Detailed responses to reviewer comments

Worldwide soil moisture changes driven by future hydro-climatic change scenarios

Lucile Verrot * and Georgia Destouni

* Corresponding author: lucile.verrot@natgeo.su.se

Anonymous Referee #1

The authors present an interesting study by which they analyse the trends in soil mois- ture characteristics under two climate change scenarios. This is important because soil moisture is a key variable for runoff partioning. Also, it is a major control on agricultural production. Although I feel this work is of interest to HESS I have a number of issues, some of which quite major:

1) ***Comment:*** The first question that arises is why they authors used a single additional soil moisture model and not the soil moisture states from the GCM land models? Or are they not available from the CMP5 repository? They should state a reason for this is in the paper.
Answer: The reviewer refers to the CMIP5 variable *mrlsl,* the water content "in each soil layer, the mass of water in all phases, including ice" (as described in the general CMIP5 output variables available at http:// cmip-pcmdi.llnl.gov/ cmip5/docs/standard_output.pdf) and to *mrso* the total soil moisture content in "the mass per unit area (summed over all soil layers) of water in all phases" (http://cmip-pcmdi.llnl.gov /cmip5/docs/ standard_output.pdf).
There are several reasons why we decided not to choose those outputs in this study. The main one is that it has been shown that combining the main catchment water balance components (precipitation, evapotranspiration and runoff) from the CMIP5 outputs lead to large inconsistencies (Bring et al., 2015): therefore we cannot expect soil moisture derived from the water balance as it is calculated in the land surface schemes to follow meaningful trends. This highlights the need to use independent soil moisture models that do not rely on the combination of the water balance components. According to the reviewer's comment, we have now made that clearer in the introdution:
"Even though CMIP5 models to some degree provide own outputs of (mostly near-surface) soil moisture, Bring et al. (2015) have shown that the catchment-scale water balance implications of these climate models are often far from realistic. As such, direct CMIP5 model outputs for soil moisture may thus not be suitable for relevant quantification of catchment-scale soil moisture dynamics, as this is strongly related to and relies on realistic water balance representation. Not least because we also aim here to investigate projected climate-driven change in soil water content over the entire unsaturated zone (and not just near the surface), we therefore use in this investigation an other soil-moisture modeling framework (Destouni and Verrot, *2014; Verrot and Destouni, 2015,*

2016) than the direct output provided by some CMIP5 models for mostly near-surface soil moisture.
" (Lines 70-77 of the revised manuscript).

Additionally, a number of other reasons prevent a consistent global-scale cross-catchment comparison based on the soil moisture outputs from the CMIP5 models:

- Not all the selected models have those outputs available: among the 14 selected models, *mrlsl* is not an available output from the repository for CSIRO-Mk3.6.0, IPSL-CM5A-MR, MPI-ESM-MR, MPI-ESM-LR, MRI-CGCM3.
- The soil depth is not the same between models: therefore the comparison between models would be possible only for the upper layer common to all the models (down to 3 meters approximately). Here is the table of the soil layers for the models that provide the *mrlsl* output:

Model	Depths of the layers in *mrlsl* output [m]
BNU-ESM	0.01, 0.04, 0.08, 0.15, 0.27, 0.46, 0.78, 1.30, 2.16, 3.57
CCSM4 (NCAR)	0.02, 0.05, 0.09, 0.117, 0.29, 0.49, 0.83, 1.38, 2.30, 3.80, 6.28, 10.38, 17.13, 28.25, 43.74
CESM1-CAM5	0.02, 0.05, 0.09, 0.117, 0.29, 0.49, 0.83, 1.38, 2.30, 3.80, 6.28, 10.38, 17.13, 28.25, 43.74
FGOALS-g2	0.02, 0.05, 0.09, 0.117, 0.29, 0.49, 0.83, 1.38, 2.30, 3.43
FIO-ESM	0.01, 0.04, 0.08, 0.15, 0.27, 0.46, 0.78, 1.30, 2.16, 3.57
GISS-E2-H	0.10, 0.27, 0.57, 1.08, 1.97, 3.50
GISS-E2-R	0.10, 0.27, 0.57, 1.08, 1.97, 3.50
NorESM1-MN	0.02, 0.05, 0.09, 0.117, 0.29, 0.49, 0.83, 1.38, 2.30, 3.80, 6.28, 10.38, 17.13, 28.25, 42.10
NorESM1-ME	0.02, 0.05, 0.09, 0.117, 0.29, 0.49, 0.83, 1.38, 2.30, 3.80, 6.28, 10.38, 17.13, 28.25, 42.10

- Each land grid cell in those models is considered as a 1D cell. There is no lateral flows eventhough adjacent cells may have different soil depth or different elevation. The model we present, although simple, relies on the assumption of negligible lateral flows which is physically more realistic at the catchment scale than at the grid cell scale
- From the general description of CMIP5 outputs (http://cmip-pcmdi.llnl.gov/cmip5/docs/standard_output.pdf): "If soil layer thicknesses vary from one location to another, interpolate to a standard set of depths. Ideally, the interpolation should preserve the vertical integral." This standard set of depths is therefore not necessarily physically based, and knowing which cells have had their soil layer thicknesses corrected in such a way is not possible.

2) ***Comment:*** The question is also why the authors did not look at evaporation directly (probably also available from the repository). This is a more direct indicator for agricultural and ecosystem productivity. Please provide a reason why soil moisture was chosen here!
Answer: Soil moisture is not only relevant for agriculture or ecosystem functionality. It is of primary interest for many other processes and activities such as human water consumption and solute transport. We have provided

further references in the introduction to account for this comment (lines 21 and 22 of the revised manuscript).

3) ***Comment:*** The soil moisture model that is used assumes free drainage from the soil; i.e. the time-average soil moisture is such that it supports the unsaturated conductivity that allows the time-average recharge to pass through the soil under a 1:1 (is gravity) gradient. This is a realistic assumption when looking at larger time scales (which is what they do) and for unsaturated zones with deep water tables. This latter assumption does not hold for many basins they have chosen. For instance the Ob has large wetlands (peat bogs) and the lower Danube has a number of topographically flat areas (Pan- nonian Plain, Wallachian Plain) with shallow groundwater tables. The soil moisture dynamics in such areas may be much less sensitive to climate change due to ground- water convergence or impaired drainage. This is not accounted for. The question then is: what are the errors made by this assumption?
Answer: The approximation of a gravity driven flow is not a new one and is the subject of an extended literature. Some of those studies focused on the experimental and numerical analysis of the time scale and depth for which such an approximation can be held: for instance, Graham et al., (1998) have shown that it can be valid for smaller time scales than the one presented here (7-38 days). To account for this comment, we have now explained this approximation in more details in the manuscript: "This approximation was introduced and used by Dagan and Bresler (1979) and Bresler and Dagan (1981) in the context of large-scale solute transport through the entire unsaturated zone, with associated average time periods for such transport ranging from four months to five years, as quantified by the spatial-average travel time (around which there is also large spatial variability) of infiltrated water to different soil depths and in different soil types. The same approximation has also been used in multiple studies of large-scale solute transport through the unsaturated zone thereafter (e.g., Destouni and Cvetkovic, 1989, 1991; Destouni, 1993; Destouni and Graham, 1995; Graham et al., 1998), with associated mean travel times of 7-38 days, again with also large spatial variability in travel times around that spatial mean value. (lines 106-112)

4) ***Comment:*** What is lacking is a proper validation of the model. GRACE is not particularly useful for validating soil moisture variations if a proper correction for especially groundwater volume changes is not done. This is difficult as there is limited info about this. The reverse has been done a lot: estimating groundwater variations by subtracting from the total storage change TWS soil moisture and surface water volume changes as obtained by land surface models. There are now close to 20 years of soil moisture data available from remote sensing (merging passive microwave and radar-based soil moisture retrievals – TU Vienna and VU University). I wonder why these were not used to validate the basin-scale soils moisture simulations? I think a validation with these data is in order.
Answer: We invite the reviewer to consult the article "Data-model comparison of temporal variability in long-term time series of large-scale soil moisture" (Verrot and Destouni, 2016) now available online that explains in details the model

validation. The reviewer will notice that the changes in groundwater storage was indeed taken into account in the model validation.

We remain skeptical about any validation of this model with remote sensing data: in fact those methods can provide data only for the very top layer of the soil (around 5-10cm), while this model aims at quantifying soil moisture changes over the entire unsaturated zone. Ground-penetrating radar could however be a great alternative, but the use of such method for watershed-scale validation of modeled soil water content would be the subject of another study, as a validation of this model (with GRACE) is already available.

As the aim of the study submitted in HESS is not to validate the model (this is now available in JGR), and following the reviewers' comment, we have now removed the figure 2 and the related content from this manuscript.

5) ***Comment:*** The spatial variation within the basins (as big as the Danube) is neglected, as- suming that the most dominant soil type forced with basin-average recharge will yield basin-average soil moisture or soil wetness. This is a pretty big assumption given that runoff generation and evaporation are non-linear processes and heterogeneity within basins (both in soil type, orography and climate – e.g. the Danube) can be very large. The author should at least show that the assumption is warranted that their approach produces the correct trends and tendencies. This can be done with a numerical experiment by choosing a heterogeneous catchment and do the analyses on subcatchments first (or grids of the GCM) average the results over the basin and compare these to their basin-average method.

Answer: We disagree with the statement "the spatial variation within the basin is neglected". In fact, the output variable of the model is the area-averaged soil moisture: this quantity exists and does not inherently neglect any of the spatial heteoregeneities (in horizontal and in vertical space), eventhough they can be large as highlighted by the reviewer.

The now published validation of the model also provides a detailed comparison of the modeled soil moisture with small scale data (see Verrot and Destouni, 2016, in JGR-atmosphere). We have however added a figure in the supplementary material and provided additional results and discussion to account for the uncertainty in the results due to soil texture : see figure S2 and related text in section 3.2: "Model result sensitivity with regard to choices of soil parameters values is overall small in most catchments for the relative changes in mean soil water content (Fig. S3 a,b,c,d) and its inter-annual variability (Fig. S3 e,f,g,h); most importantly, a different choice of different soil parameter values does not yield a different direction of change. Overall, the greater the resulting relative change is, the smaller is the related result sensitivity with regard to choices of soil parameters values. Consequently, the relative changes in mean seasonal soil moisture under RCP 2.6 display the greatest sensitivity to soil parameter choices, while the relative changes in inter-annual variability of seasonal soil moisture under RCP 8.5 scenarios display smaller sensitivity. The relative changes in the frequency of occurrence of rare events are not sensitive to soil parameter choices (Fig. S3 i,j,k,l) as their quantification is directly and linearly related to q. For almost all the catchments and for all three soil moisture statistics, the set of chosen soil parameters values (Fig. S1) lies well within the median absolute deviation calculated from the 11 sets of soil parameters. “ (Lines 329-339 of the revised manuscript)

6) ***Comment:*** The uncertainty is only marginally taken into account. The authors have an ensemble of GCMs to do the analyses on but only use the ensemble mean (except in the plots of Figure 2). If the ensemble was used as a whole, not only the percentage change could have been reported but also a t-test to signify if this change is significant. Alternatively, they could have made a percentage change map also indicating the number of the models showing the same tendency. Working with an ensemble but not using its potential to include uncertainty is an omission that should be corrected.

Answer: Following the reviewer’s comment, we have made further analysis about models’ variability that lead us to change the variable of focus : instead of ensemble mean, we have preserved the CMIP5 models outputs and show results for the median values derived from the individual models results. Additionally, we have now provided a detailed analysis presented in the modified section 2.5, its associated results and discussion (see also figure S3) on the uncertainty based on models’ results in the manuscript :

“For the three studied statistics, the uncertainty due to inter-model variability among the CMIP5 models is greater (as quantified by the median absolute deviation) for the RCP 2.6 scenario (Fig. S4 a,c,e,g,i,k) than the RCP 8.5 scenario (Fig. S4 b,d,f,h,j,l). This means that the project change trend (sign of relative change) for each catchment is more consistent across models for the RCP 8.5 scenario than for the RCP 2.6 scenario, especially for relatively large projected changes. For instance, in the catchment Eur1, which displays the greatest increase in frequency of occurrence of dry events under RCP 8.5, the median absolute deviation ranges from approximately 200% to 650%, indicating a relatively robust projection of this change to effectively happen under the RCP 8.5 scenario. Large projected changes in terms of the ensemble mean (800%) and mean model (500%) result for this catchment also show that some climate models imply considerably greater changes than the median model result” (lines 340-348 of the revised manuscript).

“Regarding climate models, their results, including projected directions of changes, vary greatly across models and especially under RCP 2.6 scenario, as also pointed out by previous studies of projected hydro-climatic (Bring et al., 2015) and temperature (Knutti and Sedláček, 2013) changes. This suggests that the lack of consistency in hydrologically relevant outputs among CMIP5 models leads to much greater uncertainties than soil parameter choices for projection of soil moisture changes. The results shown and mostly discussed here in terms of median model results represent relatively conservative projections of such changes, emphasizing that worrying soil moisture statistics changes may be expected to occur in some catchments, particularly under the RCP 8.5 scenario, even when considering the inter-model uncertainty among CMIP5 models.“ (lines 369-377 of the revised manuscript).

Anonymous Referee #2

This paper analyzes the change in soil moisture features (dry/wet event frequency, change in water storage) for different projected climate regimes. I am not very con- vinced about the methodology, or about the relevance of this paper. Major revisions are needed before the paper could be considered for publication.

1) ***Comment:*** What is new in this paper compared to earlier studies that investigated the effect of climate projections on soil moisture? Please explicitly state the new findings or advancements. The introduction refers excessively to Destouni or Verrot and findings by major research institutes specialized in climate projections are barely discussed.
Answer: We have now revised the introduction according to the reviewer's comment (lines 33-58 of the revised manuscript "Soil moisture in the top layer is…. any soil depth of interest"). However we would like to point out to the reviewer that, as stated now in the introduction, most of the studies focusing on soil moisture at catchment scales focus on part only of the unsaturated zone (first few centimers down to the root depth), while the presented model covers the entire unsaturated zone, making difficult any direct comparison with other results.

2) ***Comment:*** The paper refers to Verrot and Destouni (2016), which is in review and not available.
Is fig. 2 copied from that paper? Why even spend time on GRACE in this paper in HESS, if it is already included in another paper? If GRACE is essential in this paper to justify the validity of the new approach, then please explain exactly how the climatology of GRACE is compared to the model. How are the scaling parameters used in the GRACE data processing, which spatial resolution is used? These GRACE scaling parameters are model-based, so the evaluation would have to be done very carefully to make any sense.
p.5, L.113 refers to Fig 2 without discussing it in the text. Why are only a handful of catchments shown, if both CMIP5 and GRACE have global data? How is GRACE soil moisture extracted from the total water storage (=snow+soil moisture+biomass+groundwater) changes? How is the comparison in snow-covered catch- ments? Please discuss the figures or leave them out if already included in a previous paper.
Answer: We invite the reviewer to consult the article "Data-model comparison of temporal variability in long-term time series of large-scale soil moisture" (Verrot and Destouni, 2016) now accepted and available online that explains in details the model validation. Following the reviewer's comment, we have now removed Figure 2 and related text from the manuscript.

3) ***Comment:*** Honestly, I don't understand why this new modeling approach is introduced and I see nothing but problems with it. Please clearly justify the need for the new modeling approach in this study:

- depth-average soil moisture: up to which depth? The depth to bedrock varies in space. How can we make consistent conclusions about the soil moisture features

if the depth is different everywhere? A shallow layer will respond very differently to a deep layer (different memory).
Answer: As stated in the introduction and modeling approach section, the soil moisture derived from the model is the value averaged over the unsaturated zone. However, in order to account for the reviewer's comment, we have now made the definition of the unsaturated zone clearer (see lines 91-93 of the revised manuscript "The unsaturated zone is here defined as the soil depth bounded by the land surface at the top and the groundwater table at the bottom. By definition, at each point in time, the groundwater table position is where the water pressure equals the air pressure.")
The model does not aim at reproducing short time scale absolute values of soil moisture, where antecedent soil moisture value has to be accounted for to calculate infiltration rate (in fact we do not calculate infiltration rate here). Here the presented modelling approach relies on the relationship between the ability of the soil to generate (vertical) outflow and the water content, under a unit hydraulic gradient (this is a well known process indeed). The approximation k~q is not new, but the model links those two relationships to the oberserved hydroclimate. This is stated and explained in details the methodology section.

- ***Comment:*** Eq. 1 essentially says that soil moisture = scaled runoff. All other terms are constant parameters in time. I do not think that any of the subsequent analyses would differ if the constant parameters were simply omitted, so why even worry about them?
Answer: We have now provided an analysis of the uncertainty due to soil texture parameters values: see lines 219-22, new section 3.2 lines 328-348. As now stated in the revised manuscript, the frequency of occurrence of rare events does not change, however the relative changes in the mean water content and its interannual variability is affected by soil texture.

Comment: This Eq also assumes that evapotranspiration is constant (not affecting soil moisture) and consequently, this assumes that the relative partitioning of runoff and ET varies in time. Why introduce all these assumptions, if we have land surface models to calculate soil moisture? The CMIP5 model output must have soil moisture estimates that are ready for use and they must be superior because they come from a coupled simulation (with feedback between land and atmosphere), whereas the presented simulations presumably include no feedback.
Answer: We disagree with this comment:

1) Equation 1 (and none of the equations) doesn't assume that the evapotranspiration is constant. We do not understand this comment.
2) "they must be superior because they come from a coupled simulation". Land-surface schemes rely on a heavy number of assumptions too (many of which are not available). Soil moisture is the result of complex processes that none of the models can capture: Models need to rely on a certain number of symplifying assumptions depending on their intended use and therefore assuming that soil moisture from land surface schemes is inherently 'superior' to any other model because they include a land-atmosphere feedback seems to be a very strong generalization. Moreover the presented model relies on the quantification of the water that

infiltrates the soil layer, which is a result of the land surface schemes (and is therefore affected by all the processes that the land surface schemes include).

We also refer to reviewer's 1 first comment for a more detailed explanation of the differences between this model and the relevant CMIP5 land-surface schemes.

This comment probably comes from a misunderstanding of the model's conceptual representation of processes and the study's goals: we have now revised the introduction to make it clearer (see lines 33-50 and 70-87 of the revised manuscript)

- ***Comment:*** the method assumes an insignificant change in long-term subsurface storage. (L.130). This is an invalid assumption in many regions where the groundwater is depleted (cfr. studies using GRACE data over California, East Africa, India).

Answer: We have specifically adressed this question in the manuscript (lines 130-134 of the original manuscript and lines 157-161 of the revised manuscript): the CMIP5 outputs for the water balance does not show significant change in water storage.

- ***Comment:*** around L.174: an upwards flux may perhaps be a replenishing of the surface layer by the groundwater or some other deeper layer soil moisture. There is nothing unphysical about it. Please check the model structure and explain this phenomenon, rather than treating the data as if they came out of a black box. It may affect the analysis results.

Answer: The physical meaning of negative values of *Reff* does not interfere with any of the methodology or results from this study: the model relies on the assumption of a gravity drainage flow, therefore it is necessary to discard the catchments where the flow is upwards. Following this reviewer's comment we have tehrefore removed the mention of the physical meaning of negative Reff values.

- ***Comment:*** around L. 191: why did the authors derive soil parameters based on the HWSD texture information? Why not simply use the parameters that were used in the model simulations to be consistent?

Answer: To our knowledge, those parameters are not available. However to account for the uncertainty in the parameters' estimation, we have now provided the quantification of the uncertainty in the results due to the 11 USDA soil textures that cover a wide range of values of soil hydraulic properties: see lines 219-22, new section 3.2 lines 328-348.

4) ***Comment:*** Results: please verify all figures and explain the findings:

-L.262: Nam9 is not shown in fig3

Answer: We have now removed figure 3 and the associated supplementary figures as we have refocused the study on the median of the models' results following reviewer's 1 comments.

- ***Comment:*** explain the reason why catchments may react in "opposite" ways under RCP 2.6 and 8.5.

Answer: This has to do with the underlying land surface schemes modeling and global circulation models, to which we don't have access. More importantly, the goals of this study is not to provide an analysis of the internal schemes of global circulation and land surface models.

- ***Comment:*** how are all these results affected by the lack of feedback from the land surface to the atmosphere?

Answer: This model, as well as many other models focusing on soil moisture (e.g. Rodriguez-iturbe et al., 1999, now cited in the revised manuscript) aims at quantifying the impacts of a given hydroclimate on soil moisture: it does not quantify the evapotranspiration or the precipitation, but rather uses them to quantify soil moisture.

Anonymous Referee #3

Comment: This study presents a global analysis of hydro-climatic change. The authors performed a post processing of existing scenarios by computing a proxy of the soil moisture using a simplified model developed and published in previous studies.

My main concerns are linked to the model and the adding value it provides in comparison to more direct climatic indicators (P-ET, ET/ET0 Precipitation indexes) or simple water balance approaches, which for me would be more appropriate since all the water flow terms are available in CMIP 5 simulated data set. In the model presentation and in the discussion it would be important to better position the method and discuss its relevance with respect to other approaches.

Answer: We have now provided further justification for the use of such an independent soil moisture model in the manuscript: see lines 70-77 of the revised manuscript. We also refer to the answer to the first comment of reviewer 1.

1) ***Comment:*** The presentation of the model is not always easy to follow. A schematic diagram defining clearly the modelled system and the flows and how they can be related to the CMIP 5 output variables would be very useful.

The principal difficulty come with the definition of the Runoff Reff and R. To my understanding, Reff is the ground water recharge and R the sum of ground water recharge and surface runoff. This can be clearly defined in a figure.

Answer: As the number of figures is already quite large, we would like to refer the reviewer to Destouni and Verrot, 2014, where such a schematic model structure was provided. Reff is the contribution of the sursurface discharge to the total runoff (streamflow) as stated in lines 123-125 of the revised manuscript (unchanged from the original version: ”This subsurface runoff component R_{eff} complements the runoff component $(1-\gamma)R$ of overland and pure (not fed by subsurface water into the) surface water flow”)

2) ***Comment:*** The depth of the soil layer remains unclear. Does it correspond to the depth of the water table, which means that it could reach several hundreds of meters in the case of deep aquifer? What would be the value of the soil parameters, which described basically the top first meter?

Answer: Yes the model quantifies the depth-averaged soil moisture in the unsaturated zone. This is now clarified in the manuscript : “The unsaturated zone is here defined as the layer of the soil bounded by the land surface at the top and by the groundwater table at the bottom. By definition, at each point in time, the groundwater table position is where water pressure equals air pressure” (lines 91-94 of the revised manuscript).

To quantify the uncertainty due to the definition of the soil parameters and to account for the fact that the soil parameters encountered at the surface from surveys may not be representative of the overall unsaturated zone condition, as pointed out by the reviewer, we have provided an additional figure (Figure S2) and associated results (see new section 3.2) and discussion (lines 369-377 of the revised manuscript)

3) ***Comment:*** What is the interest of showing equation 3, which is never used in the study? What is the difference between deltaS and the soil moisture?
Answer: Equation 3 describes the change in mean cumulative water storage. It is essential to justify the the assumption of a negligeable water storage (necessary for the approximation $q \approx R_{eff}$) for the study period in the catchments of interest, as described in the paragraph following the equation (lines 130-134 of the original manuscript and lines 157-161 of the revised version).

4) ***Comment:*** The model use an equation describing local and instantaneous flows as analog of large scale and monthly integrated. It is audacious to use such a non linear equation considering that spatial integration (with very strong spatial heterogeneities) and temporal averaging tend to smooth non linear processes. In fact the resulting value can just be a crude proxy of the moisture content and it would be interesting to show how the adding value of such a proxy in comparison to that given by a simple soil water balance approaches since all the terms required to implement it are given by CMIP5 outputs. A discussion of this point would be very important in part 4, in particular to demonstrate the potential of the proposed approach to provide an original view for CMIP5 scenarios analysis.
Answer: We have now provided a more detailed justification of the use of such a model based on existing litterature that showed that the use of catchment scale water balance from CMIP5 variables lead to inconsistencies (lines 70-77 of the revised manuscript): "Even though CMIP5 models to some degree provide own outputs of (mostly near-surface) soil moisture, Bring et al. (2015) have shown that the catchment-scale water balance implications of these climate models are often far from realistic. As such, direct CMIP5 model outputs for soil moisture may thus not be suitable for relevant quantification of catchment-scale soil moisture dynamics, as this is strongly related to and relies on realistic water balance representation. Not least because we also aim here to investigate projected climate-driven change in soil water content over the entire unsaturated zone (and not just near the surface), we therefore use in this investigation an other soil-moisture modeling framework (Destouni and Verrot, *2014; Verrot and Destouni, 2015, 2016)* than the direct output provided by some CMIP5 models for mostly near-surface soil moisture. "
Regarding the validity of the model for large-scale quantification of soil moisture, the now published model data comparison (Verrot and Destouni, 2016) provides such justification.

