referee #1, we will add a dedicated sub-section in the results (3.4) where we look into the impacts of soil texture in the most impacted regions.

C5: Finally, I am wondering why the authors did choose to scale up the high resolution soil texture dataset to the model resolution as a function of the dominant USDA soil texture class. Why not, when applicable, calculate the soil hydraulic parameters at high resolution, and then scale up (with appropriate scaling operators (for example in the line with Samaniego et al., 2010))?
By default, ORCHIDEE upscales the input soil texture map to the model resolution (0.5°) by selecting the dominant USDA soil texture. This choice is hard-coded, and it is not in the purpose of our study to test different upscaling methods. However, we would like to point out that only the Reynolds map was upscaled by the model; the Zobler soil map is available at 1° resolution, so no upscaling was performed for this map, and the used SoilGrids map was provided by the SP-MIP team at the 0.5° resolution.

Specific comments

C6: A detailed description of the ORCHIDEE LSM would be helpful.
Based on this comment, and the ones from Referee #2 regarding root uptake and the effect of LAI on evapotranspiration, we will expand the description of ORCHIDEE in section 2.1. To this end, lines 61-74 will be changed to the following text (changes in bold):

"*The physically-based soil hydrology scheme solves the vertical soil moisture redistribution based on a multi-layer solution of saturation-based Richards equation, using a 2-m soil discretized into 11 soil layers* ***of increasing thickness with depth*** *(de Rosnay et al., 2002).* ***Infiltration is processed before soil moisture redistribution, owing to a time-splitting procedure inspired by the model of Green and Ampt (1911), with a sharp wetting front***

propagating like a piston (d'Orgeval et al., 2008; Vereecken et al., 2019)*. The unsaturated values of hydraulic conductivity and diffusivity are given by the model of Mualem (1976) - Van Genuchten (1980).*

In each grid cell, the corresponding parameters (saturated hydraulic conductivity K_s, inverse of air entry suction α, shape parameter m, porosity, and residual moisture) are taken from Carsel and Parrish (1988), as a function of the dominant USDA soil texture class, itself derived from an input soil texture map. ***The tabulated values of the different soil parameters are given for each USDA class in Figure S1. Soil texture is assumed to be uniform over the soil column in ORCHIDEE, which does not permit to distinguish several soil horizons. However, K_s decreases exponentially with depth, to account for the effects of soil compaction and bioturbation, as introduced by d'Orgeval et al. (2008) following Beven & Kirkby (1979). It must also be noted that the horizontal variations of K_s are taken into account by an exponential probability distribution, but only for calculating infiltration and surface runoff (Entekhabi & Eagleson, 1989; Vereecken et al., 2019). The soil texture also influences heat capacity and conductivity, and heat diffusion is calculated with the same vertical discretization as water diffusion in the top 2m, but extended to 10 m (Wang et al., 2016).***

Evapotranspiration is described by a classical bulk aerodynamic approach, distinguishing four sub-fluxes: sublimation, interception loss, soil evaporation, and transpiration ***(Krinner et al., 2005)****. The latter two* ***are directly coupled to soil water redistribution, and depend on soil moisture and soil properties****, which control how the corresponding rates are reduced compared to the potential rate: transpiration is limited by a stomatal resistance, increasing when soil moisture drops from field capacity to wilting point; soil evaporation is not limited by a resistance, but only by upward capillary fluxes, which control the soil propensity to meet the evaporation demand* ***(d'Orgeval et al., 2008; Campoy et al., 2013) . Evapotranspiration also depends on the vegetation of each grid-cell, described here as a mosaic of up to 15 Plant Functional Types (PFTs), based on the global land cover map used in the IPSL simulations for CMIP6 (Boucher et al., 2019). In each PFT, root density is assumed to decrease exponentially with depth, with a PFT-dependent decay factor. The resulting root density profile is combined to the soil moisture profile and a water stress function depending of field capacity and wilting point to define the integrated water stress factor of each PFT to transpiration.***

