FINAL REPORT

Project Title: Process Orientated Metrics of Land Surface-atmospheric Interactions for Diagnosing Coupled Model Simulations of Land Surface Hydro-meterological Extremes

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Main goals of the project, as outlined in the funded proposal

Introduction: Hydro-meteorological extremes such as droughts and heat waves have enormous impacts on water resources, agriculture, health, energy production and infrastructure. Understanding how these events have varied in the past and how they are expected to change in the future are key to mitigation and adaptation. Land-atmosphere (L-A) interactions and feedbacks are increasingly acknowledged as important processes that contribute to climate variability and can amplify droughts and heat waves through changes in partitioning of surface fluxes and interactions with the atmospheric boundary layer. Climate models are central to understanding future changes, but they continue to show problems in depicting climate extremes and the processes that lead to their development and persistence, despite incremental improvements in model resolution and more comprehensive treatment of physical processes. Their future projections are therefore inherently uncertain, especially as L-A interactions are expected to intensify in the future and play a more important role in modulating these extremes.

Rationale: Given the potential for high impacts of droughts and heat waves, and our general lack of understanding of future changes in these extreme events, there is a pressing need to evaluate coupled models for their representation of surface fluxes and L-A interactions at the process level. We propose to develop and test a suite of process-based metrics to diagnose the coupling and feedbacks between the land and the atmosphere, and apply these to climate models to help identify deficiencies in parameterizations. This has potential to improve our understanding of the contribution of the land to climate variability and its role in amplifying extreme events, as well as to lead to model developments that provide better understanding of past changes and reduction of uncertainties in future projected changes.

Summary of work to be completed: We will evaluate the observational uncertainties in surface climate, hydrology and L-A interactions from it-situ, remote sensing and observationally constrained models, globally, with a focus on the U.S. We will develop and test a suite of process-

based diagnostic metrics on the observational data, with a focus on droughts and heat waves. These metrics will be applied to the CMIP5 ensemble for the historical simulation and a set of future scenarios. The metrics will be used to identify deficiencies in coupled model parameterizations, attribute historic and future changes to L-A interactions, and link the robustness of future projections to historic performance.

Results and accomplishments

The project has focused on evaluating land-atmosphere coupling in CMIP5 models in a number of different ways. Particular attention was paid to understanding the coupling of soil moisture with evapotranspiration (ET) and ET's different components, as well as to characterizing model differences in the simulation of that coupling. The evolution of that coupling in simulations of climate change was also analyzed; we focused in particular on the role that model differences in coupling plays in the model spread in simulated present climate, as well as in future projections. The results from these different lines of work led to new insights on how to interpret CMIP5 projections of increased continental aridity and altered water cycle under global warming.

More precisely, during the project duration, the following lines of work have been pursued (detailed further down):

1) Using idealized simulations from the **GLACE-CMIP5** experiment and focusing on **West Africa** (a known region of strong land-atmosphere coupling), we showed that different climate models exhibit different qualitative feedbacks of (future) soil moisture changes on simulated precipitation changes, illustrating **model diversity in land-atmosphere coupling**.
2) We have characterized **soil moisture-evapotranspiration (SM-ET) coupling in CMIP5** climate models, and its spread across models; we have shown the role of this spread, inferred from inter-model differences across the CMIP5 ensemble, in model spread in simulated climate and in model projections of climate change, particularly summertime continental climate.
3) We have analyzed the **simulated partitioning of ET in CMIP5 climate models** into its three main components: plant transpiration, soil evaporation and evaporated canopy interception. We characterized uncertainties and biases in the way this partitioning is represented, the relationship with land-atmosphere coupling and simulated climate across models, as well as patterns of model-projected changes in ET partitioning into the future.
4) Combining points 2 and 3 above, we have analyzed how simulated **SM-ET coupling in CMIP5** models arise from the different **contributions of soil moisture coupling with the different ET partitioning terms**. We also showed how these contributions evolve under future climate change.
5) We have evaluated **how CMIP5 models simulate the Budyko Relationship**, a long-standing, well-established empirical relationship in land hydrology. We showed how, according to model projections, the shape of this relationship is invariant to climate change, and showed how the physiological and radiative effects of CO2 act in opposite way to explain

this invariance.