Comment: The relevance of the computed soil moisture is justified by a comparison with Grace. In the evaluation with Grace how the author estimate Reff, the soil depth (since soil moisture is given in term of Storage variations).
Moreover, Grace measured the total amount of water. How the authors separate the variation in soil water content and those linked to the aquifer variations.
Answer: The comparison with GRACE data has now been removed from this manuscript as the full study is now accepted and published (see Verrot and Destouni 2016)

Specific comments

Comment: L126-132 : In the hydrological balance, DeltaS seems to be a second order quantity in comparison to P. Can the authors comment that statement and the consequence for the study.
Answer: ΔS is much smaller than P which in fact allows the approximation $q \approx Reff$ as stated in the manuscript (lines 157-161 of the revised manuscript). This does not have any consequence on the relevance of looking at long-term dynamics of soil moisture as it is central for many processes and human-related needs (agriculture, water consumption, solute transport…) . We have provided further references to make this point clearer : "Soil moisture plays a major role in the hydrologic and climatic systems, by influencing the water and energy partitioning between the atmosphere and the subsurface (Corradini, 2014; Seneviratne et al., 2010). It also affects and is affected by the water fluxes into and from the groundwater system (Chen and Hu, 2014) involved in solute transport (Charbenau, 1984), and is of major importance for human societies (Oki and Kanae, 2006)." (lines 19 to 22 of the revised manuscript)

Comment: L170-180 : this paragraph is difficult to follow. What is the physical meaning of an upward flux (exfiltration? Contribution to river flow? lateral aquifer flow? Numerical artifact? . . .)
Answer: As the physical meaning of negative values of *Reff* does not interfere with any of the methodology or results from this study: the model relies on the assumption of a gravity drainage flow, therefore it is necessary to discard the catchments where the flow is upwards. We have removed the mention of the physical meaning of negative Reff values.

Comment: L197 I would say Equation 2 rather than Eq. 4
Answer: This sentence refers to the CMIP5 output variables *mrro* and *mrros* used in equation 4.

Comment: L198-209. This paragraph is difficult to follow. It seems that the rainfall threshold to distinguish wet and dry season is changing every year. This means that a given climate event, it can be classified as dry or wet according to the year (wet or dry). Can the authors comment that.
Answer: Dry and wet events as studied here are not dependent on the definition of dry and wet season. It is now more clearly stated in section 2.5: "Furthermore, we have assessed the change from 2006-2025 to 2080-2099 in the occurrence frequency of wet and dry events; these are defined as monthly average θ_{uz} values that exceed the 95% upper percentile θ_{uz} value (for wet events) or are below the 5% percentile θ_{uz} value (for dry events) of the first period 2006-2025 regardless of when during the year this may happen and of the season definition." (lines 245-248 of the revised manuscript)

Comment: L201-202 : I don't understand what is done
L205-209 : I don't understand what is done
Answer: We rephrased the methodology for this comparison (lines 223-227 of the revised manuscript).

Comment: L210-L215 : This could be supported by a synthetic figure in the main text.

Answer: We are unsure what the reviewer refers to here: lines 210-215 is the short methodology of the comparison of precipitation output from CMIP5 with GPCC values. We do not understand what type of figure could be helpful.

Comment: L219-220 : "and not . . ..landscape". I don't understand what is meant here
L233-240 :" inter-model differences are relatively small" looks contradictory to the sub- sequent statement "long term term average soil moisture may vary greatly". In general the paragraph is difficult to follow.
Answer: Following reviewer 1 comment and other comments, we have now removed the study based on the ensemble mean and the associated text.

Comment: L248-250 : difficult to understand the agreement of results (which agreement? Which results?).
Answer: As stated in the sentence that the reviewer refers to, the agreement is defined in section S3.

Comment: L324-L328 : very long sentence difficult to read.
Answer: We have reformulated the sentence according to this comment: "For most of the study catchments, the pattern of changes in frequency of wet/dry events (Fig. 2) is consistent with that in average seasonal soil moisture (Fig. 4); the Pearson correlation coefficient between the calculated relative changes in frequency of rare events and in mean seasonal soil moisture is -0.68 for RCP 8.5 and -0.55 for RCP 2.6 regarding the frequency of dry events and average soil moisture during the dry season, and 0.71 for RCP 8.5 and -0.72 for RCP 2.6 regarding the frequency of wet events and average soil moisture during the wet season." (lines 350-355 of the revised manuscript)

Comment: L342-L346 : one of the interest of the approach is to bring some soil information in the analysis. It would be interesting to go above the simple non-linearity observation. How soil properties affect the impact hydroclimatic change on soil moisture variability
Answer: Following this comment and reviewers 1 and 2 comments, we have now included an analysis of the effect of soil parameter values on the presented results and discussion (see section 3.2) based on the new figure S2 in the supplementary information.

Comment: Results and discussion. Are the results consistent with previous analysis on hydroclimatic changes. What original conclusions can be highlighted by the use of the proposed model?
Answer: We have broaden the discussion according to this comment (see lines 369-377 of the revised manusript).

Worldwide soil moisture changes driven by future hydro-climatic change scenarios

Lucile Verrot[1], Georgia Destouni[1]

[1]Department of Physical Geography & Bolin Centre for Climate Research, Stockholm University, SE-106 91 Stockholm, Sweden

Correspondence to: Lucile Verrot (lucile.verrot@natgeo.su.se)

Abstract. Soil moisture is a key variable in hydrology, ecology, and climate change science. It is also of primary importance for the agricultural and water resource sectors of society. This paper investigates how hydro-climatic changes, projected by 14 CMIP5 models and for different radiative forcing (RCP) scenarios to occur from 2006-2025 to 2080-2099, may affect different soil moisture aspects in 81 large catchments worldwide. Overall, for investigated changes in the occurrence frequency of rare dry/wet events and in the average value and inter-annual variability of seasonal water content, different RCP scenarios imply opposite directions of change in around half or more of the study catchments. Regardless of RCP scenario, the greatest projected changes are found for the occurrence frequency of dry/wet events. Especially large increases in dry-event frequency, combined with increased inter-annual variability of dry-season water content, indicate increased drought risk for several large catchments over the world, with the considered RCP scenario determining which these catchments are.

1. Introduction

Soil moisture plays a major role in the hydrologic and climatic systems, by influencing the water and energy partitioning between the atmosphere and the subsurface (Corradini, 2014; Seneviratne et al., 2010). It also affects and is affected by the water fluxes into and from the groundwater system (Chen and Hu, 2014) involved in solute transport (Charbenau, 1984), and is of major importance for human societies (Oki and Kanae, 2006). Soil moisture is a dynamic variable defined as the volume of water in a given volume of soil. It is also spatially heterogeneous, and depends on both dynamic (e.g. vegetation, spatial distribution of hydro-climatic conditions) and static factors (soil type, topography) (Destouni and Cvetkovic, 1989; Russo, 1998; Mohanty et al., 2000).

authors 29/9/16 09:42
Deleted: Destouni

authors 29/9/16 09:42
Deleted: Verrot,

Long-term and large-scale shifts in climate as well as in land-use and water-use conditions in the landscape (Destouni et al., 2013; Jaramillo and Destouni, 2014) are shown to impact the hydro-climate and the water resources in various regions of the world. Considerable hydro-climatic shifts have occurred in the past (Jaramillo and Destouni, 2015) and are expected to occur in the future (Bring et al., 2015) locally and globally. In particular for future projections, the hydro-climatic shifts are uncertain and depend on the path that our societies will take regarding greenhouse gas (GHG) emissions (Peters et al., 2013; IPCC, 2014) and on the societal paths for local land- and water-uses (Destouni et al., 2010; Jarsjö et al., 2012).

Soil moisture in the top soil layer is often studied in energy-related applications, such as ones relating to large-scale climate modelling (Wu et al., 2015; Dirmeyer et al., 2013; Kumar et al., 2014). Corresponding large-scale historical data is now provided for almost 20 years of remote sensing of soil moisture from the missions SMAP and SMOS, allowing for global-scale studies of top-layer soil moisture dynamics in relation to vegetation (De Jeu et al., 2008) or climatic (Wagner et al., 2003) patterns. Root-depth soil moisture dynamics have been the focus of many model-based and data-based studies (e.g. Rodriguez-iturbe, 1999), and can be derived from the land-surface schemes of climate models exploring future climate projections, such as in the Coupled Model Intercomparison Project (CMIP). However, the water storage dynamics over the entire unsaturated zone, the extent of which and the position of the groundwater table that determines this extent also vary in time, is the subject of significantly less modeling work at large scales, even though such quantifications are indeed needed in many environmental and societal sustainability applications, for example related to water supply, security and safety (Botter et al., 2010). In fact soil moisture over the entire time-variable unsaturated zone extent, or over some fixed depth that is mostly but not always unsaturated, is typically more difficult to study over large scales as it is related to conditions both at and close below the surface, and in deeper soil and the saturated groundwater zone. Impact of hydro-climatic changes on such soil moisture conditions at different temporal and spatial scales (D'Odorico et al., 2000) may be derived from complex modeling of the full dynamics of soil water hydraulics, but such complex computations may not be readily carried out, and particularly not so with sufficient availability and quality of required input data, over long time periods and on regional to global scales.

Catchment-scale water balance can be a useful physically based constraint for quantification of long-term and large-scale soil moisture dynamics over the whole unsaturated zone and also some depth into (sometimes) saturated soil. Such an approach relies then inherently on the quality and consistency of available large-scale data for the key hydrological fluxes (precipitation evapotranspiration and runoff) that determine this balance in a

authors 29/9/16 09:42
Deleted:

authors 29/9/16 09:42
Moved (insertion) [1]

authors 29/9/16 09:42
Deleted: Hydro

authors 29/9/16 09:42
Deleted: impact

authors 29/9/16 09:42
Moved up [1]: 2015; Dirmeyer et al., 2013; Kumar et al., 2014).

authors 29/9/16 09:42
Deleted: ; Destouni and Verrot, 2014; Destouni and Verrot, 2015). Such impacts

authors 29/9/16 09:42
Deleted: , for instance,

authors 29/9/16 09:42
Deleted: or directly from large-scale climate model outputs (Wu et al.,

authors 29/9/16 09:42
Deleted: While the former approach does not readily allow for the

authors 29/9/16 09:42
Deleted: calculations to

authors 29/9/16 09:42
Deleted: for

authors 29/9/16 09:42
Deleted: , the latter approach is limited in its process representation and soil depth coverage.

catchment. Attempting to bridge key data and computational gaps for such soil moisture quantification, Destouni and Verrot (2014) and Verrot and Destouni (2015) have developed a modeling framework that links large-scale hydro-climatic flux variables with soil hydraulic properties over whole catchments and distinguishes the dynamic interactions between the unsaturated zone and the groundwater zone down to any soil depth of interest.

This modeling framework, first described by Destouni and Verrot (2014), has been applied to various parts of the world and its results have since also been successfully tested against independent observation data (Verrot and Destouni, 2016). The latter include both large-scale data from the GRACE satellites (CSR-RL05, from Swenson (2012), Landerer and Swenson (2012), Swenson and Wahr (2006)) regarding large-scale water storage changes, and data from local measurements of soil water content and groundwater level within a set of smaller-scale catchments (i.e., smaller than the catchments considered in the GRACE comparison). This data-model testing has provided support for sufficient model realism in reproducing long-term time series of soil moisture across various scales and world regions along steep climate gradients. The present study will use this modeling framework in a novel application of quantifying possible future changes in key large-scale long-term statistics of soil moisture dynamics, as implied by the phase 5 of the Coupled Model Intercomparison Project (CMIP5) (Taylor et al., 2012), for a worldwide set of large hydrological catchments.

Even though CMIP5 models to some degree provide own outputs of (mostly near-surface) soil moisture, Bring et al. (2015) have shown that the catchment-scale water balance implications of these climate models are often far from realistic. As such, direct CMIP5 model outputs for soil moisture may thus not be suitable for relevant quantification of catchment-scale soil moisture dynamics, as this is strongly related to and relies on realistic water balance representation. Not least because we also aim here to investigate projected climate-driven change in soil water content over the entire unsaturated zone (and not just near the surface), we therefore use in this investigation an other soil-moisture modeling framework (Destouni and Verrot, 2014; Verrot and Destouni, 2015, 2016) than the direct output provided by some CMIP5 models for mostly near-surface soil moisture.

With this framework, we specifically quantify and regard climate-driven changes in important long-term large-scale statistics of soil moisture in 81 large hydrological catchments spread over the world (Fig. 1). The investigated statistics include long-term catchment-average conditions and inter-annual variability around these for soil water content in the dry and the wet season, and occurrence frequency of particularly dry and wet events in the 81 study catchments around the world. To investigate climate-driven changes in these soil moisture statistics, we use relevant hydro-climatic outputs from projections of the CMIP5 model ensemble for the time period 2006-2099

authors 29/9/16 09:42
Deleted: such quantification

authors 29/9/16 09:42
Deleted: modelling

authors 29/9/16 09:42
Deleted: The

authors 29/9/16 09:42
Deleted: of

authors 29/9/16 09:42
Deleted:) and Verrot and Destouni (2015)

authors 29/9/16 09:42
Deleted: .

authors 29/9/16 09:42
Deleted: (Verrot and Destouni (2016)).

authors 29/9/16 09:42
Deleted: the

authors 29/9/16 09:42
Deleted: catchment

authors 29/9/16 09:42
Deleted: to quantify

authors 29/9/16 09:42
Deleted: conditions in a worldwide set of large catchments

authors 29/9/16 09:42
Deleted:).

authors 29/9/16 09:42
Deleted: Using this framework, we

authors 29/9/16 09:42
Deleted: ,

authors 29/9/16 09:42
Deleted: regarding

authors 29/9/16 09:42
Deleted: the occurrence frequency

authors 29/9/16 09:42
Deleted: particularly dry and wet events

authors 29/9/16 09:42
Deleted:). Furthermore, we investigate the

authors 29/9/16 09:42
Deleted: the

authors 29/9/16 09:42
Deleted: the

authors 29/9/16 09:42
Deleted: of these catchments. ... [1]

and compare their resulting implications for soil water content changes between the recent-to-near-future 20-year period 2006-2025 and the far-future 20-year period 2080-2099. These comparisons are further made for two different Representative Concentration Pathways (RCP) scenarios: RCP 2.6 (van Vuuren et al., 2007) and RCP 8.5 (Riahi et al., 2011).

authors 29/9/16 09:42
Deleted: conditions

2. Material and methods

2.1 Modeling approach

From the modeling framework proposed by Destouni and Verrot (2014), we focus here on the time-variable depth-averaged soil water content θ_{uz} [-] over the entire unsaturated zone. The unsaturated zone is here defined as the soil depth bounded by the land surface at the top and the groundwater table at the bottom. By definition, at each point in time, the groundwater table position is where the water pressure equals the air pressure. The unsaturated water content θ_{uz} is in this framework evaluated as:

authors 29/9/16 09:42
Deleted: over the unsaturated zone θ_{uz} [-], which is in that

$$\theta_{uz} = \left(\frac{q}{K_s}\right)^{\beta}(\theta_s - \theta_{ir}) + \theta_{ir} \approx \left(\frac{R_{\mathrm{eff}}}{K_s}\right)^{\beta}(\theta_s - \theta_{ir}) + \theta_{ir} \qquad (1)$$

In Eq. (1), q [LT^{-1}] is average vertical soil water flux through the unsaturated zone, R_{eff} [LT^{-1}] is a catchment-scale approximation of q in terms of effective subsurface runoff through a whole catchment (explained further below), K_s [LT^{-1}] is saturated hydraulic conductivity, θ_{ir} [-] is residual irreducible soil water content, , $\beta = \alpha/(3\alpha + 2)$ [-] and α [-] is a characteristic soil texture parameter linked to the pore size distribution of different soil types (Rawls et al., 1982; Saxton et al., 1986). Furthermore, θ_s is saturated soil water content, which can be equated to porosity (Kumar, 1999; Entekhabi et al., 2010). The θ_{uz} quantification in Eq. (1) is based on the Brooks and Corey (1964) model of unsaturated hydraulic conductivity K [LT^{-1}]:

authors 29/9/16 09:42
Deleted:

$$K(\theta_{uz}) = K_s\left(\frac{\theta_{uz} - \theta_{ir}}{\theta_s - \theta_{ir}}\right)^{1/\beta} \qquad (2)$$

Alternative expressions of K as function of θ_{uz} are also available from van Genuchten (1980) and Morel-Seytoux et al. (1996) with soil parameters that are related to those of Brooks and Corey.

The first part of Eq. (1) is based on a first-order approximation and extension from the Brooks and Corey Eq. (2), considering unit hydraulic gradient and gravity as a dominant, even though not the only, driver of large-scale flow through the unsaturated zone. This approximation was introduced and used by Dagan and Bresler (1979) and Bresler and Dagan (1981) in the context of large-scale solute transport through the entire unsaturated

authors 29/9/16 09:42
Deleted:),

zone, with associated average time periods for such transport ranging from four months to five years, as quantified by the spatial-average travel time (around which there is also large spatial variability) of infiltrated water to different soil depths and in different soil types. The same approximation has also been used in multiple studies of large-scale solute transport through the unsaturated zone thereafter (e.g., Destouni and Cvetkovic, 1989, 1991; Destouni, 1993; Destouni and Graham, 1995; Graham et al., 1998), with associated mean travel times of 7-38 days,, again with also large spatial variability in travel times around that spatial mean value. The approximation implies that, the unsaturated hydraulic conductivity K in Eq. (2) can be equated to the average vertical soil water flux through the unsaturated zone q, with further equation rearrangement leading to the first part of Eq. (1). The studies of Destouni and Verrot (2014), Verrot and Destouni (2015, 2016) further introduced the second part of Eq. (1) for data-based quantification of the temporal variability of the large-scale depth-average unsaturated water content θ_{uz} around its long-term average value. This equation part expresses the main assumption that, on the scale of a whole catchment, both the long-term average value of q and the temporal q variability around it can be estimated from and constrained by available observation data for runoff R through the catchment.

Specifically, the assumption is that q can be approximated by an effective subsurface runoff component $R_{eff} = \gamma R$ [LT^{-1}] (with $0 \leq \gamma \leq 1$) that feeds water through the subsurface into the total runoff R [LT^{-1}] of the catchment over some considered time period. This subsurface runoff component R_{eff} complements the runoff component $(1-\gamma)R$ of overland and pure (not fed by subsurface water into the) surface water flow, which also adds to the total R over the same time period. Published simulations have quantified and shown $\gamma = R_{eff}/R$ to be typically above 0.5 and in many cases close to 1 for a wide range of investigated temperate, through cold, to permafrost region conditions (Bosson et al., 2012). In the present study, γ values and their variability in time do not need to be explicitly evaluated, because CMIP5 model output includes directly quantified R_{eff} times series for future climate change scenarios, as explained in the subsequent section 2.2.

For a long climatic time period of twenty or more years, the long-term average R_{eff} should relatively well approximate the long-term average q because the subsurface water storage change can be expected to be close to zero when averaged over such long time periods (Jaramillo et al., 2013; Destouni et al., 2013; Jaramillo and Destouni, 2015). Over shorter time scales, such as a month or a day, however, q and R_{eff} may differ due to non-zero water storage change occurring over the same time, with q through the soil being transiently partitioned between feeding water into R_{eff} and increasing water storage in the soil, and conversely R_{eff} being fed by both q and a transient decrease in soil water storage. However, even under such conditions of non-zero water storage change,

authors 29/9/16 09:42
Deleted:).

the relative variability of R_{eff} around its long-term average value may still be relevant and sufficient for estimating the corresponding relative variability of large-scale depth-average unsaturated water content θ_{uz} around its long-term average value, through the second part of Eq. (1). This assumption is tested by direct comparison of θ_{uz} results, as given by the second part of Eq. (1), against independent observation data provided from GRACE (Swenson, 2012; Landerer and Swenson, 2012; Swenson and Wahr, 2006) supports the main model assumption (Verrot and Destouni, 2016). The comparison supports (i.e., does not falsify) the assumption by showing that the model results realistically capture the temporal variability in large-scale water storage change around its expected near-zero long-term average value, across various large catchments around the world. The study also shows that the model also captures main intra-annual dynamics observed by point measurements of soil moisture. Furthermore, previous work by Jaramillo and Destouni (2013) has explicitly investigated the effects of accounting or not accounting for observed water storage changes on the variability of main water fluxes in a catchment-scale water balance. Specifically they quantified for different catchments the effect of estimating catchment-scale evapotranspiration ET [LT^{-1}] as simply $ET=P-R$ or as $ET=P-R-\Delta S$, where P, R and ΔS are observed precipitation, runoff and storage change, respectively (all with dimensions [LT^{-1}]). Their results show somewhat greater short-term fluctuations around essentially the same longer-term ET variation if the observed non-zero ΔS is accounted for compared to if it is not. Similar effects, of relatively minor underestimation of relatively short-term fluctuations of θ_{uz} around its essentially captured seasonal and longer-term variation, are also expected here from neglecting the influence of ΔS-driven differences between q and R_{eff} in the estimation of θ_{uz} by Eq. (1). To even further quantify and clarify this influence for the present study, consider for example the mean cumulative water storage change ΔS as:

$$\Delta S = \left(\sum_{i=1}^{n} P_i - ET_i - R_i\right)/n \tag{3}$$

with P, ET, R and ΔS all being monthly water fluxes and n being the total number of months with associated CMIP5 flux outputs (n=1128). The resulting cumulative ΔS over the whole study period accounts then for less than 1% of the mean monthly P, on average across all 81 study catchments (the average value across catchments is 0.75% and the standard deviation is 2.3%). This quantification provides further support for the assumption of insignificant long-term change in subsurface water storage that underlies the approximation of $q \approx R_{eff}$ in Eq. (1)

2.2 Use of CMIP5 model output data

authors 29/9/16 09:42
Deleted: irect

authors 29/9/16 09:42
Deleted: support

authors 29/9/16 09:42
Deleted: realistic

authors 29/9/16 09:42
Deleted: (Fig. 2).

The aim of the present work is to study climate-driven change patterns and statistics of θ_{uz}, as quantified by the second part of Eq. (1), in the present 81 study catchments, spread over the world. The study uses relevant hydro-climatic outputs for estimating R_{eff} from two of the CMIP5 scenarios for the 21st century, the RCP 2.6 and RCP 8.5 scenarios. Those scenarios represent a low (RCP 2.6) and a high (RCP 8.5) GHG-increase scenario, corresponding to reaching a radiative forcing of 2.6 $W.m^{-2}$ and 8.5 $W.m^{-2}$ by the end of the 21st century, respectively. The relevant CMIP5 model outputs were downloaded from the World Data Center for Climate (WDCC) available from the Deutsche Klimarechenzentrum GmbH website (http://cera-www.dkrz.de/WDCC).

The CMIP5 models' outputs of relevance for estimating R_{eff} are the mean monthly surface runoff (overland flow, denoted *mrros*) and the total runoff (denoted *mrro*) in the CMIP5 output files. The total runoff *mrro* is the sum of the overland flow and the soil-groundwater flow (in short underground flow), both of which eventually feed into the streams of each catchment. With *mrros* then being just the overland flow, R_{eff} could be calculated directly from these CMIP5 model outputs (without need for separate evaluation of the factor $\gamma = R_{eff}/R$) as:

$$Reff = mrro - mrros \tag{4}$$

For evaluation of Eq. (4), the model output values of *mrro* and *mrros,* given from the CMIP5 modeling in units $kg.m^{-2}.s^{-1}$, were transformed to relevant units for R_{eff} [LT^{-1}] using the water density value of 1000 $kg.m^{-3}$. Furthermore, in errata files published for the CMIP5 models GISS-E2-H and GISS-E2-R (with the errata files available online only, at: http://data.giss.nasa.gov/modelE/ar5/), it is specified that for those two models the variable *mrro* is the underground flux only, in contrast to the definition of *mrro* in all other models (underground flux + surface runoff). For those two models, R_{eff} is therefore directly equated to *mrro.*

In addition to the two R_{eff} related variables, we also used from the CMIP5 model outputs the precipitation variable *pr* ($kg.m^{-2}.s^{-1}$). This was used to determine the model-implied dry and wet season for each selected study catchment, which was also compared with a corresponding dry and wet season determination based on observation data for precipitation, as described further in section 2.4.