This flux is also coupled to photosynthesis, which depends on soil moisture, light availability, CO2 concentration, and air temperature, following Farquhar et al. (1980) and Collatz et al. (1992) for C3 and C4 plants, respectively. The resulting carbon assimilation is allocated to several vegetation pools, including leaf mass thus leaf area index (LAI), owing to a dynamic phenology module called STOMATE (Krinner et al., 2005). It must be underlined that LAI has an important influence on the partition between soil evaporation and transpiration, via the fraction that is effectively covered by foliage, which increases exponentially with LAI with a coefficient of 0.5, also controlling light extinction through the canopy (Krinner et al. 2005). This fraction contributes to transpiration and interception loss, while the complementary fraction is assumed to be bare of vegetation, and only contributes to soil evaporation*."*

C7: Line 13: explain "medium texture", I think not every reader knows what medium means
Medium textures are the loamy textures, with medium *dm* (median diameter). To clarify this in the abstract, we will use the term loamy texture, which is clearer.

C8: Line 13-14: “The three tested complex soil texture maps being rather similar by construction…”. Do the authors mean that the soil texture maps are similar because of the way how they were constructed (taking the dominant USDA soil texture class)?
The soil texture maps are similar because of the way they are upscaled but also, and more importantly, because of their common origins (FAO/UNESCO soil map). Based on Referee #1 comments, we think that these lines are misleading, since they suggest that the similarity between the soil texture maps is *a priori* knowledge of this study, while it is a result. These lines will be replaced by a new sub-section, inserted in the beginning of the Results, and gathering quantified analyses of the similarities/differences between the tested texture maps (cf. answer to Referee #1).

C9: As mentioned in the General comments, why not calculate soil hydraulic parameters at the high resolution scale?
As mentioned earlier, testing different upscaling methods is out of the scope of this paper.

C10: Indeed the soil texture maps are quite similar. Why then not focus more on sensitivity of PTFs (now two are used in this study)?
The sensitivity to various PTFs has been the scope of many studies, as recently reviewed by van Looy et al. (2017). In contrast, the main objective of our study is to examine the hydrological response to different soil texture maps. We consider two different PTFs in our simulations (EXP4 and EXP5) because of the SP-MIP protocol, but we don’t focus our analysis on the resulting changes, which will be explored within the SP-MIP project, and are very weak based on land averages, but for soil moisture, noted by the Referee in comment C15.

C11: Line 35: 1-km SoilGrids database. A 250 m version is also available. Were the different soil layers also included in the analysis? And if yes, how? Also for example to calculate the exponential decline of Ks?
We will mention the availability of the 250m version of SoilGrids (Hengl et al., 2017) at line 35. As said in the paper, the SoilGrids map used in this study was processed at 0.5° for the SP-MIP project, and we will add it is based on the texture at 0cm depth (section 2.2). But even if SP-MIP had provided soil textures for different horizons, this information cannot be used in ORCHIDEE, as explained in the description of the model, in the revised version of the paper (cf. response to C6): *“Soil texture is assumed to be uniform over the soil column in ORCHIDEE, which does not permit to distinguish several soil horizons. However, K_s decreases exponentially with depth, to account for the effects of soil compaction and bioturbation, as introduced by d’Orgeval et al. (2008) following Beven & Kirkby (1979).”* We also underline that the simplifying hypothesis of a uniform texture over the whole soil column is discussed in the concluding section of the submitted manuscript (lines 239-240).