6) We have comprehensively analyzed **CMIP5 climate change projections of soil moisture**, showing that root-zone future changes are more nuanced than surface moisture changes, which had been previously analyzed in the literature. These results, combined with insights gained from the above sections on the role of land-atmosphere coupling in future continental climate change, have been leveraged in a **review article on the impacts of climate change on drought and aridity**.

7) Finally, SM-ET coupling was evaluated in a number of observational or observation-constrained datasets, in order to provide a **benchmark** for CMIP5 model evaluation; the metric and the associated observational reference are to be included in the Model Diagnostic Task Force **diagnostic package**.

1) <u>Model differences in role of soil moisture feedbacks in projections of future Sahel precipitation</u>

In a first line of work, we used idealized model simulations from a subset of climate models participating in the Global Land Atmosphere Coupling Experiment (GLACE)-CMIP5 experiment to analyze the feedback on monsoon precipitation from projected long-term changes in soil moisture. By comparing GLACE-CMIP5 simulations that include model runs with and without future changes in soil moisture, we were able to isolate this feedback. We focused on one semi-arid region, the Sahel, where future hydroclimatic projections are particularly uncertain, and which is recognized as a "hot spot" of land-atmosphere coupling. In four out of five models, soil moisture feedbacks significantly influenced the projected West African precipitation response to warming; however, we found contrasted feedbacks across models, as even the sign of the feedback differed among the five models analyzed. In two models, changes in soil moisture amplify changes in precipitation; in two other models they oppose it. These results demonstrate the contributions of soil moisture-atmosphere interactions to precipitation projections over West Africa; perhaps more importantly, they further illustrate the uncertainties associated with simulated land-atmosphere coupling in climate models, and the importance of understanding and evaluating the set of processes underpinning this coupling in these models.

These results were published in *Geophysical Research Letters* (Berg et al., 2017a).

2) <u>Soil Moisture–Evapotranspiration Coupling in CMIP5 Models: Relationship with Simulated Climate and Projections</u>

Soil moisture–atmosphere coupling is a key process underlying climate variability and change over land. The control of soil moisture (SM) on evapotranspiration (ET) is a necessary condition for soil moisture to feed back onto surface climate. In this part we investigated how this control manifests itself across simulations from the CMIP5 ensemble. We defined our coupling metric as correlations on the interannual time scale, over 1950-2005, using summertime-mean values:

SM-ET coupling = cor(SM, ET).

This coupling is positive in dry regions where soil moisture limits ET and thus drives its variations, and negative in wetter regions, where ET is energy-limited (**Figure 1a**). In the latter case, radiation anomalies drive ET variations, which in turn affect soil moisture in opposite ways; in addition, radiation anomalies are also anti-correlated with precipitation, which affect soil

moisture; for both reasons, ET thus appears anti-correlated with SM in these regions Analysis of CMIP5 historical simulations indicated significant model spread in SM–ET coupling, both in terms of patterns and magnitude (**Figure 1b**).

We investigated the relationship of this spread with differences in simulated background climate. Mean precipitation was found to be an important driver of model spread in SM–ET coupling (e.g., drier models show stronger SM-ET coupling), but did not explain all of the differences, which we interpreted as reflecting model differences, for a given amount of precipitation, in the treatment of land surface processes related to vegetation and hydrology. Because of ET feedbacks on air temperature, differences in SM–ET coupling induce model differences across the CMIP5 ensemble in mean surface temperature and temperature variability.

We also explored the relationships between model uncertainties in SM–ET coupling and climate projections. We found that, in particular over mid-to-high-latitude continental regions of the Northern Hemisphere but also in parts of the tropics, models that are more soil moisture–limited in the present tend to warm more in future projections, because they project less increase in ET and (in midlatitudes) greater increase in incoming solar radiation. Our results thus show how soil moisture–atmosphere processes contribute to the positive correlation, described before in the literature, between summertime present-day simulated climate and future warming projections over land.

The results obtained under this section were published in an article in *Journal of Climate* (Berg & Sheffield, 2018a).