2.3 Selection of study catchments and CMIP5 models

The 81 study catchments were chosen in analogy with such selection basis in previous work (Bring et al., 2015), taking into account that the catchments should be large enough for sufficient coverage by the commonly coarse spatial resolution of global climate models. In the selection process, we first extracted relevant model output

authors 29/9/16 09:42
Deleted:

authors 29/9/16 09:42
Deleted:

authors 29/9/16 09:42
Deleted: for

values for 608 catchments in the Global Runoff Data Center (GRDC, 2015) with an area equal or greater than 100'000 km^2. The model output values were then averaged to represent monthly conditions over each catchment.

For the catchment-scale use of model output, we further also identified 20 CMIP5 models that could provide all three variables of interest (*mrro*, *mrros* and *pr*) for download over the whole study period (2006-2099). However, for some catchments and for some models, the time series provided for *mrro* and/or *mrros* included just a constant number over time. Models and catchments with too many such constant time series were discarded (see SM section S1 for more details on this selection criterion).

A second selection basis for the study models and catchments was to discard the model-catchment combinations that yielded negative catchment-scale R_{eff} values. Modeling soil water content conditions and statistics for such a negative R_{eff} flow situation is outside the scope of the present soil moisture model and in contradiction with its basic flow approximations.

The two above-described catchment-model selection steps were repeated for each of the two considered RCP 2.6 and RCP 8.5 scenarios and finally also all small remaining catchments that were nested into larger ones were removed. This selection process yielded the final set of 81 study catchments (Fig. 1) and 14 CMIP5 models (listed in SM Table S1) used in the present study (SM Table S2 lists the models and number of catchments discarded in each selection step). The study catchments are spread around the globe, and clustered here for discussion convenience into 6 regions, as shown on Fig. 1, in analogy with regional divisions made by the World Meteorological Organization (WMO, 2014).

2.4 Use of soil and precipitation data for the study catchments

In addition to the runoff output data from the CMIP5 models, the calculation of unsaturated water content θ_{uz} also requires catchment-characteristic values for the soil hydraulic properties included in Eq. (4). The dominant USDA soil texture (Baldwin et al., 1928) for each catchment was extracted from the Harmonized World Soil Database map (Nachtergaele et al., 2008; FAO, 2012). SM Fig. S1 shows the major soil textures within each catchment and Table S3 lists soil parameter values for different soil textures from Rawls et al. (1982). The parameter values from Table S3 that apply to the dominant soil texture within each catchment (Fig. S1) were used to evaluate θ_{uz} for that catchment from Eq. (4). In addition, in order to also analyze uncertainty in these results due to the soil texture choices and account for a generally broader range of soil properties within each individual

authors 29/9/16 09:42

Deleted: Knowing that a positive flux value in CMIP5 output implies a flux leaving the considered atmospheric grid cell, a negative flux value thus quantifies a flux of water that must enter the atmospheric cell from the soil. The implication of negative catchment-scale monthly R_{eff} is then that an upward flux of water from the soil to the atmosphere (independent from and in addition to the separately evaluated evapotranspiration flux in the same direction) is sustained on average over a whole catchment and a whole month. Such a flow situation may be neither realistic nor consistent with the separately evaluated evapotranspiration flux output from the same climate model, and is at least unusual compared to the more generally expected flow situation of an excess amount of water being on average generated from precipitation minus evapotranspiration on land and flowing as runoff toward the outlets of hydrological catchments. At any rate, modeling catchment, we performed a supplementary sensitivity analysis based on various combinations of soil properties values (Table S3). The results are presented in Fig. S2 and in the section 3.2, and discussed further in section 4.

Furthermore, we used the precipitation output *pr* from the CMIP5 models to determine the model-implied dry and wet season extents for each selected study catchment and considered climatic time period. The dry season is defined by the months during which 8% or less of the total annual precipitation falls (after Koutsouris et al., (2015): the exact value of this threshold is set to maximize the agreement between the CMIP5 precipitation time series and that from the Global Precipitation Climatology Centre, GPCC). The wet season is then defined as the remaining months of the year. Results for this season determination were obtained for each of the 81 study catchments (Fig. 1) and for both the RCP 2.6 and the RCP 8.5 scenario from the ensemble mean precipitation output of the 14 CMIP5 models (SM Table S1). These model-based results were further tested against a corresponding data-implied dry-wet season determination obtained from the 1.0°x1.0° monthly precipitation dataset provided by the Global Precipitation Climatology Center (GPCC, see Schneider et al., 2011). This model-data comparison was made over the 9-year period (2006-2014) that is common between the GPCC dataset (extending over 1901/01 – 2014/12) and the studied CMIP5 output period (2006-2099).

The comparison between the model- and data-based results for wet and dry season extent shows that the results are largely consistent (SM Fig. S2). For both the RCP 2.6 and the RCP 8.5 scenario, 40% of the catchments display perfect agreement on the dry season months, and for more than 85% of the catchments at least half of the dry season months match between the data and the model results. From these comparative results, we concluded that it is reasonable to study dry and wet season changes in soil moisture between the climatic periods 2006-2025 and 2080-2099 based on the season determination implied by the CMIP5 ensemble mean.

2.5 Study of soil moisture change and its variability across CMIP5 models

For each of the two climatic periods 2006-2025 and 2080-2099 we have derived the intra-annual variability in monthly average water content θ_{uz} over the average annual cycle in each time period, for the CMIP5 model ensemble and for each model. Furthermore, we have assessed the change from 2006-2025 to 2080-2099 in the occurrence frequency of wet and dry events; these are defined as monthly average θ_{uz} values that exceed the 95% upper percentile θ_{uz} value (for wet events) or are below the 5% percentile θ_{uz} value (for dry events) of the first period 2006-2025 regardless of when during the year this may happen and of the season definition. Changes in wet

authors 29/9/16 09:42
Deleted: used definition of the

authors 29/9/16 09:42
Deleted:), with the

authors 29/9/16 09:42
Deleted: **Ensemble-mean model study**

authors 29/9/16 09:42
Deleted: **and change**
Figure S3 in SM illustrates the relative temporal variability (coefficient of variation CV, determined as the inter-annual standard deviation divided by the long-term average value) of monthly average soil water content θ_{uz}, as obtained from each CMIP5 model (Table S1) over the entire time period of study (2006-2099). The individual model results for each month of the year and each catchment show relatively small CV values (mostly below 0.25), which also do not differ much among the 14 CMIP5 models. Some exceptions are notable: the model IPSL-CM5A-MR displays a particularly high temporal variability in many catchments, and the two MPI models (MPI-ESM-LR and MPI-ESM-MR) display a higher temporal variability than other models for some catchments. However, for the other 11 models, the CV values for all months, both scenarios, and most catchments are commonly less than 0.25. ... [2]

authors 29/9/16 09:42
Deleted: **(Table S1) in the temporal variability patterns of soil moisture.**

authors 29/9/16 09:42
Deleted: Figure S3 in SM illustrates the temporal variability (coefficient of variation CV, determined as the inter-annual standard deviation divided by the long-term average value) of monthly average soil water content θ_{uz}, as obtained from each CMIP5 model (Table S1) over the entire time period of study (2006-2099). The individual model results for each month of the year and each catchment show relatively small CV values (mostly below 0.25), which also do not differ much among the 14 CMIP5 models. Some exceptions are notable: the model IPSL-CM5A-MR displays a particularly high temporal variability in many catchments, and the two MPI models (MPI-ESM-LR and MPI-ESM-MR) display a higher temporal variability than other models for some catchments. However, for the other 11 ... [3]

authors 29/9/16 09:42
Deleted: then

authors 29/9/16 09:42
Deleted: .

authors 29/9/16 09:42
Deleted: .

and dry season conditions of θ_{uz} have further been quantified in terms of the average value and the inter-annual variability around it for seasonal θ_{uz} in 2006-2025 and in 2080-2099.The agreement of results obtained for any investigated variable in the two scenarios RCP 2.6 and RCP 8.5 has also been calculated in terms of a simple agreement indicator as detailed in SM section S3.

CMIP5 output variables values can vary greatly among the 14 selected CMIP5 models (Table S1). To account for such inter-model variability, we have calculated each θ_{uz} statistic change as implied by the R_{eff} output of each individual climate model and the associated mean and median change (and inter-model standard deviation) across all climate models (referred to as mean and median model results), as well as the corresponding θ_{uz} statistic change given by the ensemble mean and ensemble median of the R_{eff} time series outputs of all climate models (referred to as ensemble mean and median). These results are presented and compared in Fig. S4, showing that the ensemble mean and median projected changes are mostly greater than the corresponding mean and median model results, across catchments and the three statistics of interest (relative change in mean seasonal soil water content, relative change in inter-annual variability of seasonal soil water content, and relative change in the occurrence frequency of rare events). This is in agreement with results from previous studies (see Bring et al., 2015; Knutti and Sedláček, 2013) showing a wide spread of model results and a lack of convergence across CMIP5 models. The typically greater ensemble mean changes than ensemble median changes reflect that a small number of climate models yield extreme R_{eff} time series outputs, thereby heavily skewing the ensemble mean results in their result direction. There is also large inter-model variability and thereby associated large projection uncertainty. In absence of consistent literature pointing at some generally robust choice among the median or mean of individual model results or the ensemble mean or median results, we present and map results in the following section 3.1 in terms of the median of individual model results. The main quantification and illustration choice of the median model result is made because this often yields the least extreme change results for the three studied soil moisture statistics and may thus be viewed as a relatively conservative change quantification under each of the two considered climate forcing scenarios.

3. Results

3.1. Relative changes in soil moisture statistics

The greatest relative changes are overall found for the occurrence frequency of both dry and wet θ_{uz} events, as defined in section 2.5. The changes are greatest under the scenario RCP 8.5 (Fig. 2). For this scenario,

authors 29/9/16 09:42

Deleted: Figure 3 shows results for the intra-annual variability in monthly average water content θ_{uz} in the two climatic periods 2006-2025 and 2080-2099 for 6 study catchment examples, one in each WMO region; SM Fig. S4 shows corresponding results for all study catchments. These figures also show in more detail than in the SM Fig. S3 the resulting inter-model variability (standard deviation) around the ensemble mean model result. Overall, projected changes in intra-annual variability of monthly average θ_{uz} are relatively small, and mostly smaller than the inter-model standard deviation around the ensemble mean result, representing a measure of model uncertainty, for each climatic period.

authors 29/9/16 09:42

Deleted: greatest of these

authors 29/9/16 09:42

Deleted: projected to occur

authors 29/9/16 09:42

Deleted: 3

the catchment Eur1 in Spain exhibits the greatest increase in dry-event frequency, by up to 4 times (417%) greater than that in 2006-2025; this means that this catchment may reach a 27.5% frequency in 2080-2099 for the dry events with only 5% frequency in 2006-2025. Under scenario RCP 2.6, the same catchment Eur1 is projected to experience a smaller relative increase in dry-event frequency (20%); this means an 8% frequency in 2080-2099 for the dry events with 5% frequency in 2006-2025. The catchment Eur1 represents an extreme case among the studied catchments; overall, the cross-catchments average projected relative change in dry-event occurrence frequency is an increase of 11% under the RCP 8.5 scenario (average increase of 6% , under the RCP 2.6 scenario).

Overall, there are multiple catchments with projected opposite change directions in their dry-event frequency under the two scenarios, including both decreases and increases under the RCP 2.6 scenario (Fig. 2a) that shift to opposite increases and decreases, respectively, under the RCP 8.5 scenario (Fig. 2b). The overall geographic pattern of dry-event frequencies mostly decreasing in higher latitude regions (North America, Europe, Northern Asia) and increasing in mid- and lower latitude regions (South America, Africa, South East Asia, Australia) under the RCP 2.6 scenario becomes more heterogeneous and implies greater changes under the RCP 8.5 scenario. Analogous change patterns are also evident for the wet-event frequency, which mostly increases in higher latitude regions and decreases in mid- lower latitude regions under the RCP 2.6 scenario (Fig. 2c); this change pattern also becomes more heterogeneous, with some greater changes, under the RCP 8.5 scenario (Fig. 2d).

The greatest increase in wet-event frequency, by up to 2.5 times (238%) greater than that in 2006-2025, is projected for the Russian catchment Asi13; a frequency of up to 17% may here be reached for the wet events under the scenario RCP 8.5. Under the RCP 2.6 scenario, the projected increase in wet-event frequency in this catchment is smaller, leading to a nearly 79% increase of frequency (from 5% up to 9% frequency in the latter period). Overall, the cross-catchments average projected relative change in wet-event occurrence frequency is an increase of 44% under the RCP 8.5 scenario (increase of 6%, under the RCP 2.6 scenario). In general, the results in Fig. 2 show that the considered GHG concentration pathway to the future, as represented by each RCP scenario, is important for resulting projected changes in occurrence frequency of dry and wet soil moisture events around the world.

Shifts in geographic change patterns between the two RCP scenarios are also seen for the relative change in average soil water content during the dry and the wet season (Fig. 3). For both seasons, the average water content θ_{uz} mostly increases slightly in the higher latitude regions and decreases slightly in the lower latitude

authors 29/9/16 09:42
Deleted: Nam9…ur1 in southern US. ... [4]

authors 29/9/16 09:42
Deleted: 4a…a) that shift to opposite ... [5]

authors 29/9/16 09:42
Deleted: 9….5 times (808…38%) gre ... [6]

authors 29/9/16 09:42
Deleted: 5

regions under the RCP 2.6 scenario (Fig. 5a and 5c). This change pattern becomes more heterogeneous, including also greater changes, under the RCP 8.5 scenario (Fig. 5b and 5d). Overall the projected changes in seasonal average θ_{uz} are relatively small, up to a 15% increase for the dry season in several Arctic region catchments and up to a 15% decrease in a few scattered catchments in North America, Europe and Africa for the dry and/or the wet season.

Regarding the projected relative changes in inter-annual variability of seasonal θ_{uz} (Fig. 4), many catchments exhibit a +/- 15% increase/decrease, for both seasons and under both RCP scenarios. The greatest change is an up to 26% increase in inter-annual θ_{uz} variability for the dry season in catchment Eur10 under the RCP 2.6 scenario. Several European, South East Asian and African catchments also exhibit up to 120% change in inter-annual variability of θ_{uz} during the dry season under the RCP 8.5 scenario. The relatively large changes in inter-annual soil moisture variability, in particular during the dry season, combined with the relatively large increases in dry-event (wet-event) frequency indicate increased drought (flood) risks for several catchments. However, the geographic change pattern shows scattered large-change catchments for both RCP scenarios and is more heterogeneous for inter-annual variability (Fig. 6) than for dry- and wet-event frequency (Fig. 5).

The directions of change are opposite in many catchments between the two RCP 2.6 and RCP 8.5 scenarios for the event and seasonal changes investigated here: the frequency of dry and wet θ_{uz} events (SM Fig. S5), the average seasonal θ_{uz} (SM Fig. S6), and the inter-annual variability of seasonal θ_{uz} (SM Fig. S7). Overall, the greatest changes are in the dry- and wet-event frequency over the whole year. Seasonally, the inter-annual variability of seasonal θ_{uz} exhibits the largest differences in change direction between the two RCP scenarios; these opposite change directions are exhibited for a majority of the catchments during the dry season (44 catchments), and for almost as many catchments (40) during the wet season.

3.2 Model projection uncertainties

Model result sensitivity with regard to choices of soil parameters values is overall small in most catchments for the relative changes in mean soil water content (Fig. S3 a,b,c,d) and its inter-annual variability (Fig. S3 e,f,g,h); most importantly, a different choice of different soil parameter values does not yield a different direction of change. Overall, the greater the resulting relative change is, the smaller is the related result sensitivity with regard to choices of soil parameters values. Consequently, the relative changes in mean seasonal soil moisture under RCP 2.6 display the greatest sensitivity to soil parameter choices, while the relative changes in inter-annual

authors 29/9/16 09:42
Deleted: larger

authors 29/9/16 09:42
Deleted: 6

authors 29/9/16 09:42
Deleted: catchment

authors 29/9/16 09:42
Deleted: 40

authors 29/9/16 09:42
Deleted: 180

authors 29/9/16 09:42
Deleted: combine

authors 29/9/16 09:42
Deleted: to

authors 29/9/16 09:42
Deleted: risk

authors 29/9/16 09:42
Deleted: the

authors 29/9/16 09:42
Deleted: in this study: in

authors 29/9/16 09:42
Deleted: in

authors 29/9/16 09:42
Deleted:)

authors 29/9/16 09:42
Deleted: in

authors 29/9/16 09:42
Deleted: over the whole year

variability of seasonal soil moisture under RCP 8.5 scenarios display smaller sensitivity. The relative changes in the frequency of occurrence of rare events are not sensitive to soil parameter choices (Fig. S3 i,j,k,l) as their quantification is directly and linearly related to q. For almost all the catchments and for all three soil moisture statistics, the set of chosen soil parameters values (Fig. S1) lies well within the median absolute deviation calculated from the 11 sets of soil parameters.

For the three studied statistics, the uncertainty due to inter-model variability among the CMIP5 models is greater (as quantified by the median absolute deviation) for the RCP 2.6 scenario (Fig. S4 a,c,e,g,i,k) than the RCP 8.5 scenario (Fig. S4 b,d,f,h,j,l). This means that the project change trend (sign of relative change) for each catchment is more consistent across models for the RCP 8.5 scenario than for the RCP 2.6 scenario, especially for relatively large projected changes. For instance, in the catchment Eur1, which displays the greatest increase in frequency of occurrence of dry events under RCP 8.5, the median absolute deviation ranges from approximately 200% to 650%, indicating a relatively robust projection of this change to effectively happen under the RCP 8.5 scenario. Large projected changes in terms of the ensemble mean (800%) and mean model (500%) result for this catchment also show that some climate models imply considerably greater changes than the median model result.

4. Discussion

For most of the study catchments, the pattern of changes in frequency of wet/dry events (Fig. 2) is consistent with that in average seasonal soil moisture (Fig. 4); the Pearson correlation coefficient between the calculated relative changes in frequency of rare events and in mean seasonal soil moisture is -0.68 for RCP 8.5 and -0.55 for RCP 2.6 regarding the frequency of dry events and average soil moisture during the dry season, and 0.71 for RCP 8.5 and -0.72 for RCP 2.6 regarding the frequency of wet events and average soil moisture during the wet season. The consistency lies in that a catchment with increased average seasonal soil moisture (occurs mostly in the higher latitude regions for both the dry and the wet season, Fig. 4) is likely to also experience more frequent wet events or less frequent dry events (Fig. 2). However, there are individual catchment exceptions to this common change pattern, for example in catchment Nam3, where the RCP 8.5 scenario implies an increase in the frequency of dry events (Fig. 2b), while also implying an increase in average seasonal soil moisture during the dry season (Fig. 3b). Such a change situation may, for example, be explained by highly increased short-term fluctuation magnitudes and thereby occurrence frequency for rare wet events during the wet season even though the average seasonal soil moisture has decreased. Further study of specific wet and dry fluctuation magnitudes and event

authors 29/9/16 09:42
Deleted: 3

authors 29/9/16 09:42
Deleted: 5

authors 29/9/16 09:42
Deleted: resulting

authors 29/9/16 09:42
Deleted: 75

authors 29/9/16 09:42
Deleted: -

authors 29/9/16 09:42
Deleted: 68

authors 29/9/16 09:42
Deleted: 74

authors 29/9/16 09:42
Deleted: 5

authors 29/9/16 09:42
Deleted: 4

authors 29/9/16 09:42
Deleted: catchments Afr3 and Eur3

authors 29/9/16 09:42
Deleted: wet

authors 29/9/16 09:42
Deleted: 4d

authors 29/9/16 09:42
Deleted: a decrease

authors 29/9/16 09:42
Deleted: wet

authors 29/9/16 09:42
Deleted: 5d

frequency for each season instead of over the whole year as investigated here, can shed light on such more unusual change situations.

The scenario RCP 8.5 yields generally higher change values for all types of changes and for both dry and wet soil moisture events and seasons. Furthermore, the two RCP scenarios yield different directions of change in 36% of the catchments for dry seasonal conditions, and in 30% of the catchments for wet conditions. These results show that the representative GHG concentration pathway of forthcoming climate change is crucial for the directions and the magnitudes of future soil moisture changes over the world. Regarding climate models, their results, including projected directions of changes, vary greatly across models and especially under RCP 2.6 scenario, as also pointed out by previous studies of projected hydro-climatic (Bring et al., 2015) and temperature (Knutti and Sedláček, 2013) changes. This suggests that the lack of consistency in hydrologically relevant outputs among CMIP5 models leads to much greater uncertainties than soil parameter choices for projection of soil moisture changes. The results shown and mostly discussed here in terms of median model results represent relatively conservative projections of such changes, emphasizing that worrying soil moisture statistics changes may be expected to occur in some catchments, particularly under the RCP 8.5 scenario, even when considering the inter-model uncertainty among CMIP5 models.

The present 81 study catchments represent 27% of the Earth's land surface, which is a relatively high sampling coverage for statistical analysis, like the present one, of soil moisture changes over the world. The commonly coarse resolution of global climate models does not allow for much more detailed spatial analysis than the present one, but more fine-resolved regional climate model outputs could be used for addressing finer spatial detail and catchment resolution in follow-up work.

Although hydro-climatic changes greatly influence soil moisture changes, they are not the only predictors of the latter. By themselves, precipitation and evapotranspiration outputs taken directly from climate models correlate relatively poorly with the soil water content θ_{uz} (Eq. 3), with average Pearson correlation coefficients of 0.27 and 0.29, respectively. The relatively poor direct correlation of these climate model outputs to θ_{uz} is due mainly to the soil hydraulic parameter relation of θ_{uz} in Eq. (4), which non-linearly modulates the θ_{uz} response to the hydro-climatic forcing. This non-linearity emphasizes the importance of assessing soil moisture changes in relevant relation to soil constitutive equations rather than just directly from hydro-climatic outputs of climate models.

authors 29/9/16 09:42

Deleted: This change pattern is most evident in the dry season results: in about 86% of the catchments, the RCP 8.5 scenario yields higher absolute change in both the average seasonal soil moisture and in its inter-annual variability during the dry season, while for the wet season the corresponding ratio is closer to around 50% of the catchments being more strongly affected under RCP 8.5 than under RCP 2.6. Similarly, changes in the frequency of wet and dry events are greater in 70% and 77% of the catchments, respectively, under RCP 8.5 than under RCP 2.6. Along with the finding that

authors 29/9/16 09:42

Deleted: 44

authors 29/9/16 09:42

Deleted: 38

authors 29/9/16 09:42

Deleted: , these

authors 29/9/16 09:42

Deleted: the world

authors 29/9/16 09:42

Deleted: .

authors 29/9/16 09:42

Deleted: , sub-regional,

authors 29/9/16 09:42

Deleted: ,

authors 29/9/16 09:42

Deleted: , and R_{eff}-related (Eq. 4)

authors 29/9/16 09:42

Deleted: 39, 0.28,

authors 29/9/16 09:42

Deleted: 45

In follow-up studies, agriculturally important growing seasons for different parts of the world can be considered and accounted for similarly to the present analysis of wet and dry seasons. The growing season may in some cases even correspond to the present wet season definition, for example for some tropical catchments, while the present dry season definition may be more relevant for the growing season in Europe. Also groundwater level variability and change should be investigated in future studies, for instance by extending the present analysis approach to the full modeling framework of Destouni and Verrot (2014) and Verrot and Destouni (2015), in order to investigate soil moisture effects of a changing groundwater table (and associated variable depth of the unsaturated zone) within various soil depths of interest.

5. Conclusion

We have investigated how hydro-climatic changes, projected by 14 CMIP5 models to occur from 2006-2025 to 2080-2099 under the two radiative forcing scenarios RCP 2.6 and RCP 8.5, may affect different aspects of soil water content over the unsaturated zone for 81 large catchments worldwide. The investigated soil moisture aspects include projected changes in average annual water content and in the intra-annual variability cycle around this average. We have found projected changes in these aspects to be relatively small, well within modeling uncertainty. Projected changes are considerably greater for the occurrence frequency of dry and wet soil moisture events than for other investigated soil moisture statistics.

For the changes in the dry/wet event occurrence (Fig. 2) and in the average seasonal water content (Fig. 3), the geographic pattern variability depends on the considered radiative forcing (RCP) scenario. The greatest changes in these soil moisture aspects emerge for the RCP 8.5 scenario, with greater spatial heterogeneity under the RCP 8.5 than under the RCP 2.6 scenario. These large changes also coincide with greater inter-model agreement on the change results.

The changes in the inter-annual variability of seasonal soil water content (Fig. 4) differ from the above-described result differences between RCP scenarios in that they are more or less equally large and spatially heterogeneous over the world for both RCP scenarios. For this seasonal water content variability among years, around half of the individual study catchments exhibit opposite directions of change under the two RCP scenarios.