C12: Lines 144-145: “Rather surprisingly, we find here…”, Could you explain this in more detail? If drainage and transpiration decrease you would expect higher soil moisture values, right? The transpiration decrease is perhaps controlled by dominant vegetation type?
We agree with the reviewer, and will thus remove “Rather surprisingly”. As for the transpiration decrease for fine-textured soils, it is not controlled by dominant vegetation types, as supported by Figure 4c where each pixel of the matrix corresponds to a unique set of grid-points undergoing a soil texture change, thus with unchanged climate and vegetation

cover. This implies that the decrease of transpiration found in Figure 3 when soil texture gets finer is effectively due to soil texture. A likely reason is the increase of matric potential, thus soil moisture retention, when the texture gets finer, as shown in Figure S1 for particular values of the potential, defining the wilting point, field capacity and air entry suction point (1/α). This analysis leads to a more complex explanation of the response of transpiration to soil texture, and we propose to replace lines 142-147 by the following paragraph: "*Transpiration, however, increases as soil gets coarser (Fig. 3c), with two explanations probably acting together. Firstly, the increase of matric potential when the texture gets finer, as shown in Figure S1 for particular values of the potential, defining the wilting point, field capacity and air entry suction point (1/α), makes root uptake thus transpiration more difficult for a given soil moisture if the soil texture is finer. Secondly, the high conductivity of coarse soils enhances water infiltration at the soil surface, quickly available for plant uptake. The increase of Ks for coarse textures also explains the associated drainage increase when its dependence on mean precipitation is filtered (Fig. 3f). The fact that soil moisture decreases when drainage and transpiration get higher indicates that annual mean soil moisture is the result more than the cause of these fluxes*".

C13: Lines 148-149: Could you elaborate more (also include references)? These factors should also affect evapotranspiration…
To support this sentence, focused on the response of soil evaporation, we propose to add the following references: Martens et al. (2017) and Wang et al (2018) regarding the anti-correlation between LAI and soil evaporation (further supported by the spatial correlation of -0.32 between these two variables in our simulation EXP2); the negative impact of vegetation on soil evaporation can also develop owing to the litter, which exerts a resistance to this flux (Ogée & Brunet, 2002; Sakaguchi & Zeng, 2009). However, the dependence of soil evaporation on climatic variable (temperature, potential ET) and soil moisture will not be expanded, as it is very well established. Then, the referee is right that this dispersion transfers to evapotranspiration (Figure 3d), but to a weaker extent since soil evaporation is not the main component of total ET.

C14: Line 158: Please describe Figure 4 in more detail.
We agree with Referee #3 (and Referee #2) that Figure 4 was too briefly discussed. This figure is intended to show how the simulated variables change when only soil texture changes, to better analyze the model's response to the different soil textures. We propose to expand the last paragraph of section 3.1 addressing this Figure:
"*By focusing this time on the point-scale changes induced by changing the soil texture map (from Reynolds to SoilGrids), Figure 4 highlights that the simulated soil evaporation decreases from fine to coarse textures, so that capillary retention, which is the main limiting factor to soil evaporation in ORCHIDEE, depends more strongly on soil moisture (higher for fine soils) than on intrinsic capillary forces (stronger for fine soils). We fail to see this behavior in Figure 3, which is likely due to the greater impact of diverse climatic conditions and vegetation associated with every soil texture. Figure 4 also confirms the results of Figure 3 for the other variables, including the decrease of soil moisture with coarser soils and the greater impact of soil texture on runoff variables (surface runoff and drainage). In particular, we find that replacing fine textures with coarse textures (above the first diagonal of the matrices) results in higher drainage (due to the higher permeability of coarse-textured soils) and lower surface runoff, with changes that can exceed 1mm/d in absolute value for some textural*

changes (all involving medium texture classes). As a result, less water is available in the soil, which leads to less soil evaporation, further leading to more transpiration (Fig. 4bc).

The convex behavior of total runoff with soil texture can also be seen in Figure 4h, which is antisymmetric along the two diagonals, thus defining four different kinds of total runoff change to soil texture change. This behavior results from the fact that total runoff sums up two variables of opposite response to soil texture change (surface runoff and drainage), the net response depending on the dominant component. Hence, changes to medium textures from either coarse or fine textures (left and right red triangles in Fig. 4h) lead to reduced total runoff, owing to reduced surface runoff in the first case, and reduced drainage in the second. In contrast, changes from medium texture to either coarse or fine textures lead to increased runoff (bottom and top blue triangles in Fig. 4h), owing to increased surface runoff or drainage, respectively. This pattern thus means that the medium textures correspond the smallest total runoff. By means of long-term water conservation, the opposite patterns are found for total evapotranspiration changes (Figure 4d), because of the opposite responses of soil evaporation and transpiration to soil texture, and supporting the concave response of this flux to soil texture found in Figure 3."