<u>3) ET partitioning in climate models: uncertainties, role in land-atmosphere coupling and future changes</u>

ET in climate models is usually the sum of three separate components: plant transpiration (Tr), evaporation from bare soil (Esoil), and evaporation from water intercepted by the canopy (Ecan). How this partitioning is simulated carries potentially critical implications for the simulation of energy, water and carbon cycles in Earth System models; yet this partitioning has not been the focus of systematic investigation in current models. One obvious challenge is that this partitioning is poorly constrained by observations. In this line of work we investigated how this partitioning is represented in CMIP5 model simulations of present and future climate

We found that, although climatological spatial patterns of each component are broadly similar across models (e.g., **Figure 2**), there are large model uncertainties in the relative share of each component to total ET (**Figure 3**). Strikingly, even the ranking of the different components in the global mean differs between models. Model differences in the simulation of vegetation amounts (i.e., leaf area index, LAI) appear to be an important cause of this spread: e.g., models that simulated more vegetation tend to have a greater transpiration fraction. Although ET partitioning is not accurately known globally, we found that existing global estimates suggest that CMIP5 models generally underestimate the relative contribution of transpiration – a result consistent with other recent studies on the subject. This means that CMIP5 models generally overestimate canopy interception in wet areas and/or soil evaporation in drier areas. Interestingly, climate models also generally overestimate global mean LAI compared to satellite estimates. Given the positive relationship between Tr/ET and LAI across models, this suggests a systematic tendency across models to underestimate the sensitivity of transpiration to vegetation amount (as opposed

to models simply underestimating LAI, for instance).

Differences in ET partitioning were found to induce differences in climate characteristics over land, such as land–atmosphere fluxes and near-surface air temperature: for a given amount of ET, models that have lower transpiration and more soil evaporation tend to be warmer in summer over large continental regions. Given the systematic underestimation of transpiration by climate models shown here, this also suggests that model biases in ET partitioning may play a role in the well-known warm biases over continents in summer in CMIP5 models.

Despite significant differences in how they simulate present-day ET partitioning, CMIP5 models actually simulate robust patterns of future changes in ET partitioning under global warming, notably a marked contrast between decreased transpiration and increased soil evaporation in the tropics, whereas transpiration and evaporation both increase at higher latitudes and both decrease in the dry subtropics. We used idealized CMIP5 simulations from a subset of models, which allowed us to separate the radiative and physiological effect (e.g., stomatal closure) of increased atmospheric CO2. We showed that the decrease in transpiration in the tropics largely reflects the stomatal closure effect of increased atmospheric CO2 on plants (despite increased vegetation from CO2 fertilization), On the other hand, increase in all three components at high latitudes appear mostly due to radiatively-induced climate change (e.g., increased precipitation) as well as enhanced vegetation, presumably caused by warmer and longer vegetation seasons under greenhouse warming.

Overall, future changes in partitioning were found to be caused by a mix of radiatively and physiologically driven processes that affect the components of ET in different ways in different regions. This underscores the complexity of the evaporation response to global warming on land, and the challenges of both accurately capturing that response in numerical models and accounting for it in theory and idealized models of the water and climate system.

The results obtained under this section were published in an article in *Journal of Climate* (Berg & Sheffield, 2019a).

4) <u>Coupling of soil moisture with ET components in present and future climate: confounding role of different ET components</u>

In this section, we combined work from section 2) and 3) to investigate how each component of ET (see section 3) was separately coupled with soil moisture (as defined in section 2, with correlation analysis). In other words, we decomposed the SM-ET correlation used in section 2 into terms attributable to each ET component:

$$\mathrm{cor}(SM, ET) = \mathrm{cor}(SM, Tr)\frac{\sigma_{Tr}}{\sigma_{ET}} + \mathrm{cor}(SM, E_{can})\frac{\sigma_{Ecan}}{\sigma_{ET}} + \mathrm{cor}(SM, E_{soil})\frac{\sigma_{Esoil}}{\sigma_{ET}},$$

where Tr is transpiration, Ecan canopy interception and Esoil soil evaporation, and σ denoting standard deviation (correlation and variability being defined at the interannual time scale here). For each component, we defined the contribution to SM-ET coupling attributable to that component as the product of the correlation with soil moisture with the ratio of the standard deviations.