In general, the particularly large changes in dry/wet-event frequency and inter-annual variability of seasonal soil moisture combine in implying changed flood and drought risks across the world. Especially the largest increases in dry-event frequency and inter-annual variability for the dry season under both RCP scenarios

authors 29/9/16 09:42
Deleted: , and also relatively large

authors 29/9/16 09:42
Deleted: the average value and particularly the inter-annual variability of seasonal water content in the dry and the wet seasons of the study catchments

authors 29/9/16 09:42
Deleted: 4

authors 29/9/16 09:42
Deleted: 5

authors 29/9/16 09:42
Deleted: 6

authors 29/9/16 09:42
Deleted: ,

indicate increased drought risks for several large catchments, which need to be investigated further in focused follow-up studies.

Acknowledgments

This work has been supported by the Swedish University strategic environmental research program Ekoklim and The Swedish Research Council Formas (project 2012-790). GPCC Precipitation data was provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, and is available from their Web site at http://www.esrl.noaa.gov/psd/.

References

Asokan, S.M., Rogberg P., Bring A., Jarsjö J., and Destouni G.: Climate model performance and change projection for freshwater fluxes: comparison for irrigated areas in Central and South Asia, Journal of Hydrology: Regional Studies, 5, 48-65, 2016.

Baldwin, M., Kellogg, C.E., Thorp, J.: Soil classification, Soils and Men, Yearbook of Agriculture, U.S.D.A, pp. 979–1001, 1938.

Botter, G., Bertuzzo, E., and Rinaldo, A.: Transport in the hydrologic response: Travel time distributions, soil moisture dynamics, and the old water paradox. Water Resources Research, 46(3), 2010.

Bresler, E., and Dagan, G.: Convective and pore scale dispersive solute transport in unsaturated heterogeneous fields, Water Resources Research, 17: 1683–169, 3, 1981.

Bring, A., Asokan, S.M., Jaramillo, F., Jarsjö, J., Levi, L., Pietroń, J., Prieto, C., Rogberg, P. and Destouni, G.: Implications of freshwater flux data from the CMIP5 multimodel output across a set of Northern Hemisphere drainage basins, Earth's Future, 3(6), 206-217, doi: 10.1002/2014EF000296, 2015.

Brooks, R.H. and Corey, A.T.: Hydraulic properties of porous media, Hydrology Papers, Colorado State University, 1964.

Charbeneau, R. J.: Kinematic models for soil moisture and solute transport. Water Resources Research, 20(6), 699-706, 1984.

Chen, X., and Hu, Q.: Groundwater influences on soil moisture and surface evaporation. Journal of Hydrology, 297(1), 285-300, 2004.

Corradini, C.: Soil moisture in the development of hydrological processes and its determination at different spatial scales, Journal of Hydrology, 516, 1-5, 2014.

Dagan, G., and Bresler, E.: Solute dispersion in unsaturated heterogeneous soil at field scale: I. Theory, Soil Science Society of America Journal, 43: 461–467, 1979.

De Jeu, R.A.M., Wagner, W., Holmes, T. R. H., Dolman, A. J., Van De Giesen, N. C., and Friesen, J.:. Global soil moisture patterns observed by space borne microwave radiometers and scatterometers. Surveys in Geophysics, 29(4-5), 399-420, 2008.

Destouni, G.: Applicability of the steady-state flow assumption for solute advection in field soils, Water Resources Research, 27: 2129–2140, 1991.

Destouni, G.: Stochastic modelling of solute flux in the unsaturated zone at the field scale, Journal of Hydrology, 143: 45–61, 1993.

Destouni, G., and Cvetkovic, V.: The effect of heterogeneity on large scale solute transport in the unsaturated zone, Nordic Hydrology 20: 43-52, 1989.

Destouni, G., and Verrot, L.: Screening long-term variability and change of soil moisture in a changing climate, Journal of Hydrology, 516: 131–139, doi: 10.1016/j.jhydrol.2014.01.059, 2014.

Destouni G., Asokan S.M., Jarsjö J.: Inland hydro-climatic interaction: Effects of human water use on regional climate, Geophysical Res. Lett., 37, L18402, 2010.

Destouni G., Jaramillo F., and Prieto C.: Hydroclimatic shifts driven by human water use for food and energy production, Nature Climate Change, 3, 213-217, 2013.

Dirmeyer, P.A., Jin, Y., Singh, B., and Yan, X.: Trends in land–atmosphere interactions from CMIP5 simulations, Journal of Hydrometeorology, 14(3), 829-849, 2013.

D'Odorico, P., Ridolfi, L., Porporato, A., and Rodriguez-Iturbe, I.: Preferential states of seasonal soil moisture: The impact of climate fluctuations, Water Resources Research, 36(8), 2209-2219, 2000.

Entekhabi, D., Reichle, R.H., Koster, R.D., and Crow, W.T.: Performance metrics for soil moisture retrievals and application requirements, Journal of Hydrometeorology, 11: 832–840, 2010.

FAO/IIASA/ISRIC/ISSCAS/JRC, Harmonized World Soil Database (version 1.2). FAO (Food and Agriculture Organization of the United Nations), Rome, Italy and IIASA International Institute for Applied Systems Analysis, Laxenburg, Austria, 2012.

authors 29/9/16 09:42
Moved (insertion) [2]

GRDC, The Global Runoff Data Centre, D - 56002 Koblenz, Germany, Federal Institute of Hydrology (BfG), retrieved in October 2015.

IPCC, Summary for Policymakers. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1-32, 2014.

Jaramillo F., and Destouni G.: Developing water change spectra and distinguishing change drivers worldwide, Geophysical Research Letters, 41(23), 8377–8386, 2014.

Jaramillo, F., and Destouni, G.: Local flow regulation and irrigation raise global human water consumption and footprint. Science, 350(6265), 1248-1251, 2015.

Jaramillo, F., Prieto C., Lyon S.W., Destouni G.: Multimethod assessment of evapotranspiration shifts due to non-irrigated agricultural development in Sweden, Journal of Hydrology, 484, 55–62, 2013.

Jarsjö J., Asokan S.M., Prieto C., Bring A., Destouni G.: Hydrological responses to climate change conditioned by historic alterations of land-use and water-use, Hydrology and Earth System Sciences, 16, 1335-1347, 2012.

Knutti, R., and Sedláček, J.: Robustness and uncertainties in the new CMIP5 climate model projections, Nature Climate Change, 3(4), 369-373, 2013.

Koutsouris, A. J., Chen, D., and Lyon, S. W.: Comparing global precipitation data sets in eastern Africa: a case study of Kilombero Valley, Tanzania, International Journal of Climatology, 2015.

Kumar, P.: A multiple scale state-space model for characterizing subgrid scale variability of near-surface soil moisture, IEEE Transactions on Geoscience and Remote Sensing, 37: 182–197, 1999.

Kumar, S., Lawrence, D.M., Dirmeyer, P.A., and Sheffield, J.: Less reliable water availability in the 21st century climate projections, Earth's Future, 2(3), 152–160, 2014.

Landerer, F. W., and Swenson, S. C.: Accuracy of scaled GRACE terrestrial water storage estimates, Water Resources Research, 48(4). doi:10.1029/2011WR011453, 2012.

Mohanty, B. P., Famiglietti, J. S., and Skaggs, T. H.: Evolution of soil moisture spatial structure in a mixed vegetation pixel during the Southern Great Plains 1997 (SGP97) Hydrology Experiment, Water Resources Research, 36(12), 2000.

Morel-Seytoux, H. J., Meyer, P.D., Nachabe, M., Tourna, J., van Genuchten, M.V., and Lenhard, R.J.: Parameter equivalence for the Brooks-Corey and van Genuchten soil characteristics: Preserving the effective capillary drive, Water Resources Research, 32: 1251–1258, 1996.

Nachtergaele, F., Van Velthuizen, H., Verelst, L., Batjes, N., Dijkshoorn, K., Van Engelen, V., Fischer, G., Jones A, Montanarella L, Petri M, and Prieler, S.: Harmonized world soil database, Food and Agriculture Organization of the United Nations, 2008.

Oki, T., and Kanae, S.: Global hydrological cycles and world water resources. Science, 313(5790), 1068-1072, 2006.

Peters, G. P., Andrew, R. M., Boden, T., Canadell, J. G., Ciais, P., Le Quéré, C., Marland, G., Raupach M. R., and Wilson, C.: The challenge to keep global warming below 2 C, Nature Climate Change, 3(1), 4-6, 2013.

Rawls, W.J., Brakensiek, D.L. and Saxton, K.E.: Estimation of soil water properties, Transactions of the American Society of Agricultural Engineers, 25: 1316–1320, 1982.

Riahi, K., Rao, S., Krey, V., Cho, C., Chirkov, V., Fischer, G., Kindermann, G., Nakicenovic, N. and Rafaj, P.: RCP 8.5—A scenario of comparatively high greenhouse gas emissions, Climatic Change, 109(1-2), 33-57, 2011.

Rodriguez-Iturbe, I., D'odorico, P., Porporato, A., and Ridolfi, L.: On the spatial and temporal links between vegetation, climate, and soil moisture,Water Resources Research, 35(12), 3709-3722, 1999.

Russo, D.: Stochastic analysis of flow and transport in unsaturated heterogeneous porous formation: Effects of variability in water saturation, Water Resources Research, 34: 569–581, 1998.

Saxton, K.E., Rawls, W., Romberger, J.S. and Papendick, R.I.: Estimating generalized soil-water characteristics from texture, Soil Science Society of America Journal, 50: 1031–1036, 1986.

Schneider, U., Becker, A., Finger, P., Meyer-Christoffer, A., Rudolf, B., and Ziese, M.: GPCC full data reanalysis version 6.0 at 0.5: monthly land-surface precipitation from rain-gauges built on GTS-based and historic data. doi: 10.5676/DWD_GPCC. FD_M_V6_050, 2011.

Seneviratne, S.I., Corti, T., Davin, E.L., Hirschi, M., Jaeger, E.B., Lehner, I., Orlowsky, B. and Teuling A.J.: Investigating soil moisture–climate interactions in a changing climate: A review, Earth-Science Reviews, 99: 125–161, 2010.

Swenson, S.C.: GRACE monthly land water mass grids NETCDF RELEASE 5.0. Ver. 5.0. PO.DAAC, CA, USA. Dataset accessed 2015-12-02 at http://dx.doi.org/10.5067/TELND-NC005, 2012.

Swenson, S., and Wahr, J.: Post-processing removal of correlated errors in GRACE data, Geophysical Research Letters, 33(8), doi:10.1029/2005GL025285, 2006.

Taylor, K.E., Stouffer, R. J., and Meehl, G.A.: An overview of CMIP5 and the experiment design, Bulletin of the American Meteorological Society, 93(4), 485-498. doi:10.1175/BAMS-D-11-00094.1, 2012.

van Genuchten, M.T.: A closed-form equation for predicting the hydraulic conductivity of unsaturated soils, Soil Science Society of America Journal, 44: 892–898, 1980.

van Vuuren, D.P., Den Elzen, M.G., Lucas, P.L., Eickhout, B., Strengers, B. J., van Ruijven, B., Wonink, S. and van Houdt, R.: Stabilizing greenhouse gas concentrations at low levels: an assessment of reduction strategies and costs, Climatic Change, 81(2), 119-159 doi:10.1007/s/10584-006-9172-9, 2007.

Verrot, L., and Destouni, G.: Screening variability and change of soil moisture under wide-ranging climate conditions: Snow dynamics effects, Ambio, 44(1), 6-16, doi: 10.1007/s13280-014-0583-y, 2015.

Verrot, L., and G. Destouni G.: Data-model comparison of temporal variability in long-term time series of large-scale soil moisture, Journal of Geophysical Research Atmosphere, 121, doi:10.1002/2016JD025209, 2016.

Wagner, W., Scipal, K., Pathe, C., Gerten, D., Lucht, W., and Rudolf, B.:Evaluation of the agreement between the first global remotely sensed soil moisture data with model and precipitation data, Journal of Geophysical Research: Atmospheres, 108(D19), 2003.

WMO, Composition of the WMO, World Meteorological Organization, WMO-OMM-No5, CH-1211 Geneva 2, Switzerland, 2014.

Wu, W.Y., Lan, C.W., Lo, M.H., Reager, J.T., and Famiglietti, J.S.: Increases in the Annual Range of Soil Water Storage at Northern Mid- and High-Latitudes under Global Warming, Geophysical Research Letters, 42(10), 3903-3910, 2015.

authors 29/9/16 09:42
Deleted: Sillmann, J., Kharin, V.V., Zhang, X., Zwiers, F. W., and Bronaugh, D.: Climate extremes indices in the CMIP5 multimodel ensemble: Part 1. Model evaluation in the present climate. Journal of Geophysical Research: Atmospheres, 118(4), 1716-1733, 2013.

authors 29/9/16 09:42
Deleted: Törnqvist, R., Jarsjö,

authors 29/9/16 09:42
Moved up [2]: J.,

authors 29/9/16 09:42
Deleted: Pietrón, J., Bring, A., Rogberg P., Asokan S.M., Destouni G.: Evolution of the hydro-climate system in the Lake Baikal basin, Journal of Hydrology, 519, 1953–1962, ... [7]

authors 29/9/16 09:42
Deleted: ,

authors 29/9/16 09:42
Deleted: In review,

Figure captions

Figure 1: Map of the location of the 81 study catchments. The used region acronyms in the catchment numbering cluster the catchments according to the WMO region classification (WMO, 2014): “Nam” stands for North-America, “Sam” for South-America, “Eur” for Europe, “Swp” for South-west Pacific, “Afr” for Africa and “Asi” for Asia.

Figure 2: Map of relative change from 2006-2025 to 2080-2099 in the frequency of relatively dry (two upper panels a and b) and wet (two lower panels c and g) soil moisture events. Results are shown for the radiative forcing scenarios RCP 2.6 (panels a and c) and RCP 8.5 (panels b and d) in terms of relative change (%) from the original frequency of 5% for both types of events (dry water content below the 5 percentile value and wet water content above the 95 percentile value) in 2006-2025 to the resulting frequency of these water content values in 2080-2099. The mapped changes are quantified in terms of median model results (among different possible statistics shown further in Fig. S4).

Figure 3: Map of relative change in mean seasonal water content over the unsaturated zone. Results are shown for the dry season (two upper panels a and b) and the wet season (two lower panels c and g), and the two radiative forcing scenarios RCP 2.6 (panels a and c) and RCP 8.5 (panels b and d) in terms of relative change (in %) from 2006-2025 to 2080-2099. The mapped changes are quantified in terms of median model results (among different possible statistics shown further in Fig. S4).

Figure 4: Map of relative change in the inter-annual variability of seasonal water content over the unsaturated zone. Results are shown for the dry season (upper panels a and b) and the wet season (lower panels c and g) and the two radiative forcing scenarios RCP 2.6 (panels a and c) and RCP 8.5 (panels b and d) in term of relative change (in %) from 2006-2025 to 2080-2099. The mapped changes are quantified in terms of median model results (among different possible statistics shown further in Fig. S4).

authors 29/9/16 09:42

Deleted: **Figure 2: (a) Map of a set of hydrological catchments in the tropics, for which Verrot and Destouni (2016) have compared the unsaturated water content model expressed by the second part of main Eq. (1) with GRACE satellites data for large-scale water storage change. The model-data comparison results are here exemplified for two of the catchments: (b) Afr4 and (c) Sam11. Results in panels (b,c) show the comparison of model results (pink thinner line) with the GRACE-derived data (purple thicker line) for large-scale water storage change. The model results are based on unsaturated water content quantification through the second part of Eq. (1), by compiling** CSR-RL05 **GRACE data from** Swenson (2012), Landerer and Swenson (2012), and Swenson and Wahr (2006) **for direct comparison with corresponding model output, and synthesizing as model inputs for each catchment available independent runoff data for the same time period from** (GRDC, 2015) **with calibrated** γ factor for effective runoff R_{eff}**, along with independent soil-characteristic data from** the Harmonized World Soil Database v1.1 (Nachtergaele et al., 2008; FAO, 2012)**, and in addition also evaluating a complementary water storage change component of groundwater level change using fundamental catchment-scale flux water balance based equation (2) in Verrot and Destouni (2015) and associated required additional inputs of independent data for precipitation and evapotranspiration from** the Global Precipitation Climatology Center (GPCC, Schneider et al., 2011) and **MODIS product** (ORNL DAAC, 2011)**.** ... [8]

authors 29/9/16 09:42

Deleted: 5

authors 29/9/16 09:42

Deleted: 6

SUPPLEMENTARY MATERIALS
Worldwide soil moisture changes driven by future hydro-climatic change scenarios

Lucile Verrot[1], Georgia Destouni[1]

[1]Department of Physical Geography & Bolin Centre for Climate Research, Stockholm University, SE-106 91 Stockholm, Sweden

Correspondence to: Lucile Verrot (lucile.verrot@natgeo.su.se)

Contents :

Figure S7. Map of model result agreement between the two radiative forcing scenarios RCP 2.6 and RCP 8.5, regarding the change in inter-annual variability of seasonal soil moisture during the dry and the wet season.

Supplementary Sections

1. Model and catchment selection

From the original 608 catchments from the Global Runoff Data Center (GRDC, 2015) database with an area over 100’000 km^2, we finally selected 81 study catchments. Regarding the CMIP5 models, there were originally 20 models providing the required *mrros, mrro* and *pr* outputs, from which a final set of 14 CMIP5 models was selected (Table S1).

The first selection step was to discard the models providing too many time series with only constant values for either *mrro* or *mrros* (none of the models was giving constant *pr* values). As a first step, the maximum number of catchments with constant value tolerated for a model was set to 40. It means that if a model was giving a constant time series for more than 40 catchments, we discarded it. Then, from the remaining models, the catchments that had a constant time series from at least one model were further discarded.

The second selection step was to discard the models yielding too many negative values for R_{eff} as calculated from *mrro* and *mrros* (see main Eq. 4). As a first step, we discarded models providing at least one negative value in their R_{eff} time series for more than 154 catchments (arbitrary first-step threshold). Furthermore, the catchments were then discarded when they had at least one negative value in their R_{eff} time series from any of the remaining models. Table S2 summarizes the models and number of catchments discarded in those two selection steps, for each of the RCP 2.6 and RCP 8.5 scenarios. Finally, after all smaller nested catchments were removed, the final set of 81 study catchments (main Fig. 1) and 14 CMIP5 models (Table S1) emerged for this study.

S2. Quantification of agreement between RCP 2.6 and RCP 8.5

In order to quantify the differences between the projected changes under the climate change scenario RCP 2.6 and those under the scenario RCP 8.5, we calculated a simple indicator of agreement *a* [-] for each catchment:

$$a = \frac{min(|v_1|, |v_2|)}{max(|v_1|, |v_2|)} \; if \; sgn(v_1) = \; sgn(v_2) \tag{S1-a}$$

$$a = -\frac{min(|v_1|, |v_2|)}{max(|v_1|, |v_2|)} \; if \; sgn(v_1) \neq \; sgn(v_2) \tag{S1-b}$$

Where v_1 is the value of the variable (in our study, the frequency of dry/wet events, the mean seasonal soil moisture, or the inter-annual variability of the latter) under RCP 2.6 and v_2 is the value of the variable under RCP 8.5. Furthermore, $sgn(x)$ is the sign function: it returns -1 if $x<0$ and 1 if $x>0$; v_1 and v_2 are always different from 0. From Eq. S1-a and S1-b, the agreement value a will have a negative value if the sign of v_1 and v_2 are different (represented in two shades of red in the SM Fig. S5, S6 and S7), and a positive value if they are of the same sign (represented in two shades of green in the Fig. S5, S6 and S7).

Supplementary Bibliography

GRDC, The Global Runoff Data Centre, D - 56002 Koblenz, Germany, Federal Institute of Hydrology (BfG), retrieved in October 2015.

Nachtergaele, F., Van Velthuizen, H., Verelst, L., Batjes, N., Dijkshoorn, K., Van Engelen, V., Fischer, G., Jones A., Montanarella L., Petri M., and Prieler, S.: Harmonized world soil database, Food and Agriculture Organization of the United Nations, 2008.

Rawls, W.J., Brakensiek, D.L., and Saxton, K.E.; Estimation of soil water properties, Transactions of the American Society of Agricultural Engineers 25: 1316–1320, 1982.

Schneider, U., Becker, A., Finger, P., Meyer-Christoffer, A., Rudolf, B., and Ziese, M.: GPCC full data reanalysis version 6.0 at 0.5: monthly land-surface precipitation from rain-gauges built on GTS-based and historic data. doi: 10.5676/DWD_GPCC. FD_M_V6_050, 2011.

Supplementary Tables

Table S1. Final selected set of 14 CMIP5 models for this study.

Model Name	Institution
BNU-ESM	College of Global Change and Earth System Science, Beijing Normal University
CCSM4	National Center for Atmospheric Research
CESM1-CAM5	Community Earth System Model, Community Atmosphere Model
CSIRO-Mk3.6.0	Commonwealth Scientific and Industrial Research Organization in collaboration with Queensland Climate Change Centre of Excellence
FGOALS-g2	Flexible Global Ocean-Atmosphere-Land System Model
FIO-ESM	The First Institute of Oceanography, SOA, China
GISS-E2-H GISS-E2-R	NASA Goddard Institute for Space Studies
IPSL-CM5A-MR	Institut Pierre-Simon Laplace
MPI-ESM-MR MPI-ESM-LR	Max-Planck-Institut für Meteorologie (Max Planck Institute for Meteorology)
MRI-CGCM3	Meteorological Research Institute
NorESM1-MNorESM1-ME	Norwegian Climate Centre

Table S2. Models and number of catchments discarded in the two model-catchment selection steps described in section S1.

	Scenario RCP 2.6	Scenario 8.5
Step 1: models giving >40 constant time series	IPSL-CM5A-LR MIROC-ESM	IPSL-CM5A-LR MIROC-ESM
Number of catchments with constant time series	26	27
Step 2: models giving >154 time series with at least one negative R_{eff} value	BCC-CSM1.1 BCC-CSM1.1(m) CNRM-CM5 MIROC-ESM MIROC5	BCC-CSM1.1 BCC-CSM1.1(m) CNRM-CM5 MIROC-ESM MIROC5
Number of catchments with negative R_{eff} value	192	203

Table S3. Soil hydraulic parameters for different soil texture types after Rawls et al. (1982).