C15: Figure 5: EXP5 seems to show a large difference in soil moisture with EXP4. In my opinion an interesting result, but not mentioned in the text and explained.
While both EXP4 and EXP5 use the same soil texture map, the PTF used in each experiment is different. Moreover, in EXP5 (as well as EXP6-EXP9), Ks is constant with depth, unlike the experiments EXP1-EXP4. We will add this clarification when describing the different simulations (section 2.2, L 1109): "*It must be noted that the five simulations based on the soil parameters of Schaap et al. (2001) also differ from the four others (EXP1 to EXP4) because the decrease of Ks with depth is relaxed, to comply with the SP-MIP protocol.*"
As a consequence, the decrease of soil moisture between EXP4 and EXP5 is not only due to PTF change but also the increase of Ks at the bottom of the soil column in EXP5, because Ks does not decrease with depth. This favors drainage, thus reduces soil moisture, and we propose to add this explanation when discussing Fig. 5, at line 172.

C16: Line 187-188 and Figure 7: Ok, indeed transpiration and soil evaporation show weak sensitivity, but other variables like drainage, surface runoff and soil moisture show a stronger sensitivity. For example, when you focus on Scandinavia, drainage decreases, surface runoff increases, and soil moisture increases. I believe the manuscript should also focus on these variables, in specific regions. Why is transpiration not affected here by the soil texture maps, and the water balance components as drainage, surface runoff and soil moisture do change?
As stated earlier, a new subsection dedicated to regional zooms on the most impacted regions by soil texture change will be added in the Results (3.4). In Figure 7, the Scandinavian soils were changed from Sandy Loam (in Reynolds map) to Loam (in Zobler map). According to Figure 4, the consequence of this change is an increase in surface runoff (by 0.1-0.5 mm/d) and soil moisture (by 100-200 kg/m^2), and a decrease in drainage (by -0.1 to -0.05 mm/d). The change in transpiration is much lower than the one of surface runoff and drainage, and does not exceed 0.05 mm/d (in absolute value). The latter results are well in agreement with Figure 7, and the non-significant changes in transpiration pointed by the Referee are in fact due to the weak impact of soil texture change on transpiration.

C17: Lines 208-209: what about other variables (water balance components) than evapotranspiration?
Up to now, only preliminary results were communicated by the SP-MIP team. No information about other variables was revealed.

C18: Lines 214-215: why not calculate hydraulic parameters at high resolution to remove some of that bias?
As explained earlier, it is out of the purpose of the paper to test different upscaling methods.

C19: Lines 218-219: yes, the authors could have used these upscaling method of Samaniego.
In this paper, we do not aim at testing different upscaling methods.

C20: Lines 226-235: again the focus on evapotranspiration. What about other water balance components?
In our paper, we mapped the impact of soil texture on different hydrologic variables (Figure 7 of the submitted paper and Figure S3 of the supplementary), but we chose to map the biases of the ET variable since the distributed observation-based products are only available for this variable.

C21: Line 236-244: To include and end with this paragraph the authors should focus more on PTFs (methods and results) and describe these in more detail (methods).
It must be underlined that we don’t claim here that our paper demonstrates the need for more complex PTFs. On the contrary, it massively cites other studies supporting this conclusion, and we do so because the need for more complex PTFs is related to the specific conclusion of our paper, i.e. the weak sensitivity to soil texture maps except in some very specific areas where the USDA class for Clay is not precise enough. Thus, using other sources of information than soil texture to derive the geographic distribution of soil properties may lead to clearer and broader improvements of the simulated water budget than the ones analyzed here owing to soil texture maps alone. We propose to replace the last sentence of the paper by the above one.

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