We found that the transpiration and soil evaporation terms share similar spatial patterns, similar to the main SM-ET pattern found in section 2 (which is consistent with the dominant roles of transpiration and soil evaporation, combined, in ET); however, the contribution of

transpiration, globally, is less positive: more negative in energy-limited regions and less positive in soil moisture-limited regions (**Figure 4**). This difference indicated to us that vegetation processes in models are more efficient at extracting water from the soil to the atmosphere than soil diffusion processes involved in soil evaporation. Thus, transpiration appears more energy-limited and less SM-limited than soil evaporation. On the other hand, we found that canopy interception contributes to SM-ET coupling a term that is positive everywhere, which we interpreted as reflecting the non-causal, rainfall-forced positive correlation between SM and canopy interception.

A sizeable part of the overall SM-ET coupling actually reflects the positive contribution from the canopy interception term. In particular, this positive contribution tends to mask the negative contribution of transpiration in the Tropics and high latitudes. This shows that coupling of ET to SM is a complex response combining the different relationships of each ET component with SM and different fractions of ET.

Our results also showed that, because of the different way each ET component is coupled with SM, model differences in mean ET partitioning affect overall SM-ET coupling. For instance, models that favor transpiration (for a given level of ET) tend to be less strongly coupled with soil moisture; models that favor soil evaporation tend to be more strongly SM limited. This result, established across CMIP5 models, is consistent with single-model studies where ET partitioning was specifically modified. We also found that transpiration exhibits the most uncertainty across models in terms of coupling with SM. Thus, because of the dominant role of transpiration in total ET, model differences in SM-transpiration coupling explain most of the model spread in overall SM-ET coupling.

Finally, we analyzed how the different coupling terms are projected to change under global warming. Models project a robust pattern of widespread, more positive SM-ET correlations in the future (**Figure 5**). In parts of the midlatitudes and Tropics, this increase reflects reduced precipitation and increased SM control on transpiration and soil evaporation. However, at higher latitudes (north of 50°N), increased SM-ET coupling is driven by the increased contribution of canopy interception induced by the increase in vegetation and precipitation (**Figure 6**). Analysis of ET partitioning is thus essential to the interpretation of simulated changes in ET and its drivers: While increased SM-ET correlations may suggest a widespread increase in SM limitation on ET in a warmer world, increases in actual SM control on land-atmosphere water fluxes are generally limited to regions of negative precipitation change. North of 50N, increased SM-ET correlations actually only reflect the increased role of canopy interception, caused by enhanced vegetation and precipitation. These results carry implications for the interpretation of model projections of future drought and aridity, which in many studies have been found to indicate widespread increases in land dryness, including at higher latitudes. By focusing on individual ET components and their relationship with SM, our results help interpret concurrent model projections of future terrestrial hydrology, vegetation, and climate, which in some respects can appear conflicting in certain regions (i.e., apparent greater soil moisture control on ET in a wetter climate and with greater vegetation).

The results obtained under this section were published in an article in *Journal of Geophysical Research-Atmosphere* (Berg & Sheffield, 2019b).

5) Budyko Relationship in CMIP5 simulations.

In a separate line of work from what was described in the sections above, we have evaluated how CMIP5 models represent the Budyko Relationship, in present and future climates.

The Budyko relationship is a long-standing, well-established empirical relationship in land surface hydrology. In its original form, it relates, across watersheds, the climatological partitioning of mean precipitation (P) into mean ET and mean runoff in a given watershed to the local mean climatic aridity, characterized as the ratio of potential evapotranspiration (Ep) to P, Ep/P. Since the 1960's, the Budyko framework has spawned a whole field of hydrological and ecohydrological studies. However, how climate models represent this relationship, and how they project its evolution in a warmer world, has not received a lot of attention.

Different forms of the Budyko equation have been proposed over the years. Here we use the Turc-Pike formulation:

$$\frac{E}{P} = \left[1 + \left(\frac{E_P}{P}\right)^{-v}\right]^{-1/v}$$

where v=2 from observations, as reported in the literature.

Figure 7 shows how CMIP5 models reproduce this relationship, using annual mean ET, P and Ep from outputs from historical simulations over 1950-2005. We use net radiation as an estimator of Ep (which is not a standard output of climate models). Although the Budyko Relationship is meant to apply at the scale of watersheds, we use all land pixels in climate models as first approximation. An optimal parameter v is then fitted for each model. **Figure 7** shows that models reproduce the general form of the relationship, although the exact parameter value varies across models; further work is needed to interpret departure from the observed Budyko curve in terms of model evaluation. However, to leading order, the overall consistency of climate models' simulated hydrology with the Budyko Relationship is noteworthy, as it is an independent test of climate models' hydrology: models do not use the Budyko framework (which only applies to long-term means) to calculate ET, but rather solve the water and energy balance at short-time steps (e.g., 30 minutes). **Figure 7** suggests that models correctly capture some fundamental hydrological behavior embodied in the climatological Budyko curve.