Soil texture	K_s (m/s)	θ_{ir} (-)	θ_s (-)	β (-)
Sand	5.83×10^{-4}	0.02	0.44	0.17
Loamy sand	1.70×10^{-4}	0.04	0.44	0.15
Sandy loam	7.19×10^{-5}	0.04	0.45	0.12
Loam	3.67×10^{-5}	0.03	0.46	0.09
Silt loam	1.89×10^{-5}	0.02	0.50	0.09
Sandy clay loam	1.19×10^{-5}	0.07	0.40	0.11
Clay loam	6.39×10^{-6}	0.08	0.46	0.09
Silty clay loam	4.17×10^{-6}	0.04	0.47	0.07
Sandy clay	3.34×10^{-6}	0.11	0.43	0.08
Silty clay	2.50×10^{-6}	0.06	0.48	0.06
Clay	1.67×10^{-6}	0.09	0.48	0.07

Supplementary figures

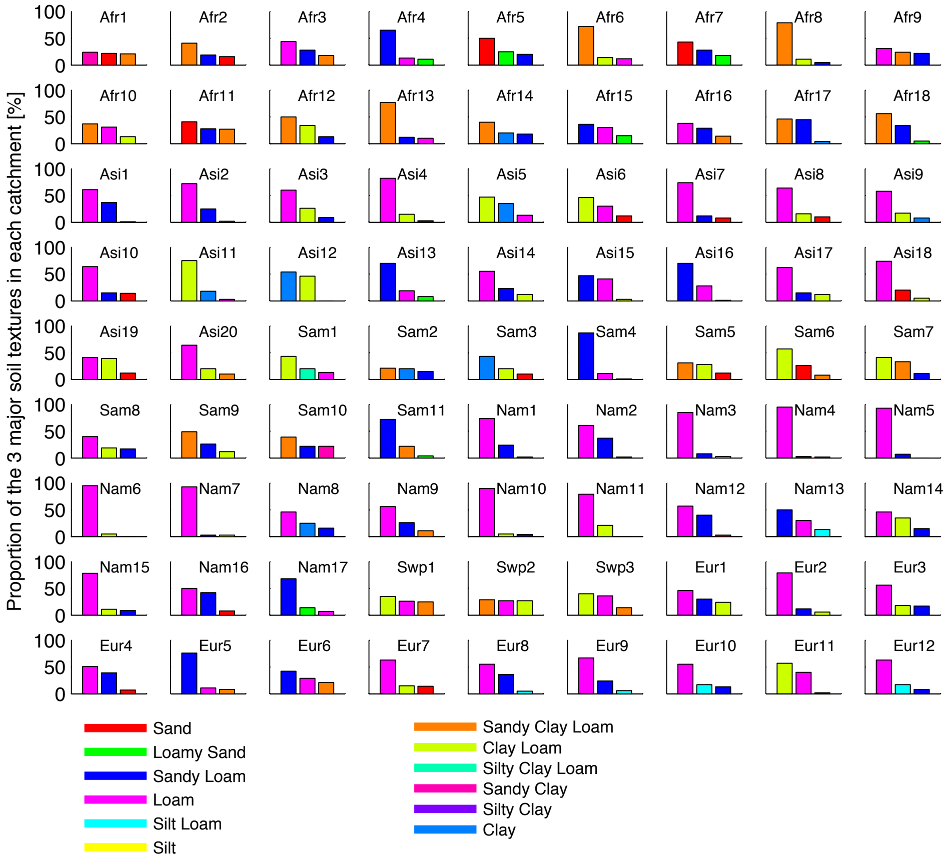
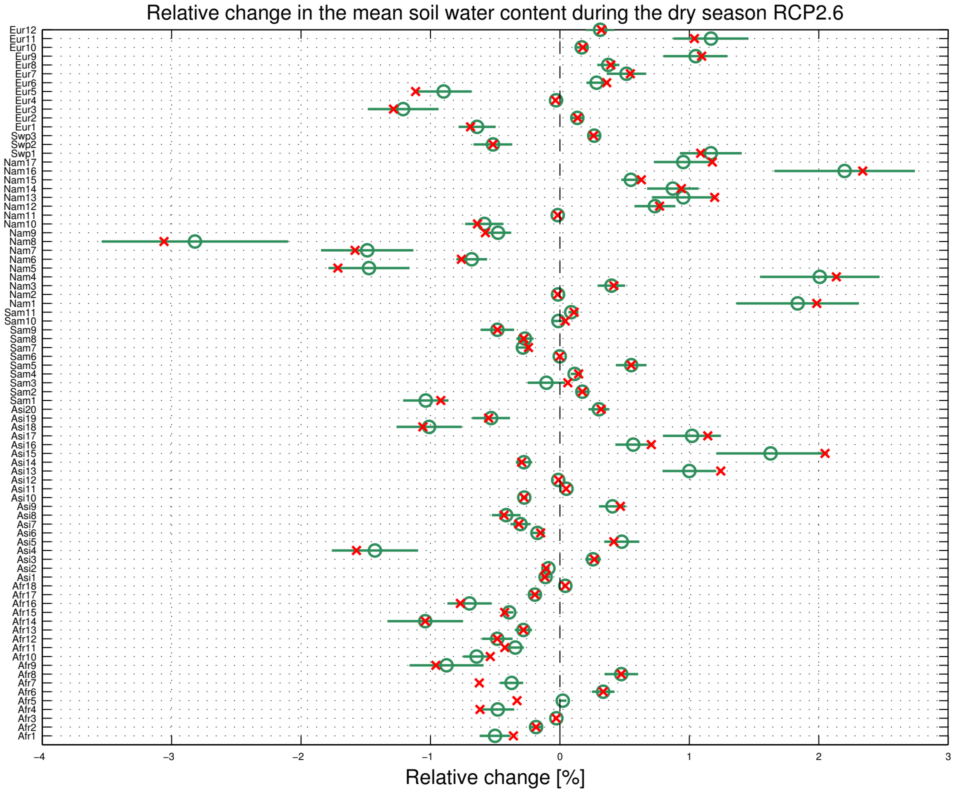


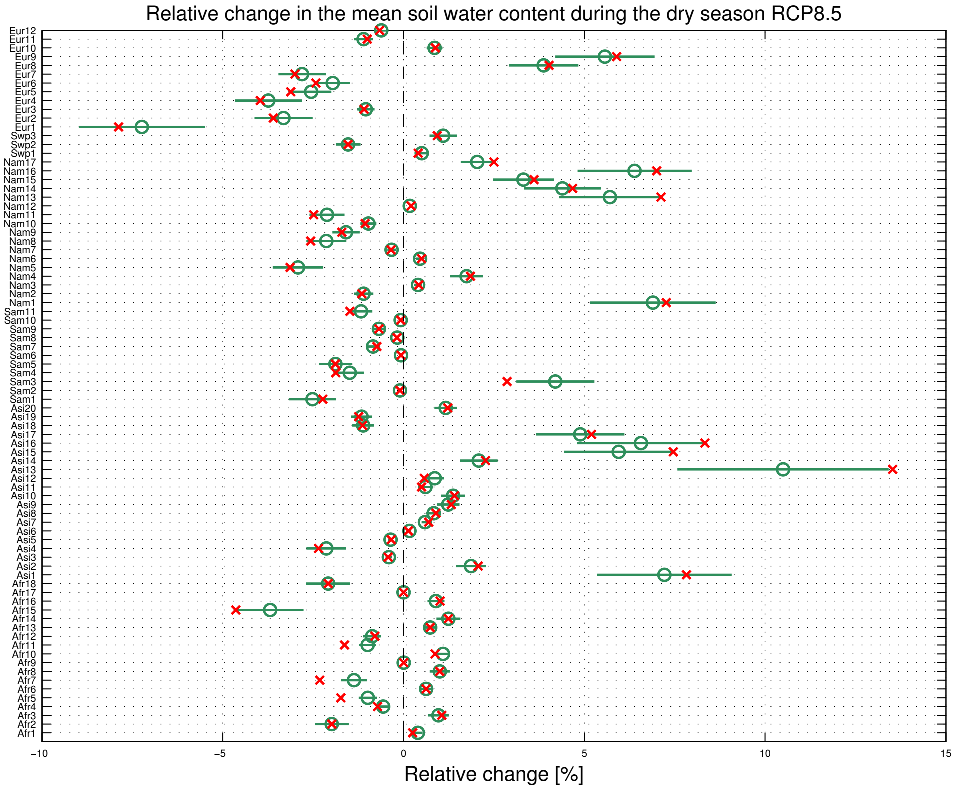
Figure S1. Proportion of the three major USDA soil textures prevailing in the catchments, as given from (Nachtergaele et al., 2008). For the calculations of θ_{uz} (main Eq. 3), only the dominant soil texture in each catchment (left bar in each bar plot) was used. The second and third most important soil textures in each catchment are represented by the middle and right bar in each subplot, respectively.

Figure S2. Sensitivity analysis of the study results towards the 11 sets of soil parameters values (Table S3). Results are shown for RCP 2.6 (a,c,e,g,i,k) and RCP 8.5 (b,d,f,h,j,l), for the mean soil water content during the dry season (a,b) and wet season (c,d), for the interannual variability of the mean soil water content during the dry (e,f) and wet season (g,h), and for the frequency of occurrence of the rare dry events (i,j) and wet events (k,l). The green circles (o) are the median values across the 11 sets of soil parameters values (and based on the median across models), the green line is the median absolute deviation from the 11 sets, and the red cross are the values for the (median across models from) major soil texture are defined from Fig. S1.

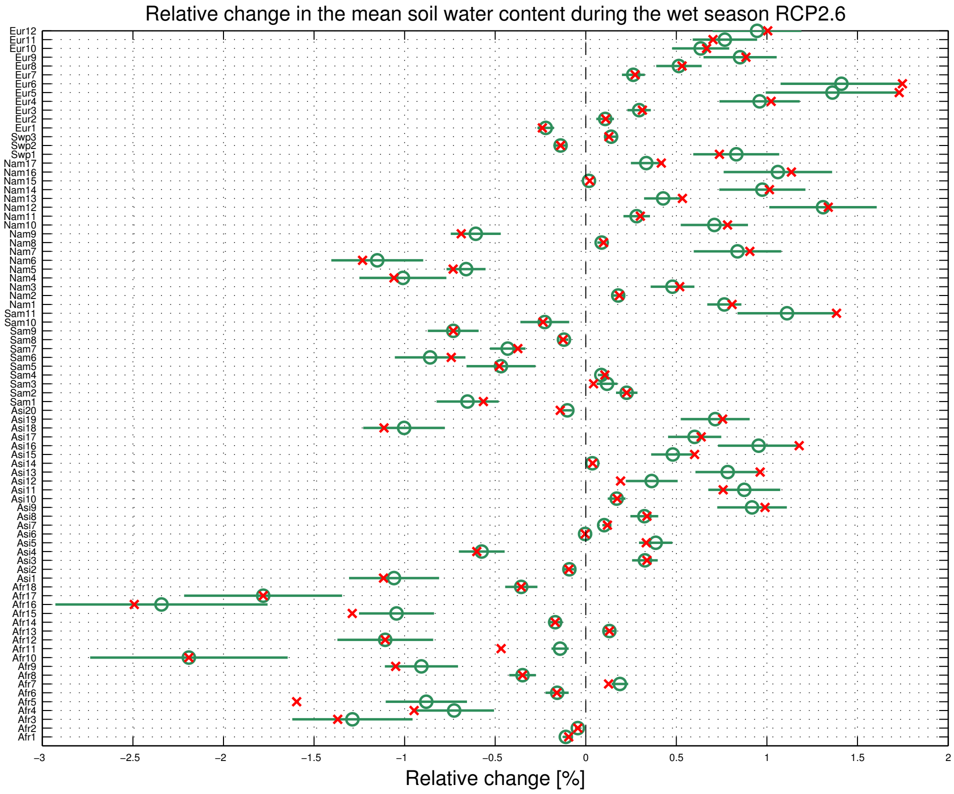
a)



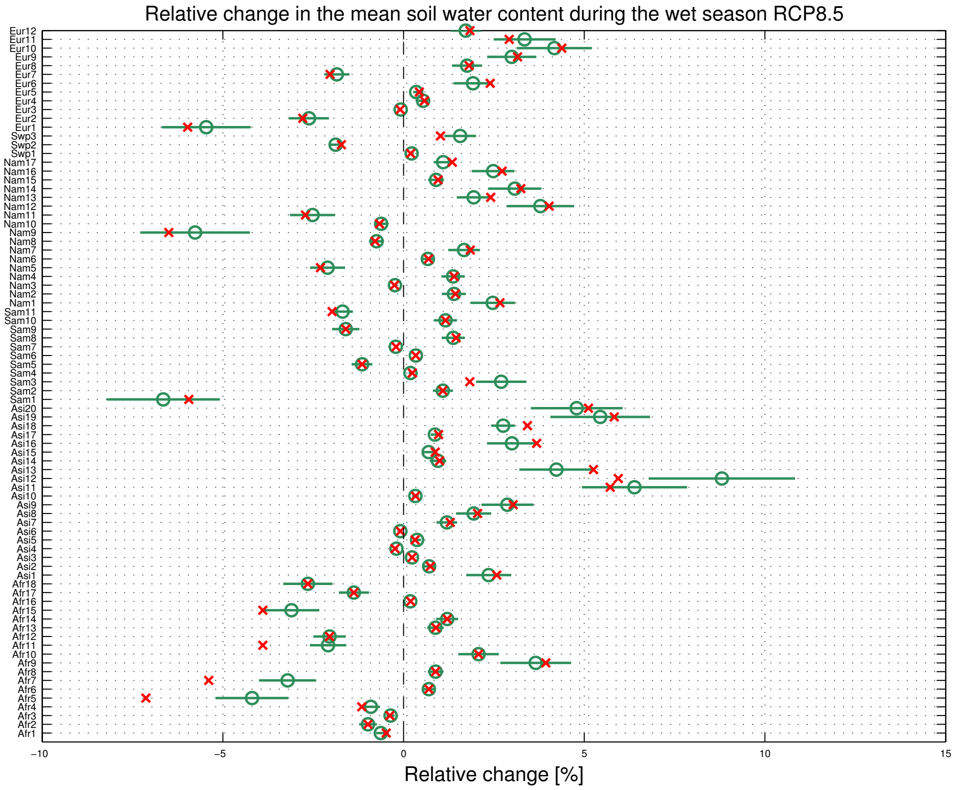
b)


Relative change in the mean soil water content during the dry season RCP8.5
Eur12
Eur11
Eur10
Eur9
Eur8
Eur7
Eur6
Eur5
Eur4
Eur3
Eur2
Eur1
Swp3
Swp2
Swp1
Nam17
Nam16
Nam15
Nam14
Nam13
Nam12
Nam11
Nam10
Nam9
Nam8
Nam7
Nam6
Nam5
Nam4
Nam3
Nam2
Nam1
Sam11
Sam10
Sam9
Sam8
Sam7
Sam6
Sam5
Sam4
Sam3
Sam2
Sam1
Asi20
Asi19
Asi18
Asi17
Asi16
Asi15
Asi14
Asi13
Asi12
Asi11
Asi10
Asi9
Asi8
Asi7
Asi6
Asi5
Asi4
Asi3
Asi2
Asi1
Afr18
Afr17
Afr16
Afr15
Afr14
Afr13
Afr12
Afr11
Afr10
Afr9
Afr8
Afr7
Afr6
Afr5
Afr4
Afr3
Afr2
Afr1
−10
−5
0
5
10
15
Relative change [%]

c)

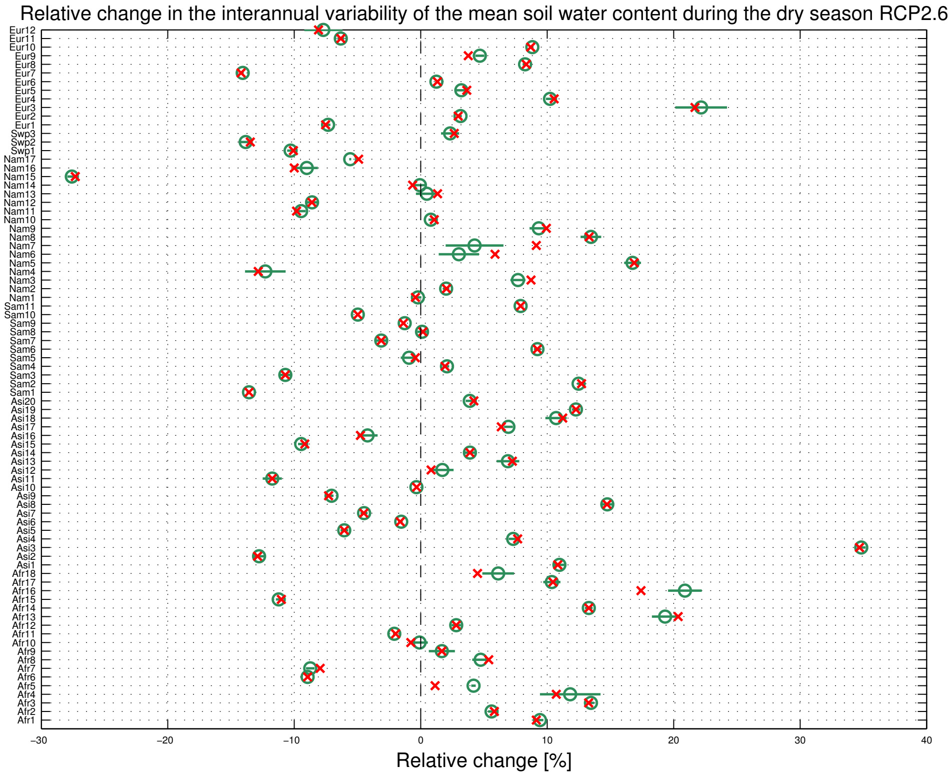

Relative change in the mean soil water content during the wet season RCP2.6
Eur12
Eur11
Eur10
Eur9
Eur8
Eur7
Eur6
Eur5
Eur4
Eur3
Eur2
Eur1
Swp3
Swp2
Swp1
Nam17
Nam16
Nam15
Nam14
Nam13
Nam12
Nam11
Nam10
Nam9
Nam8
Nam7
Nam6
Nam5
Nam4
Nam3
Nam2
Nam1
Sam11
Sam10
Sam9
Sam8
Sam7
Sam6
Sam5
Sam4
Sam3
Sam2
Sam1
Asi20
Asi19
Asi18
Asi17
Asi16
Asi15
Asi14
Asi13
Asi12
Asi11
Asi10
Asi9
Asi8
Asi7
Asi6
Asi5
Asi4
Asi3
Asi2
Asi1
Afr18
Afr17
Afr16
Afr15
Afr14
Afr13
Afr12
Afr11
Afr10
Afr9
Afr8
Afr7
Afr6
Afr5
Afr4
Afr3
Afr2
Afr1
−3
−2.5
−2
−1.5
−1
−0.5
0
0.5
1
1.5
2
Relative change [%]

d)

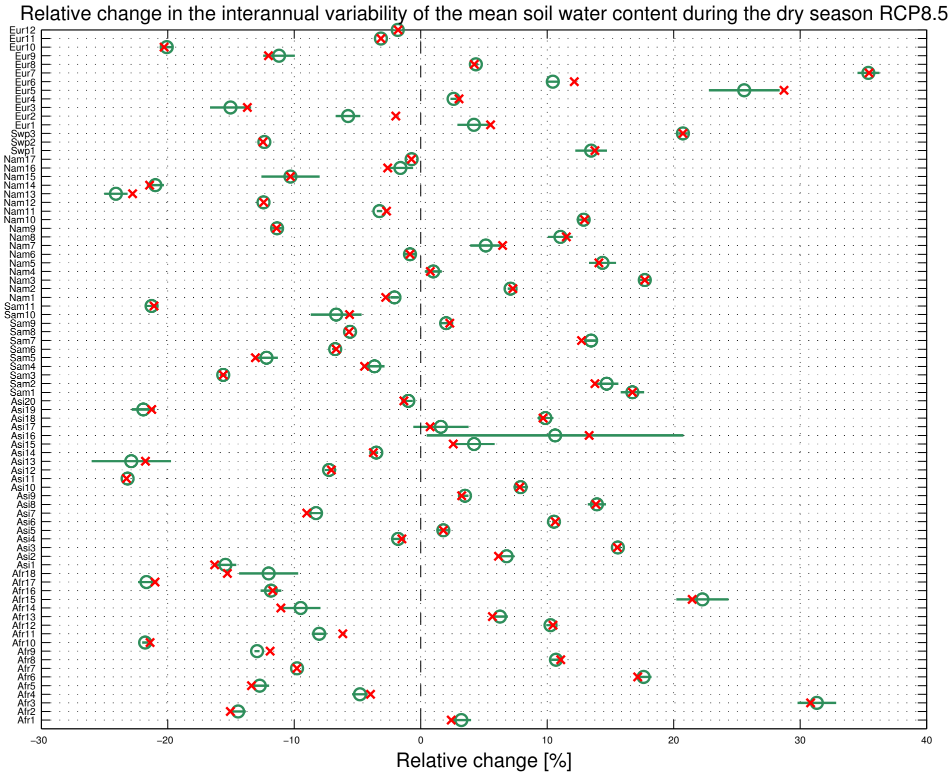


Relative change in the mean soil water content during the wet season RCP8.5

e)

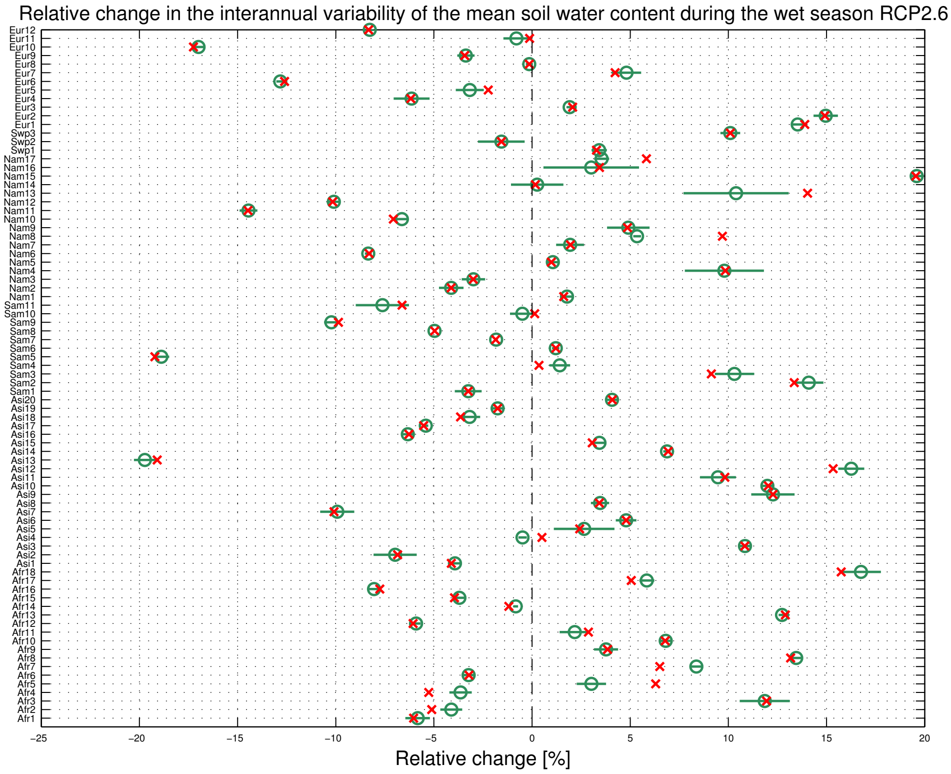

Relative change in the interannual variability of the mean soil water content during the dry season RCP2.6
Eur12
Eur11
Eur10
Eur9
Eur8
Eur7
Eur6
Eur5
Eur4
Eur3
Eur2
Eur1
Swp3
Swp2
Swp1
Nam17
Nam16
Nam15
Nam14
Nam13
Nam12
Nam11
Nam10
Nam9
Nam8
Nam7
Nam6
Nam5
Nam4
Nam3
Nam2
Nam1
Sam11
Sam10
Sam9
Sam8
Sam7
Sam6
Sam5
Sam4
Sam3
Sam2
Sam1
Asi20
Asi19
Asi18
Asi17
Asi16
Asi15
Asi14
Asi13
Asi12
Asi11
Asi10
Asi9
Asi8
Asi7
Asi6
Asi5
Asi4
Asi3
Asi2
Asi1
Afr18
Afr17
Afr16
Afr15
Afr14
Afr13
Afr12
Afr11
Afr10
Afr9
Afr8
Afr7
Afr6
Afr5
Afr4
Afr3
Afr2
Afr1
−30
−20
−10
0
10
20
30
40
Relative change [%]

f)

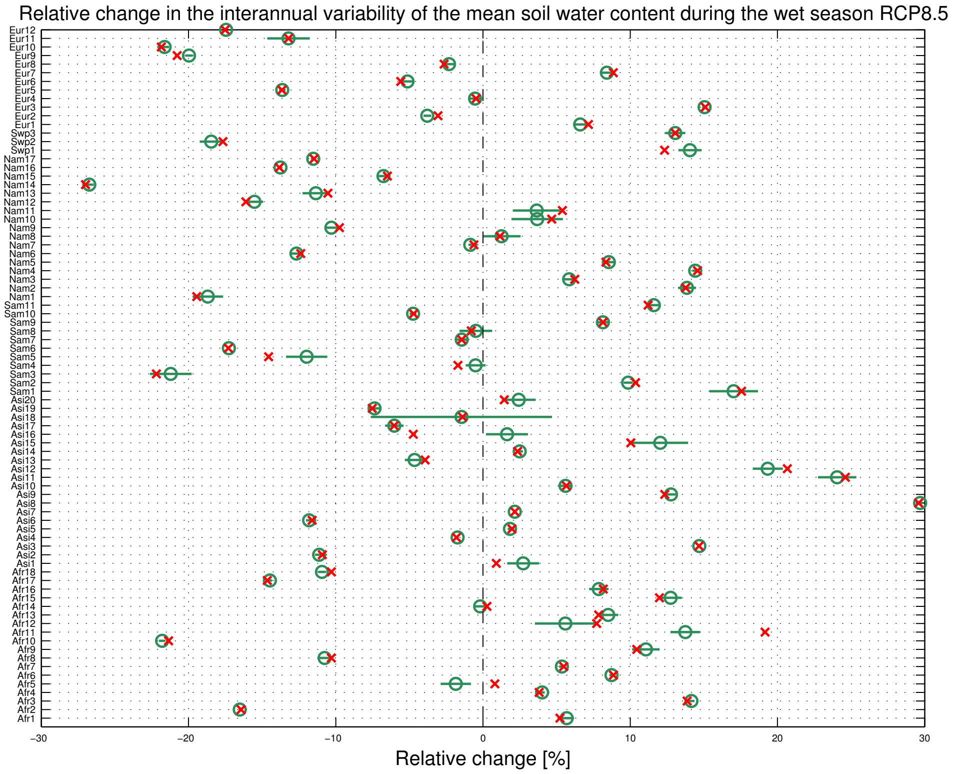


Relative change in the interannual variability of the mean soil water content during the dry season RCP8.5

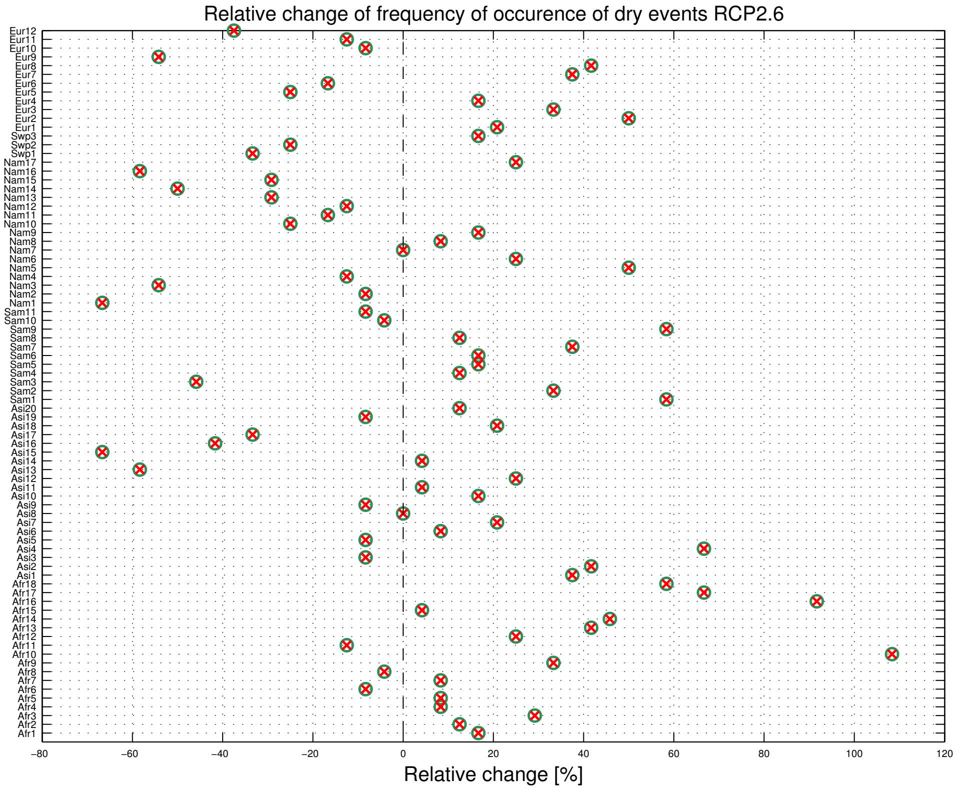
g)


Relative change in the interannual variability of the mean soil water content during the wet season RCP2.6
Eur12
Eur11
Eur10
Eur9
Eur8
Eur7
Eur6
Eur5
Eur4
Eur3
Eur2
Eur1
Swp3
Swp2
Swp1
Nam17
Nam16
Nam15
Nam14
Nam13
Nam12
Nam11
Nam10
Nam9
Nam8
Nam7
Nam6
Nam5
Nam4
Nam3
Nam2
Nam1
Sam11
Sam10
Sam9
Sam8
Sam7
Sam6
Sam5
Sam4
Sam3
Sam2
Sam1
Asi20
Asi19
Asi18
Asi17
Asi16
Asi15
Asi14
Asi13
Asi12
Asi11
Asi10
Asi9
Asi8
Asi7
Asi6
Asi5
Asi4
Asi3
Asi2
Asi1
Afr18
Afr17
Afr16
Afr15
Afr14
Afr13
Afr12
Afr11
Afr10
Afr9
Afr8
Afr7
Afr6
Afr5
Afr4
Afr3
Afr2
Afr1
−25
−20
−15
−10
−5
0
5
10
15
20
Relative change [%]

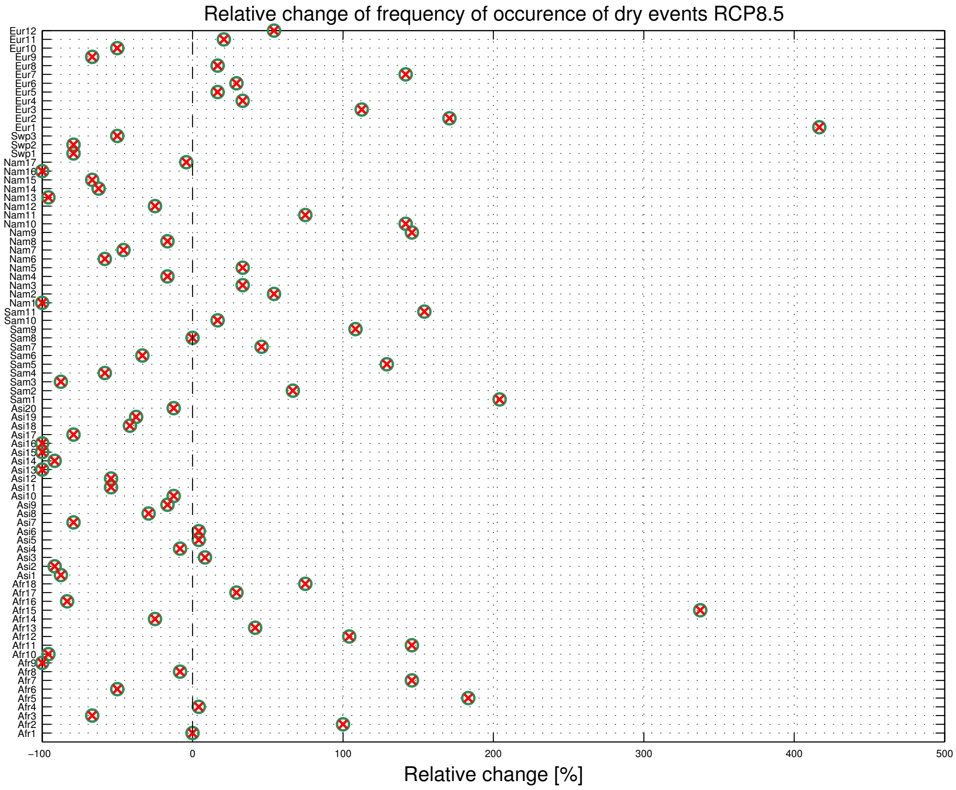
h)


Relative change in the interannual variability of the mean soil water content during the wet season RCP8.5

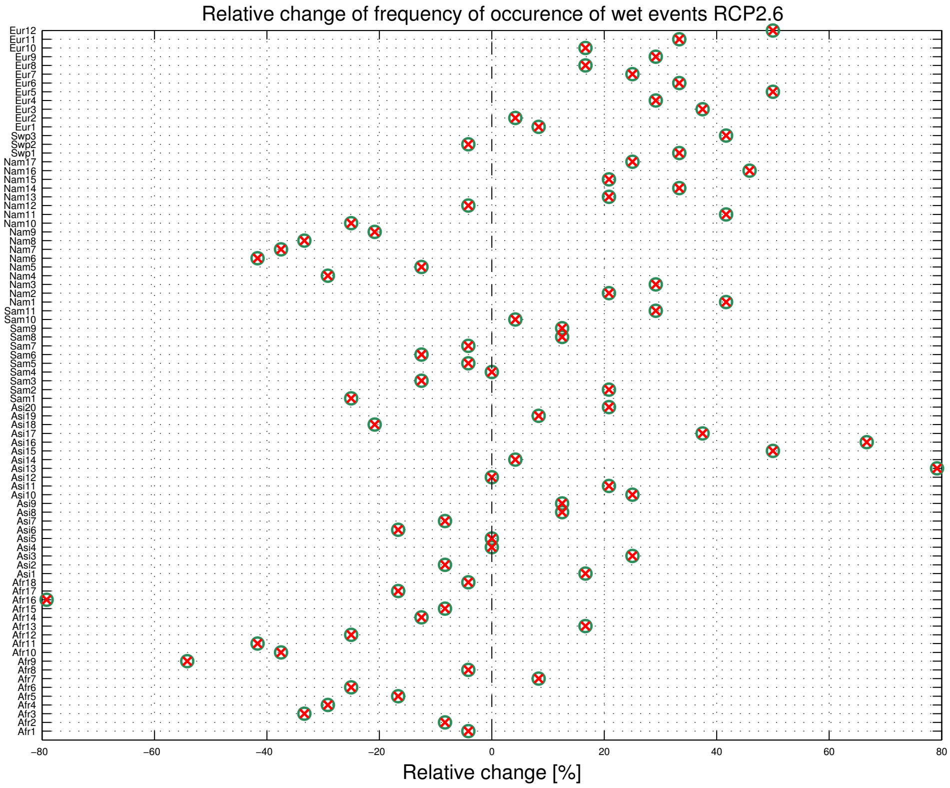
i)


Relative change of frequency of occurence of dry events RCP2.6
Eur12
Eur11
Eur10
Eur9
Eur8
Eur7
Eur6
Eur5
Eur4
Eur3
Eur2
Eur1
Swp3
Swp2
Swp1
Nam17
Nam16
Nam15
Nam14
Nam13
Nam12
Nam11
Nam10
Nam9
Nam8
Nam7
Nam6
Nam5
Nam4
Nam3
Nam2
Nam1
Sam11
Sam10
Sam9
Sam8
Sam7
Sam6
Sam5
Sam4
Sam3
Sam2
Sam1
Asi20
Asi19
Asi18
Asi17
Asi16
Asi15
Asi14
Asi13
Asi12
Asi11
Asi10
Asi9
Asi8
Asi7
Asi6
Asi5
Asi4
Asi3
Asi2
Asi1
Afr18
Afr17
Afr16
Afr15
Afr14
Afr13
Afr12
Afr11
Afr10
Afr9
Afr8
Afr7
Afr6
Afr5
Afr4
Afr3
Afr2
Afr1
−80
−60
−40
−20
0
20
40
60
80
100
120
Relative change [%]

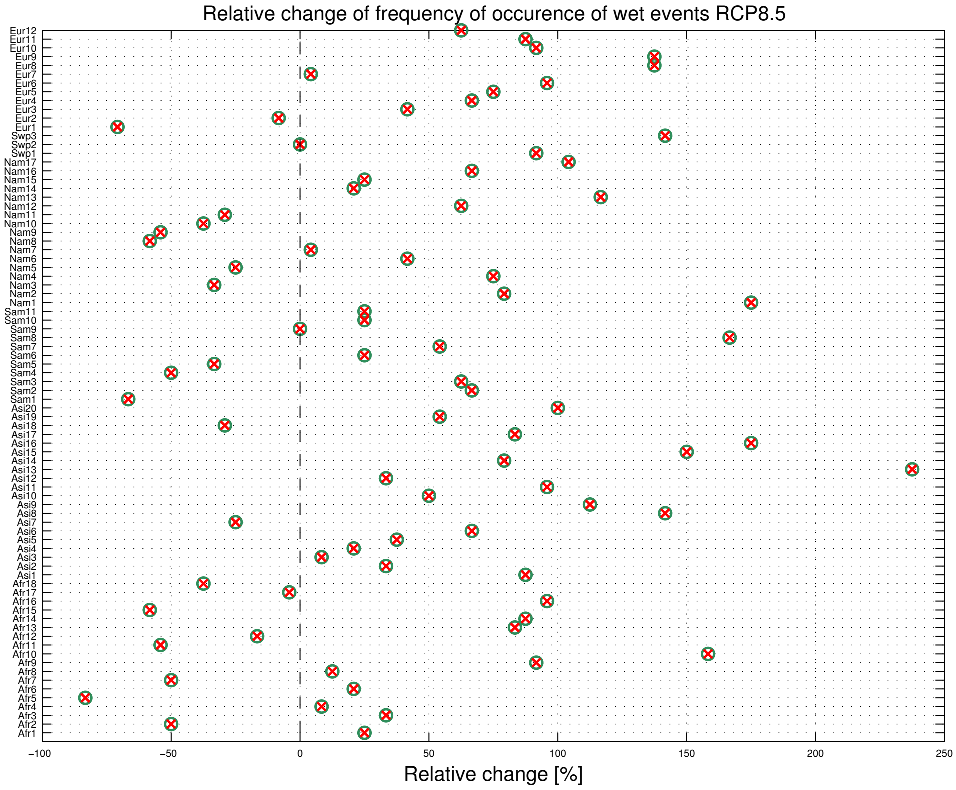
j)

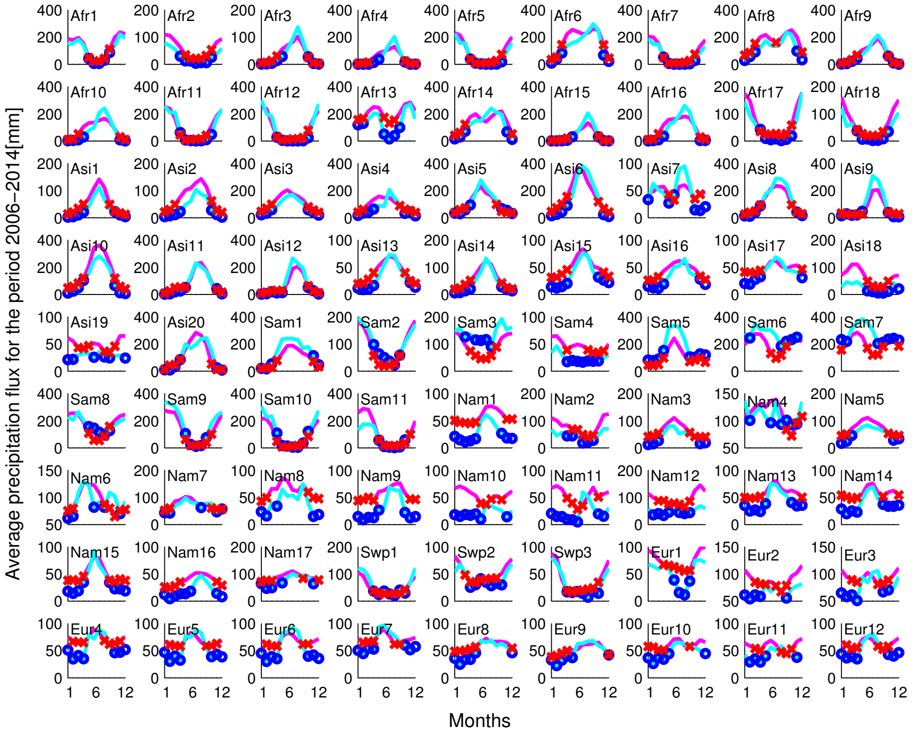

Relative change of frequency of occurence of dry events RCP8.5
Eur12
Eur11
Eur10
Eur9
Eur8
Eur7
Eur6
Eur5
Eur4
Eur3
Eur2
Eur1
Swp3
Swp2
Swp1
Nam17
Nam16
Nam15
Nam14
Nam13
Nam12
Nam11
Nam10
Nam9
Nam8
Nam7
Nam6
Nam5
Nam4
Nam3
Nam2
Nam1
Sam11
Sam10
Sam9
Sam8
Sam7
Sam6
Sam5
Sam4
Sam3
Sam2
Sam1
Asi20
Asi19
Asi18
Asi17
Asi16
Asi15
Asi14
Asi13
Asi12
Asi11
Asi10
Asi9
Asi8
Asi7
Asi6
Asi5
Asi4
Asi3
Asi2
Asi1
Afr18
Afr17
Afr16
Afr15
Afr14
Afr13
Afr12
Afr11
Afr10
Afr9
Afr8
Afr7
Afr6
Afr5
Afr4
Afr3
Afr2
Afr1
−100
0
100
200
300
400
500
Relative change [%]

k)

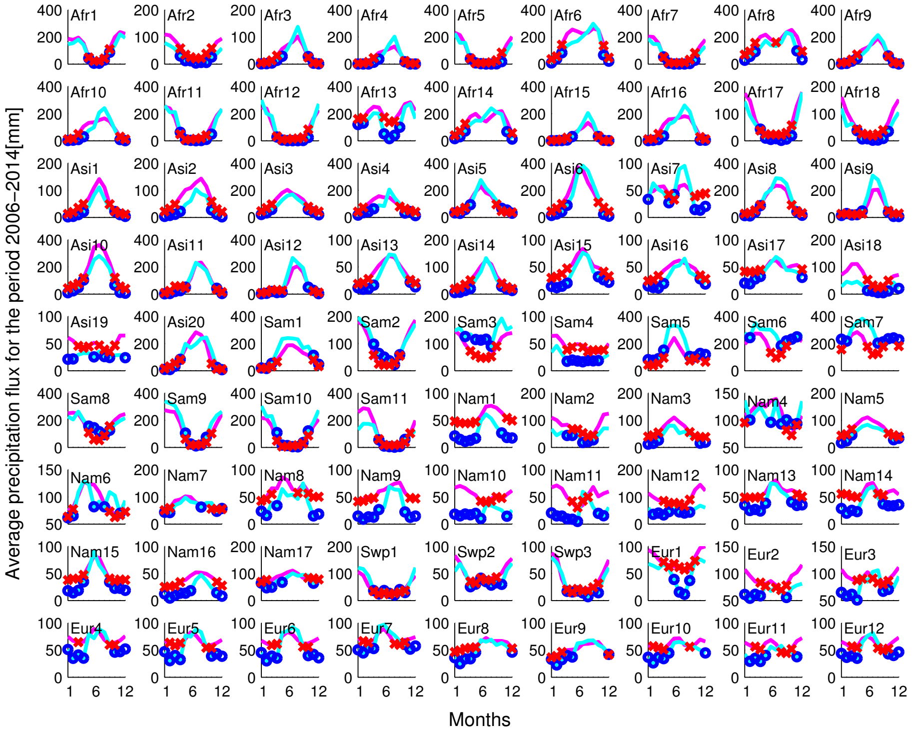

Relative change of frequency of occurence of wet events RCP2.6
Eur12
Eur11
Eur10
Eur9
Eur8
Eur7
Eur6
Eur5
Eur4
Eur3
Eur2
Eur1
Swp3
Swp2
Swp1
Nam17
Nam16
Nam15
Nam14
Nam13
Nam12
Nam11
Nam10
Nam9
Nam8
Nam7
Nam6
Nam5
Nam4
Nam3
Nam2
Nam1
Sam11
Sam10
Sam9
Sam8
Sam7
Sam6
Sam5
Sam4
Sam3
Sam2
Sam1
Asi20
Asi19
Asi18
Asi17
Asi16
Asi15
Asi14
Asi13
Asi12
Asi11
Asi10
Asi9
Asi8
Asi7
Asi6
Asi5
Asi4
Asi3
Asi2
Asi1
Afr18
Afr17
Afr16
Afr15
Afr14
Afr13
Afr12
Afr11
Afr10
Afr9
Afr8
Afr7
Afr6
Afr5
Afr4
Afr3
Afr2
Afr1
−80
−60
−40
−20
0
20
40
60
80
Relative change [%]

l)


Relative change of frequency of occurence of wet events RCP8.5
Eur12
Eur11
Eur10
Eur9
Eur8
Eur7
Eur6
Eur5
Eur4
Eur3
Eur2
Eur1
Swp3
Swp2
Swp1
Nam17
Nam16
Nam15
Nam14
Nam13
Nam12
Nam11
Nam10
Nam9
Nam8
Nam7
Nam6
Nam5
Nam4
Nam3
Nam2
Nam1
Sam11
Sam10
Sam9
Sam8
Sam7
Sam6
Sam5
Sam4
Sam3
Sam2
Sam1
Asi20
Asi19
Asi18
Asi17
Asi16
Asi15
Asi14
Asi13
Asi12
Asi11
Asi10
Asi9
Asi8
Asi7
Asi6
Asi5
Asi4
Asi3
Asi2
Asi1
Afr18
Afr17
Afr16
Afr15
Afr14
Afr13
Afr12
Afr11
Afr10
Afr9
Afr8
Afr7
Afr6
Afr5
Afr4
Afr3
Afr2
Afr1
−100
−50
0
50
100
150
200
250
Relative change [%]


Average precipitation flux for the period 2006–2014[mm]
Afr1
Afr2
Afr3
Afr4
Afr5
Afr6
Afr7
Afr8
Afr9
Afr10
Afr11
Afr12
Afr13
Afr14
Afr15
Afr16
Afr17
Afr18
Asi1
Asi2
Asi3
Asi4
Asi5
Asi6
Asi7
Asi8
Asi9
Asi10
Asi11
Asi12
Asi13
Asi14
Asi15
Asi16
Asi17
Asi18
Asi19
Asi20
Sam1
Sam2
Sam3
Sam4
Sam5
Sam6
Sam7
Sam8
Sam9
Sam10
Sam11
Nam1
Nam2
Nam3
Nam4
Nam5
Nam6
Nam7
Nam8
Nam9
Nam10
Nam11
Nam12
Nam13
Nam14
Nam15
Nam16
Nam17
Swp1
Swp2
Swp3
Eur1
Eur2
Eur3
Eur4
Eur5
Eur6
Eur7
Eur8
Eur9
Eur10
Eur11
Eur12
1
6
12
Months

(a)


Average precipitation flux for the period 2006–2014[mm]
Afr1
Afr2
Afr3
Afr4
Afr5
Afr6
Afr7
Afr8
Afr9
Afr10
Afr11
Afr12
Afr13
Afr14
Afr15
Afr16
Afr17
Afr18
Asi1
Asi2
Asi3
Asi4
Asi5
Asi6
Asi7
Asi8
Asi9
Asi10
Asi11
Asi12
Asi13
Asi14
Asi15
Asi16
Asi17
Asi18
Asi19
Asi20
Sam1
Sam2
Sam3
Sam4
Sam5
Sam6
Sam7
Sam8
Sam9
Sam10
Sam11
Nam1
Nam2
Nam3
Nam4
Nam5
Nam6
Nam7
Nam8
Nam9
Nam10
Nam11
Nam12
Nam13
Nam14
Nam15
Nam16
Nam17
Swp1
Swp2
Swp3
Eur1
Eur2
Eur3
Eur4
Eur5
Eur6
Eur7
Eur8
Eur9
Eur10
Eur11
Eur12
1
6
12
Months

(b)


CMIP5
GPCC

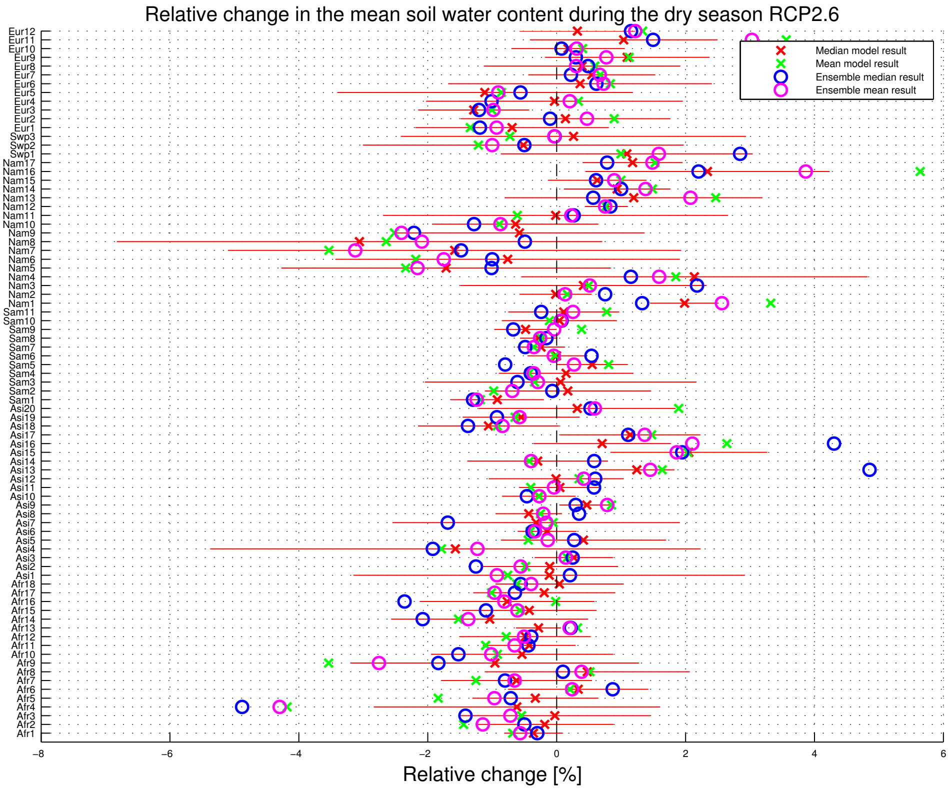
Figure S3. Mean monthly precipitation (in mm) from the GPCC dataset (Schneider et al. 2011) (light blue line) and from the CMIP5 ensemble mean of the 14 models in Table S1 (pink line). Results are shown for each catchment and the period 2006-2014, and for both radiative forcing scenarios RCP 2.6 in panel (a) and RCP 8.5 in panel (b). The month numbering is: January as month 1 through to December as month 12. The markers on the lines represent the dry season months according to the season definition given in the main section 2.4. The blue markers are the dry season months determined from the GPCC dataset and the red markers are the dry season months determined from the CMIP5 model ensemble mean.