Further, we used climate projections from 2071-2100 to investigate changes in the Budyko Relationship simulated by climate models. **Figure 8** shows that, across CMIP5 models, the shape of the Budyko Relationship does not change much: the v parameter remains broadly constant between present and future across models, and the multi-model mean relationship is unchanged. In first approximation, this suggests that land regions essentially move along the curve under global warming, but the shape of the curve itself is invariant: for a given level of aridity, hydrological behavior remains constant. This result is non-trivial, as one could have expected, for instance, that for a given level of climatic aridity (defined as net radiation over precipitation), increases in temperature and vapor pressure deficit would have influenced the partitioning of P towards more ET and less runoff.

As in section 3, we then used idealized simulations from a subset of CMIP5 models that allowed us to separate the radiative and physiological effects (e.g., stomatal closure) of increased atmospheric CO2. We found that the invariance of the Budyko Relationship to climate change is

the emerging result of opposite effects from the radiative and physiological effects of increased atmospheric CO2: the radiative effect is to push the curve "upwards", towards greater partitioning of P towards ET (for a given aridity level), as expected, but the physiological effect of CO2, by constraining stomatal conductance, and thus limiting transpiration and ET, opposes that effect and shifts the curve back towards ("downwards") less partitioning of P towards ET.

The results obtained under this section form the basis for an article in preparation for *Geophysical Research Letters*.

6) Global warming, continental drying? Interpreting projected aridity changes over land under climate change

The insights gained during this project regarding changes in soil moisture under global warming, on the coupling of soil moisture with ET and its different components, as well as on the role of land-atmosphere coupling in projected changes in summertime continental climate, allowed us to contribute to the ongoing debate in the land/climate science community regarding the evolution of continental drought and aridity under global warming.

Indeed, in recent years, a number of studies have suggested that, as climate warms, the land surface will globally become more arid. Such results usually rely on drought or aridity "offline" proxy metrics, such as the Palmer Drought Severity Index or the Aridity Index (ratio of precipitation to potential evapotranspiration, PET), applied to climate model projections of surface climate. From a global perspective, the projected widespread drying of the land surface is generally interpreted as the result of the dominant, ubiquitous warming-induced PET increase, which overwhelms the slight overall precipitation increase projected over land.

However, several lines of evidence, based in particular on paleo-data, raise questions regarding this interpretation of terrestrial hydroclimate change (e.g., past warm climates may have been wetter and more vegetated on land globally, not drier). Model projections of continental hydrology, themselves, also show little indication of widespread drying: they include globally increasing precipitation, runoff, vegetation and ET (although with changes in the spatial and temporal distribution of these variables). Most of the drying projections result from the interpretation of PET-based metrics, or PET-driven impact models (e.g., hydrological, crop models). In recent years, several studies have questioned this interpretation, pointing out that PET increase does not necessarily reflect similar changes in land vegetation or hydrology.

One argument in favor of the PET-based view exposed above is that climate model projections of global warming do show widespread decrease in surface soil moisture (top 10cm) around the world, which may indeed be viewed as indicative of land drying. To further address this issue, we investigated these projections in CMIP5 models comprehensively. We showed that root-zone (down to 3m) future changes are more nuanced than surface moisture changes, which had been previously analyzed in the literature (e.g., in IPCC reports). Considering the median of CMIP5 projections, more than two thirds of the land surface shows drying of the top surface moisture, but only half of it indicates root-zone moisture decrease (**Figure 9**). Explaining this discrepancy, we identified a robust vertical gradient of projected mean soil moisture changes, with more negative changes near the surface (**Figure 10**). In particular, some regions of the northern middle to high latitudes exhibit negative annual surface changes but positive total changes (e.g., Western

Russia, northern US). We interpreted the contrasting changes between surface and root-zone soil moisture in northern middle and high latitudes as resulting from differing seasonal P and ET responses (increased wintertime P and increased summertime ET) in conjunction with the fundamental soil physical asymmetry between infiltration and evaporation processes. (**Figure 11**). This vertical pattern implies that the extensive drying predicted by off-line drought metrics, while consistent with the projected decline in surface soil moisture, will tend to overestimate (negatively) changes in total soil water availability.