Figure S4. Uncertainty analysis of soil moisture statistics results across the 14 individual CMIP5 models. Results are shown for RCP 2.6 (a,c,e,g,i,k) and RCP 8.5 (b,d,f,h,j,l), for the mean soil water content during the dry season (a,b) and wet season (c,d), for the inter-annual variability of the mean soil water content during the dry (e,f) and wet season (g,h), and for the frequency of occurrence of rare dry events (i,j) and wet events (k,l). The purple and blue circles (o – ensemble median or mean result) represent the considered soil moisture statistic change implied by the median and mean R_{eff} time series result, respectively, obtained by averaging across the R_{eff} outputs of all 14 climate models. The red and green crosses (x – median or mean model result) represent the median and mean soil moisture statistic change, respectively, obtained by averaging across all 14 climate models the corresponding soil moisture statistic change implied by the R_{eff} time series output of each model; the red line shows the associated median inter-model deviation of the individual statistic change result of the 14 climate models.

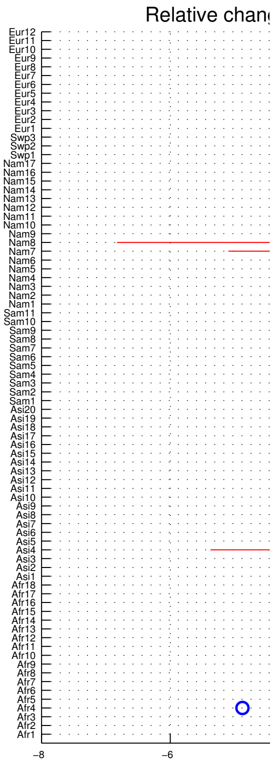
Gia Destouni 28/9/16 16:50
Comment [1]: Use this exact terminology also in the figure legend

Gia Destouni 28/9/16 16:50
Comment [2]: Use this exact terminology also in the figure legend

a)

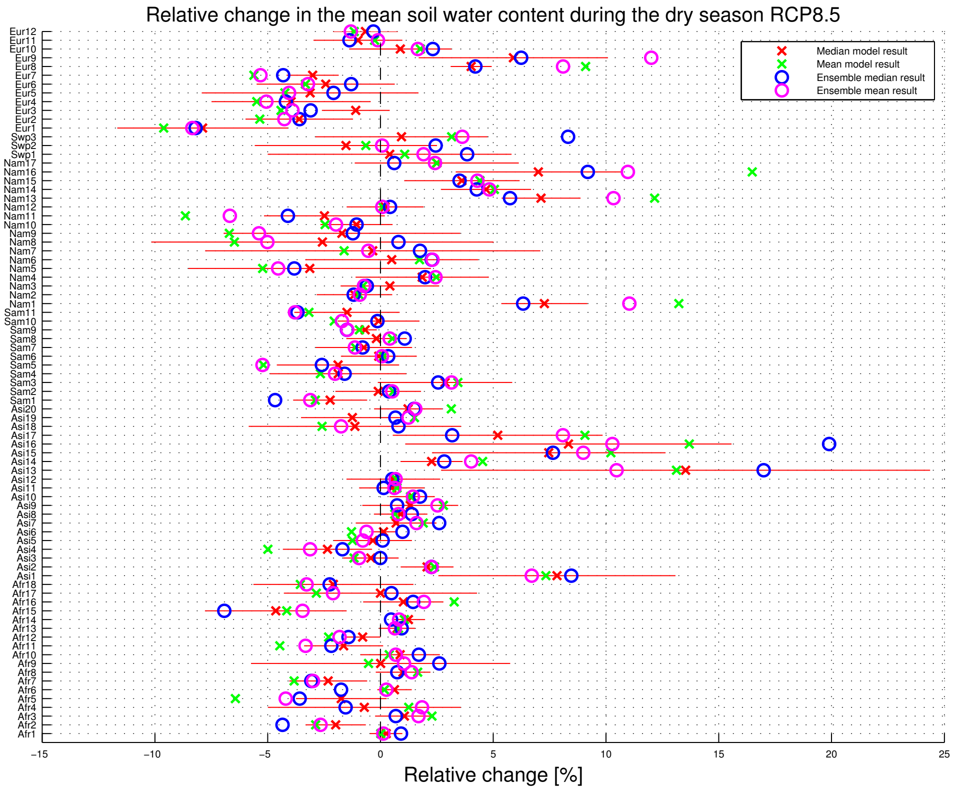


l l 28/9/16 23:13

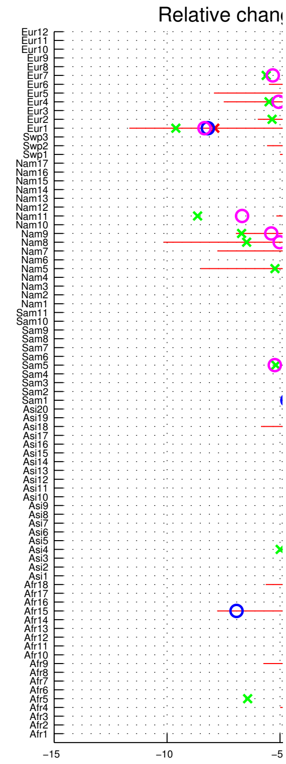


Deleted:

b)

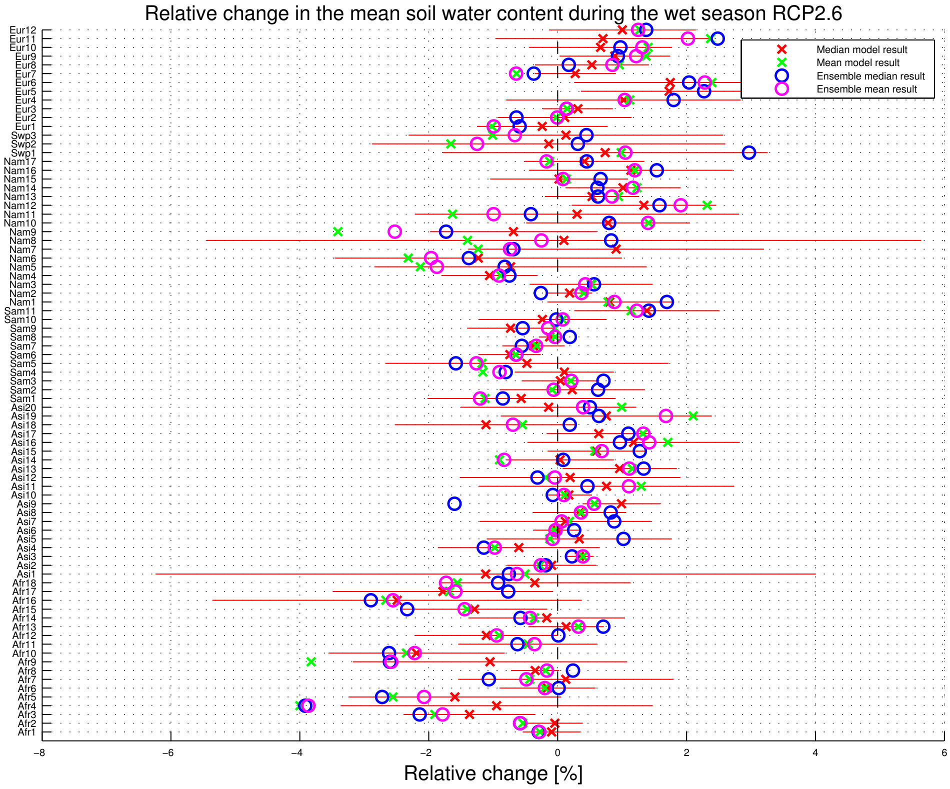


I I 28/9/16 23:13

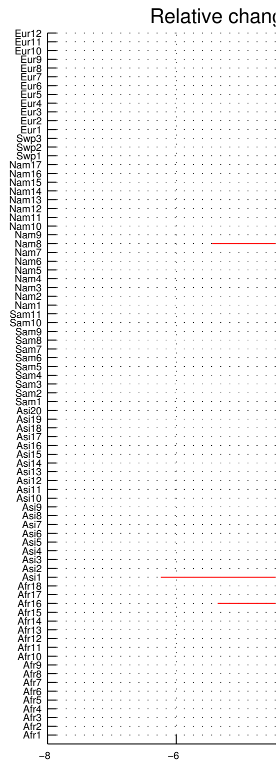


Deleted:

c)

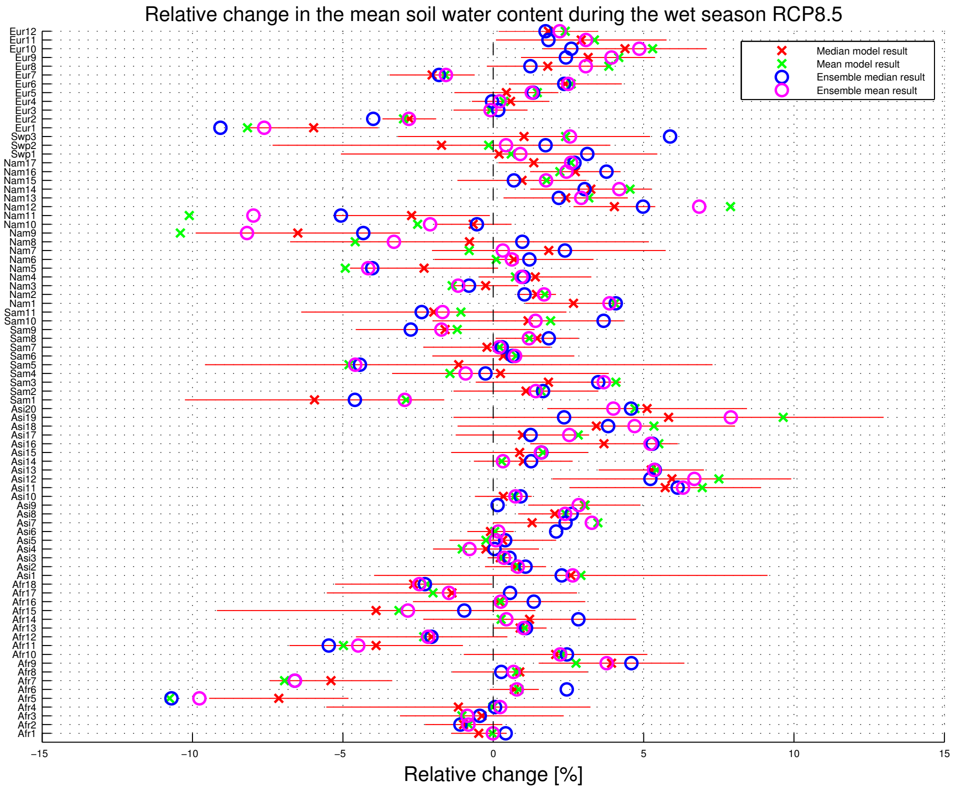


I I 28/9/16 23:13

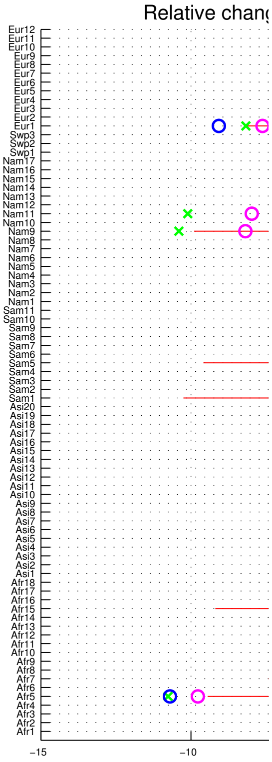


Deleted:

d)

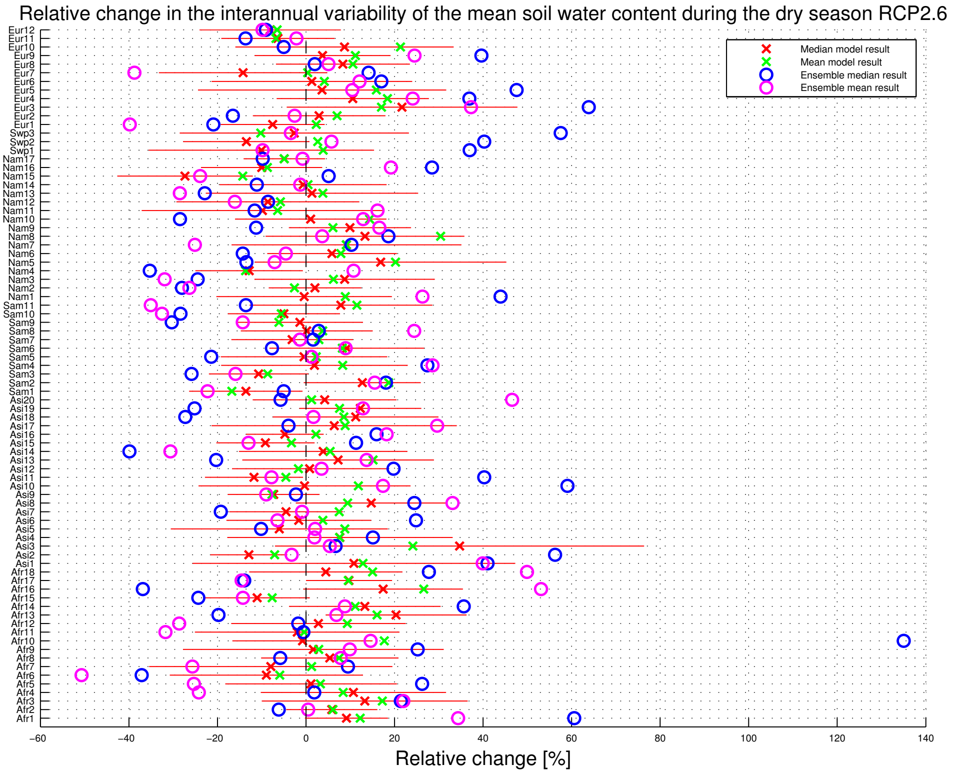


I I 28/9/16 23:14

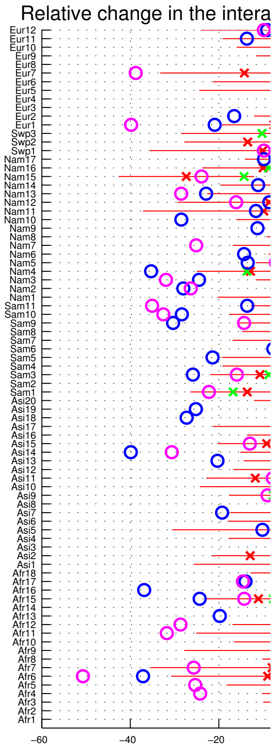


Deleted:

e)

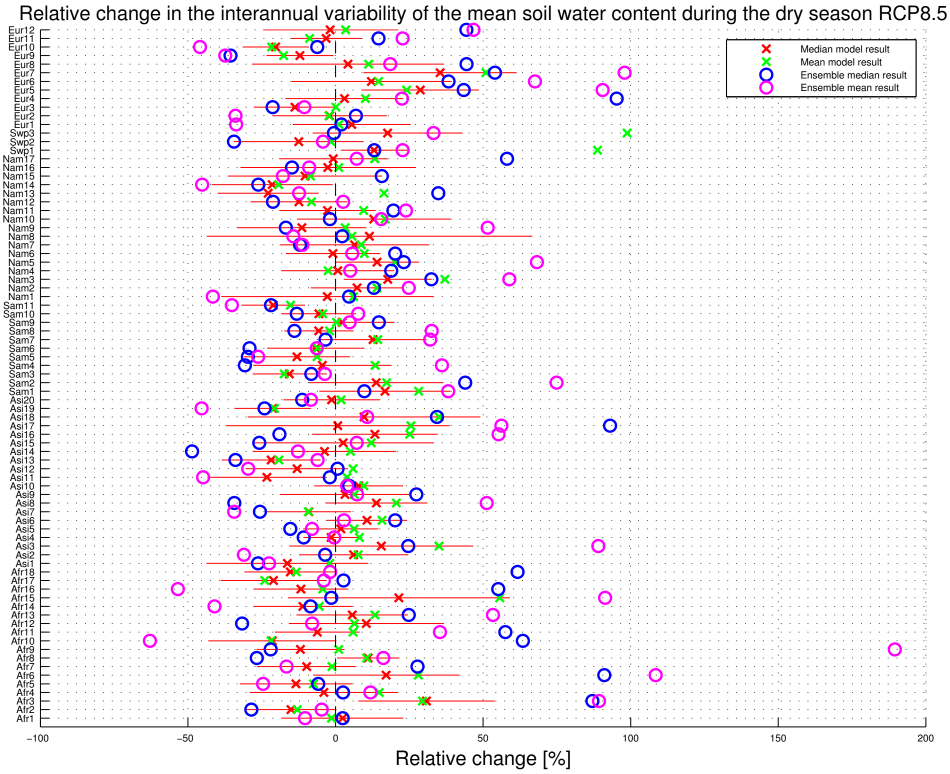


I I 28/9/16 23:14

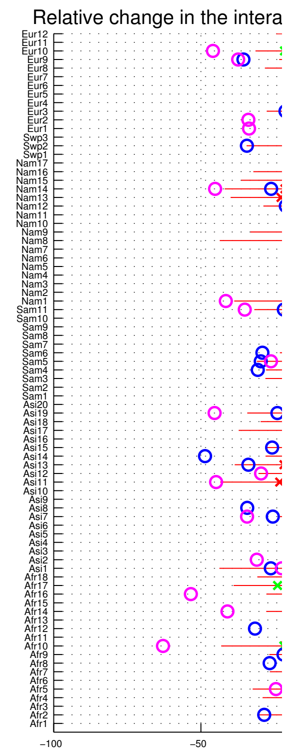


Deleted:

f)

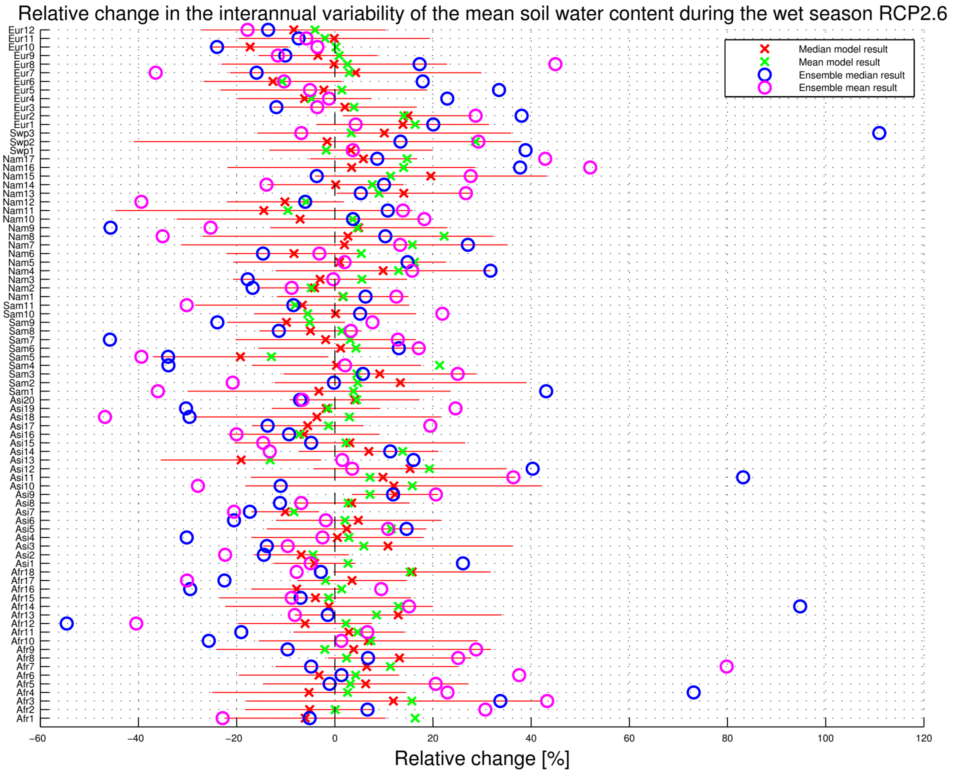


I I 28/9/16 23:14

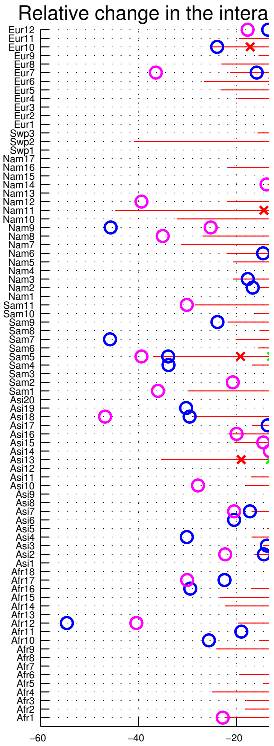


Deleted:

g)

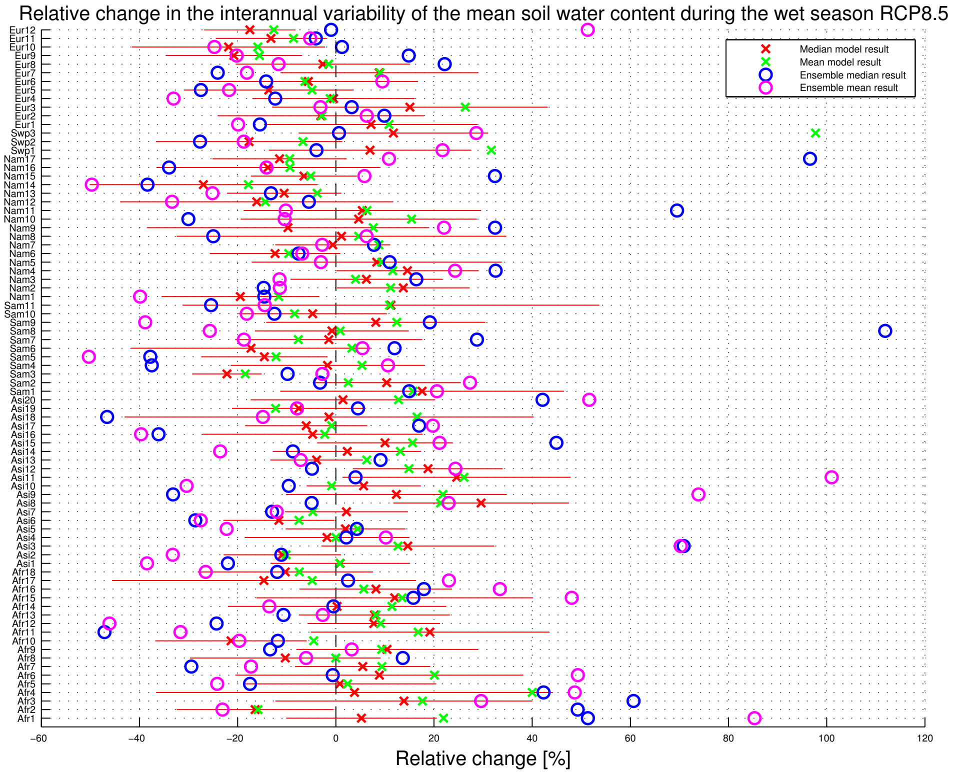


l l 28/9/16 23:14

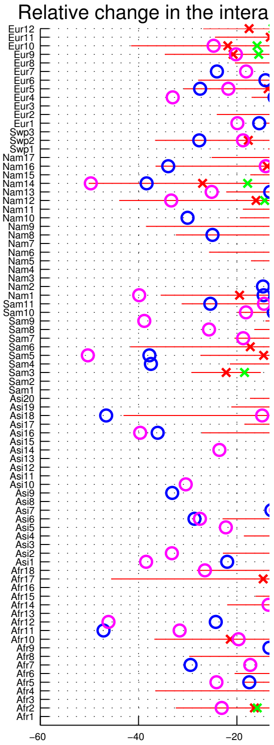


Deleted:

h)

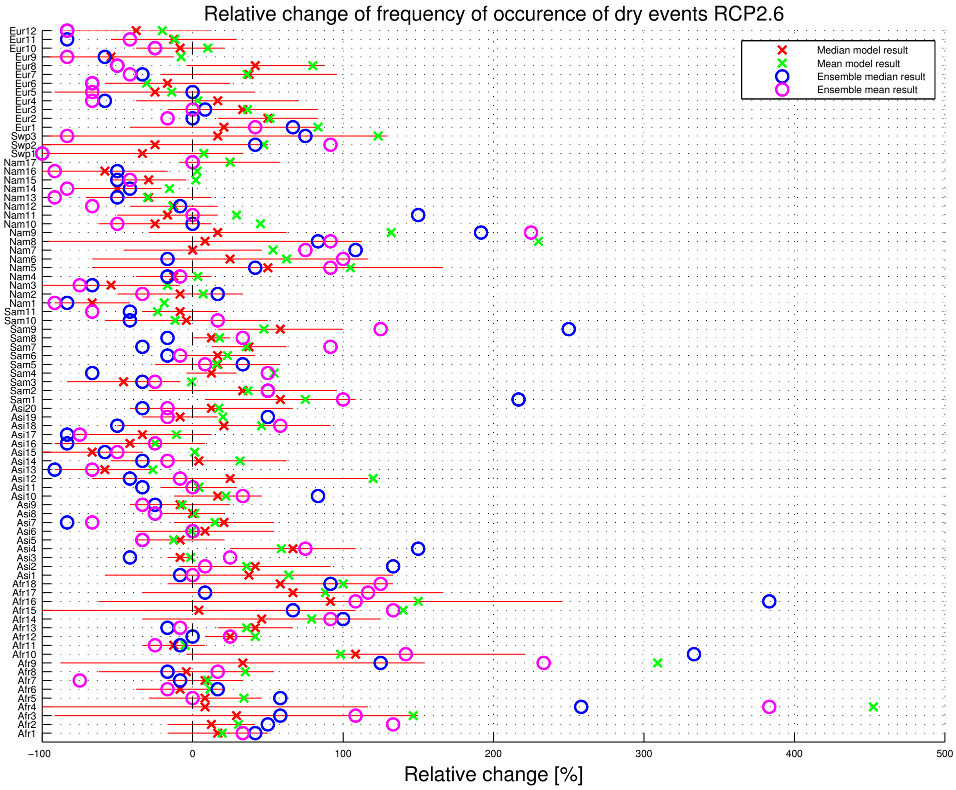


I I 28/9/16 23:14

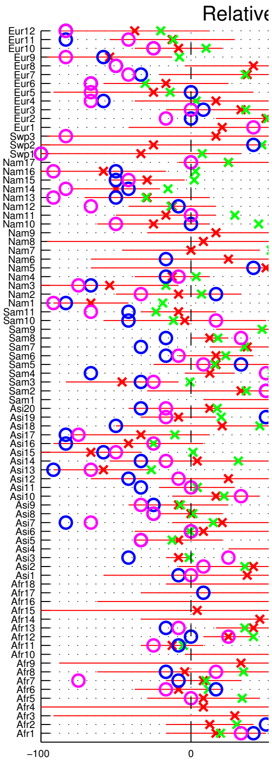


Deleted:

i)

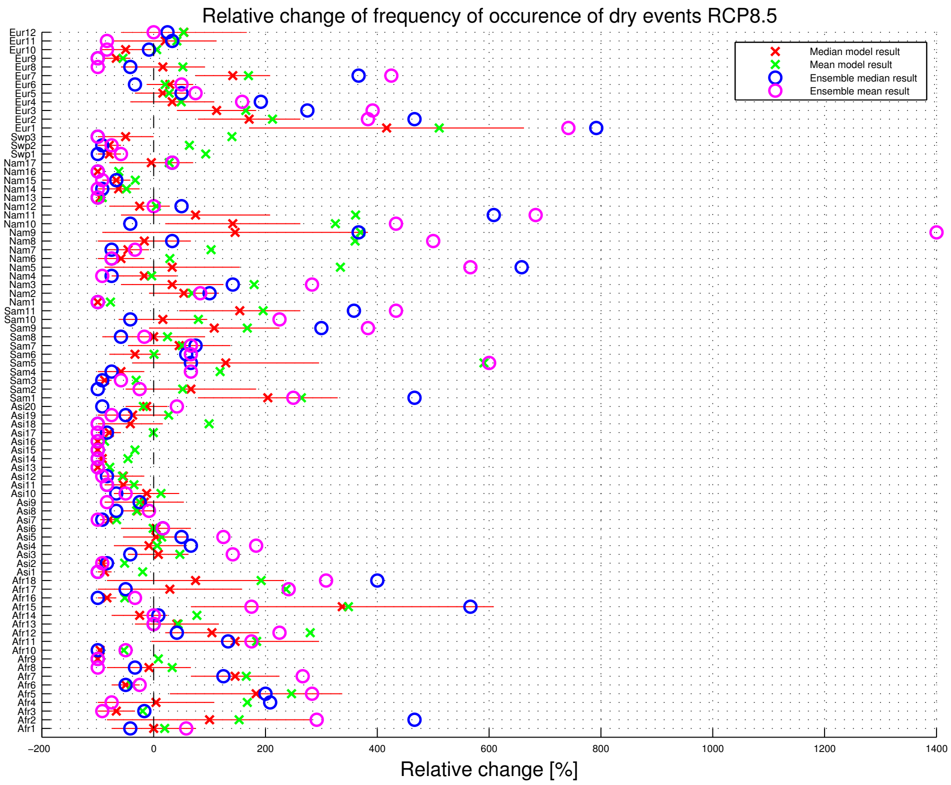


I I 28/9/16 23:15

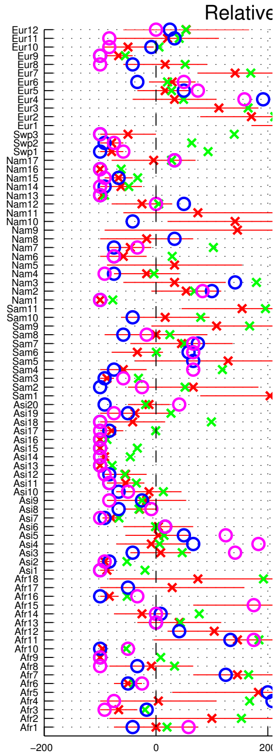


Deleted:

j)

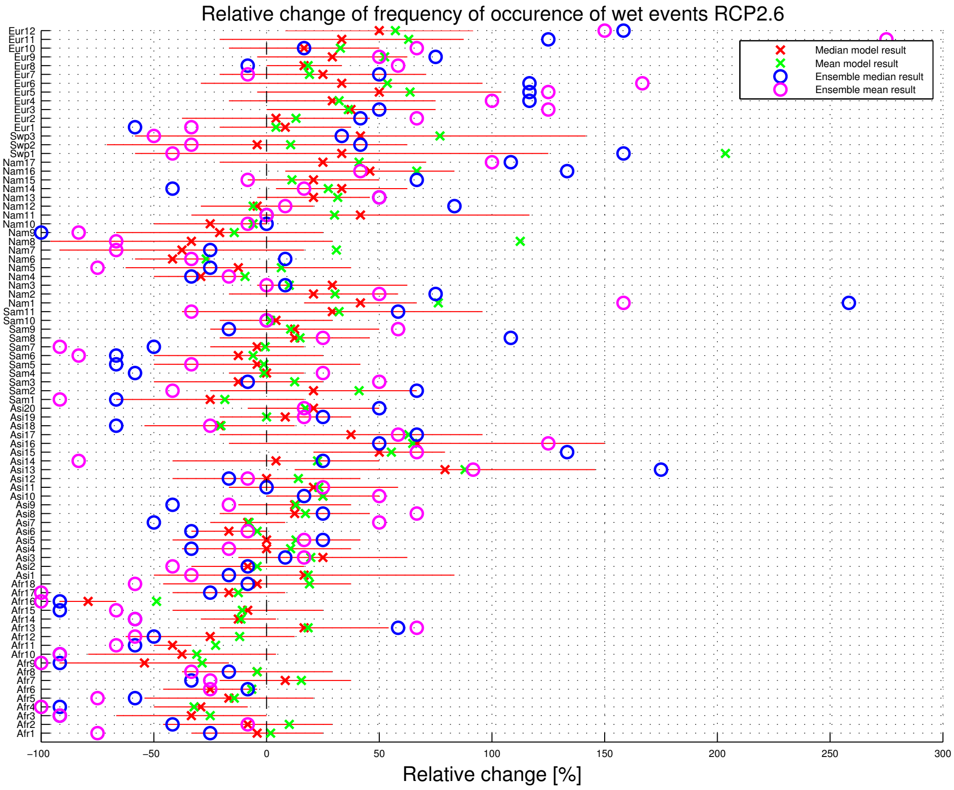


I I 28/9/16 23:15

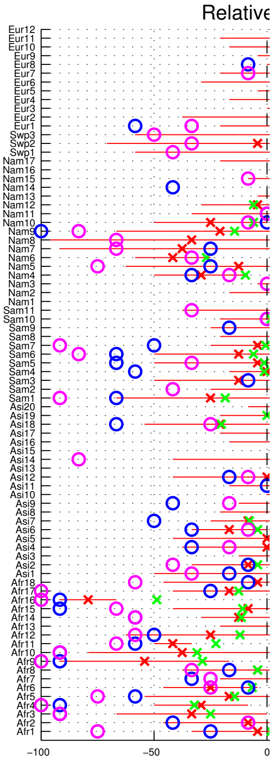


Deleted:

k)

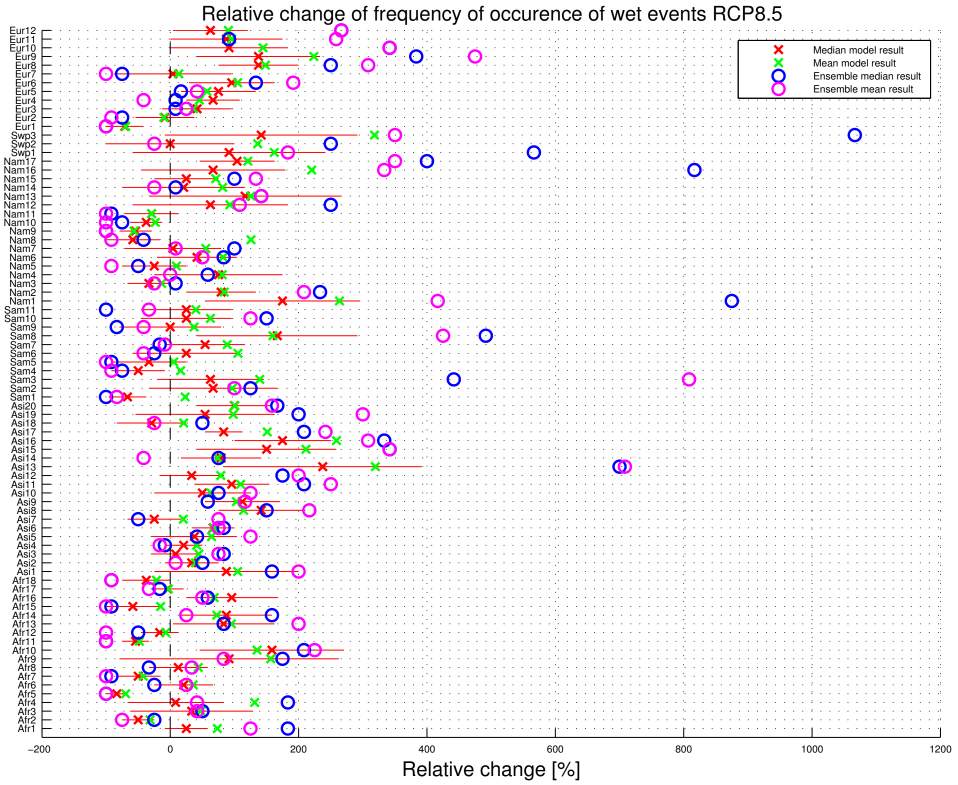


I I 28/9/16 23:15

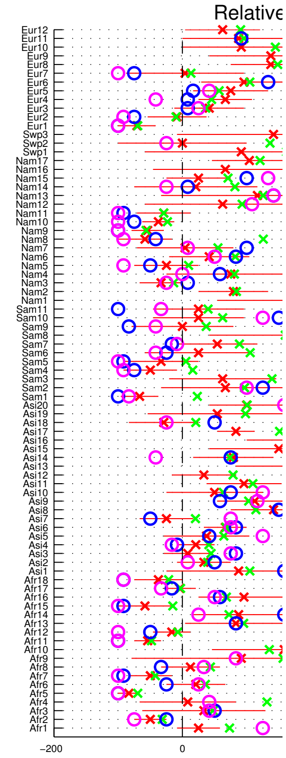


Deleted:

l)

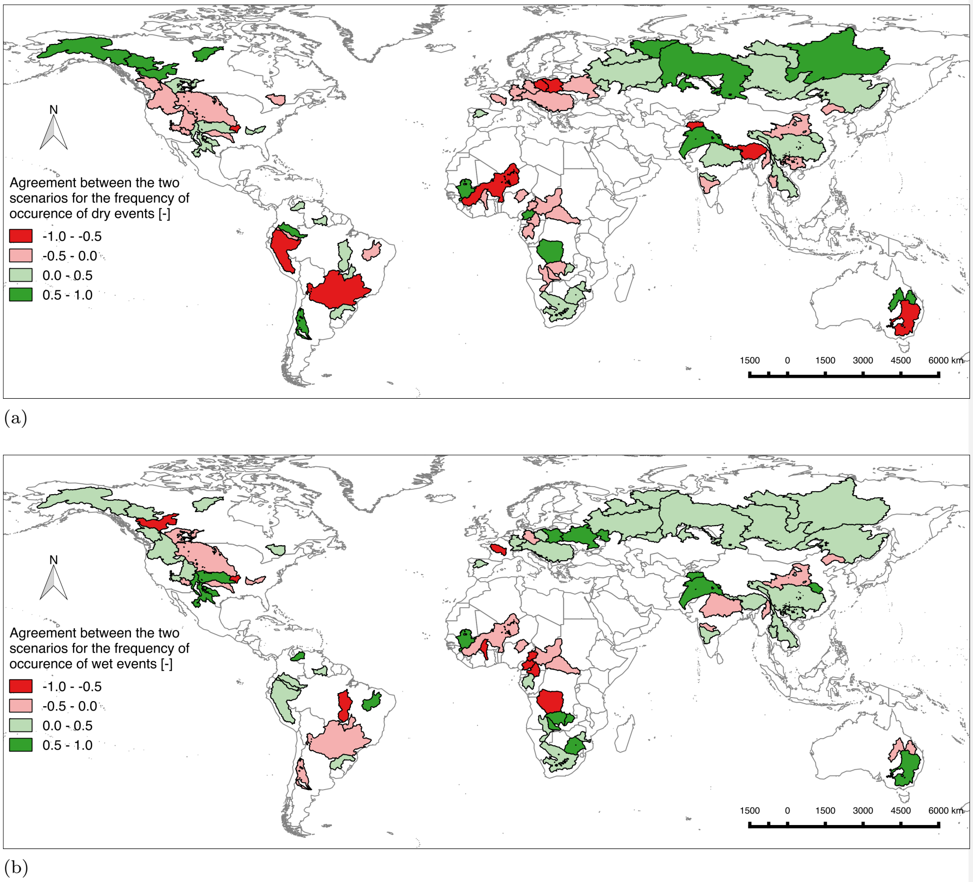


l l 28/9/16 23:15



Deleted:

Figure S4. Mean monthly relative degree of water saturation over the unsaturated soil zone. Results are shown for two radiative forcing (RCP) scenarios (red and pink lines for RCP 2.6, blue and green lines for RCP 8.5), and for the two study periods (red and blue lines for 2006-2025, pink and green lines for 2080-2099). The solid lines represent the ensemble mean model result and the dashed lines represent 1 standard deviation around the mean of the corresponding result derived from individual models. The relative degree of soil water saturation (with value 1 corresponding to full saturation) represents the unsaturated soil water content normalized by the saturated soil water content (soil porosity). The month numbering is: January as month 1 through to December as month 12.

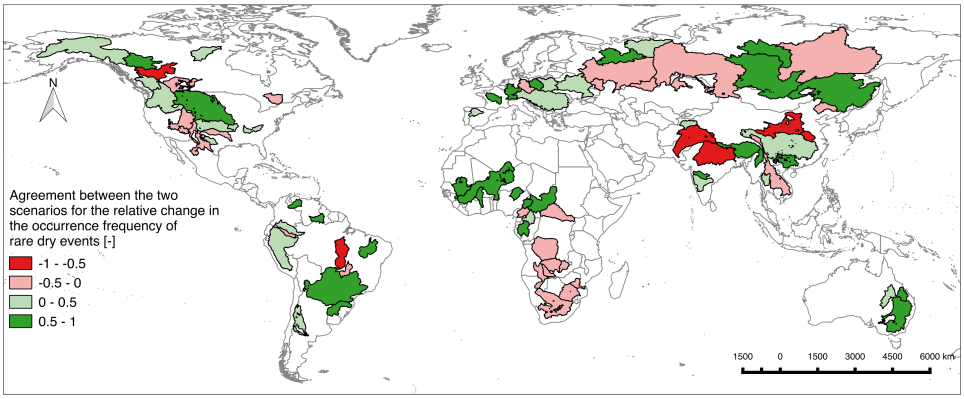


(a)

(b)

Figure S5. Map of model result agreement (as defined in SM section S2) between the two radiative forcing scenarios RCP 2.6 and RCP 8.5, regarding the change in occurrence frequency of dry (panel a) and wet (panel b) soil moisture events.

a)



b)

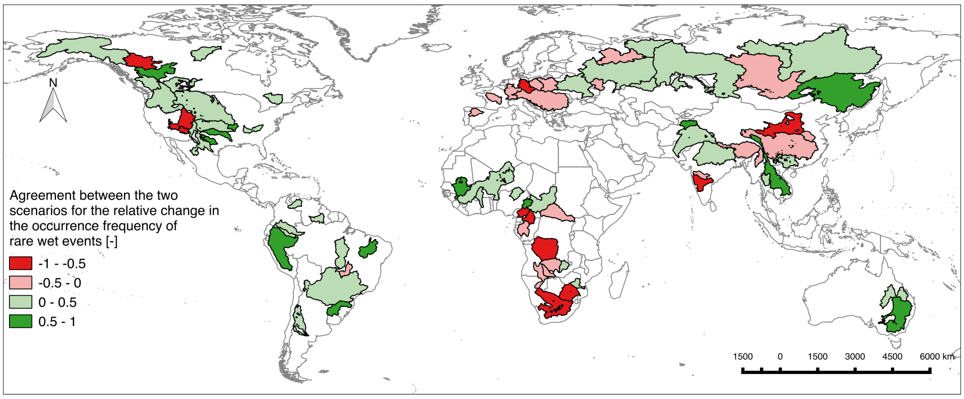
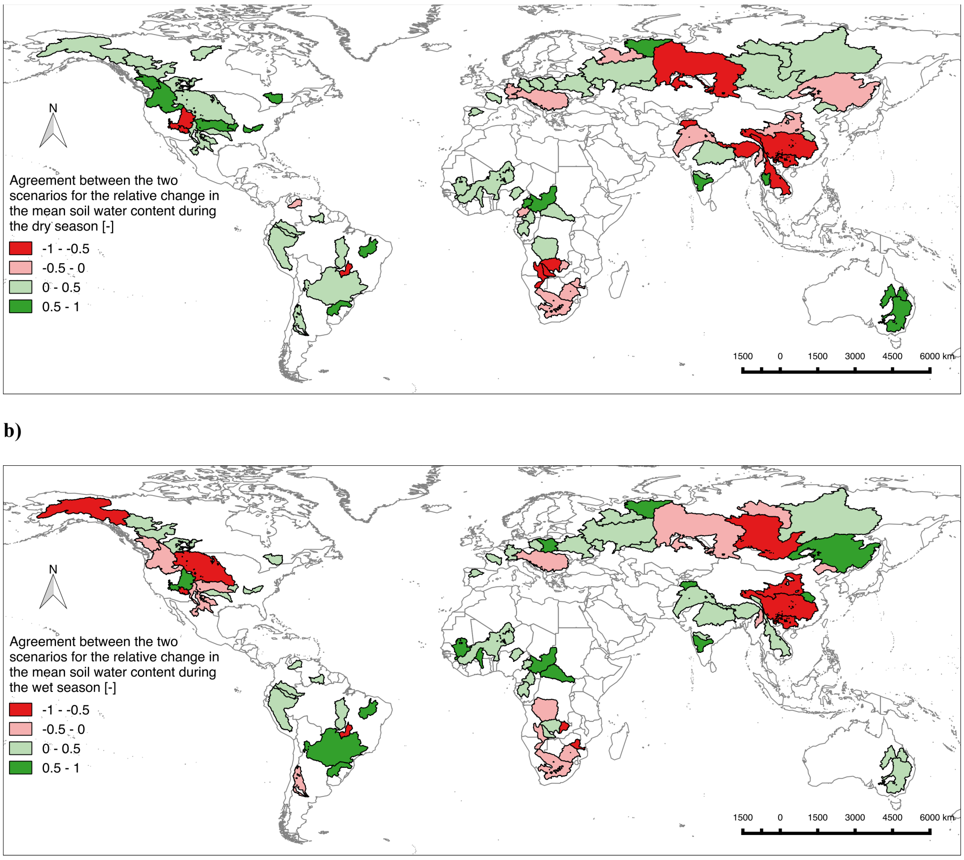


Figure S6. Map of model result agreement (as defined in SM section S2) between the two radiative forcing scenarios RCP 2.6 and RCP 8.5, regarding the change in mean seasonal soil water content during the dry (panel a) and the wet (panel b) season.

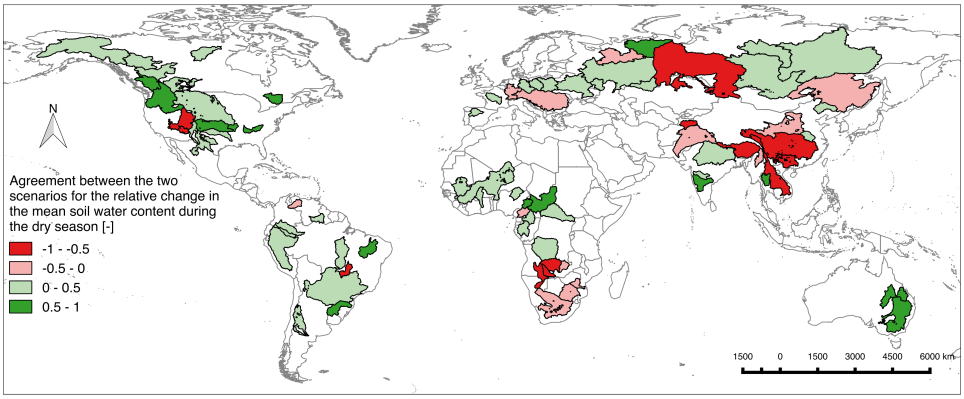
a)



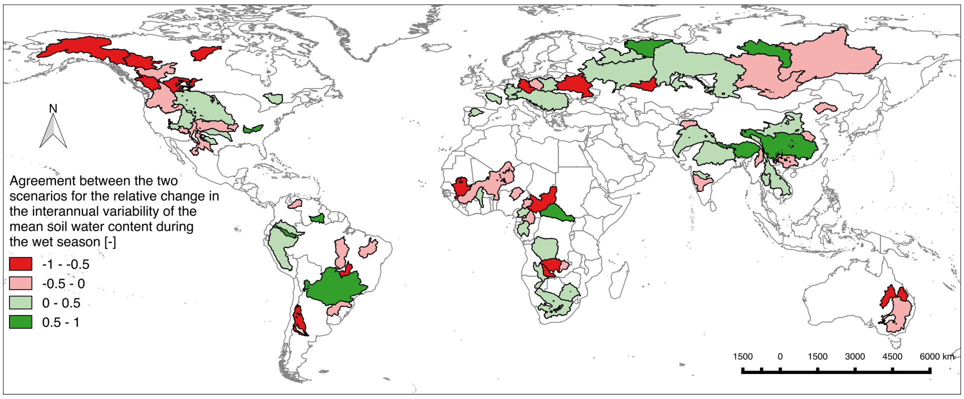
b)

Figure S7. Map of model result agreement (as defined in SM section S2) between the two radiative forcing scenarios RCP 2.6 and RCP 8.5, regarding the change in inter-annual variability of seasonal soil moisture during the dry (panel a) and the wet (panel b) season.

a)


N
Agreement between the two scenarios for the relative change in the mean soil water content during the dry season [-]
-1 - -0.5
-0.5 - 0
0 - 0.5
0.5 - 1
1500
0
1500
3000
4500
6000 km

b)


N
Agreement between the two scenarios for the relative change in the interannual variability of the mean soil water content during the wet season [-]
-1 - -0.5
-0.5 - 0
0 - 0.5
0.5 - 1
1500
0
1500
3000
4500
6000 km