These results, as well as other recent studies based on CMIP5 model projections, shed some light on the issue of future changes in drought and aridity over land. We leveraged the insights gained from this project into writing a review paper addressing future changes in drought under climate change, with a focus on changes in soil moisture. Central to the interpretation of projected land aridity changes is the understanding of projected PET trends over land in the context of the coupled land-atmosphere system. In particular, the proposed interpretation of warming-induced drying does not account for land-atmosphere coupling processes nor for the physiological impact of increased atmospheric CO2 levels. We argued that, ultimately, future changes in drought should preferably be directly assessed with prognostic climate/land model outputs of the actual land surface (water cycle, vegetation) rather than offline heuristics based only on atmospheric outputs (e.g., PET) from climate models, and should be interpreted in the context of the coupled soil-vegetation-atmosphere system. Although such mechanistic, model-based assessments of climate change's impacts on the land surface exhibit large uncertainties, they are preferable to metric-based assessments that may tend to over-emphasize the role of warming and thus to provide an overestimated sense of certainty.

These results were published in *Geophysical Research Letters* (Berg et al. 2017b), as well as a review paper in *Current Climate Change Reports (*Berg and Sheffield 2018b).

7) <u>SM-ET coupling as a metric in the MDTF Diagnostic package</u>

Finally, work was undertaken to include SM-ET coupling in the MDTF Diagnostic package, a coding package which is meant to provide modeling centers with a ready-to-use diagnostic tool applying several process-based metrics to model simulations. An essential element of the package is to provide observational assessments for the various metrics included. With respect to SM-ET coupling specifically, however, an observational value of the metric is difficult to obtain, because of the challenges associated with measuring soil moisture and evapotranspiration extensively over continents, at the required spatial and temporal scales. Global, gridded observational products of ET and soil moisture do exist (in particular from remote sensing), but are plagued by numerous uncertainties or shortcomings limiting their use in a straightforward manner, here, to compute SM-ET coupling. We then calculated SM-ET coupling from several datasets derived from the combination of modeling and observations: reanalysis (e.g., MERRA2, JRA55, ERA-I) and land surface models driven by observations (e.g., GLADS, GLDAS2). However, estimates of SM-ET coupling from these products were found to exhibit a lot of spread (comparable in some regions to the spread across CMIP5 models), even though their representation of the driving surface climate (e.g., precipitation) was very comparable. This diversity is not necessarily surprising, given that SM-ET coupling largely remains, in these types of products, a product of the underlying land model used to create the dataset.

We eventually decided to choose the GLEAM (Global Land Evaporation Amsterdam Model) dataset (see https://www.gleam.eu/), as a reference, provided along the SM-ET coupling metric in the diagnostic package. While the control of SM on ET in the GLEAM dataset ultimately remains a property of the modeling assumptions underlying this product, GLEAM is the only product, to our knowledge, assimilating available remote sensing observations of both soil moisture and vegetation, thus providing a dataset including observationally-constrained and mutually consistent variables SM and ET. **Figure 12** shows SM-ET coupling obtained from GLEAM, which is to be provided in the MDTF package alongside model results as a point of reference – with words of caution regarding associated uncertainties and comparison with model results. To account for potential precipitation biases between model and observations (which, from section 2, would influence the model-simulated SM-ET coupling, for instance towards higher values in the case of dry precipitation bias), the model-derived coupling will also be provided after a correction based on a regression between mean summertime precipitation and SM-ET coupling established across CMIP5 models in section 2 (Berg and Sheffield 2018a).

Highlights of Accomplishments

- **We have characterized soil moisture feedbacks on precipitation change in West Africa under climate change in several CMIP5 models, showing qualitatively different feedbacks in different models.**
- **We have characterized SM-ET coupling in CMIP5 models and the corresponding model uncertainties, as well as the associated impacts of this spread on model differences in simulated present and future climate.**
- **We have analyzed the uncertainties across CMIP5 models in ET partitioning, and investigated the projected changes in this partitioning under climate change. Most CMIP5 models appear to underestimate transpiration (40% of global ET on average across models, versus 60% estimated from observations).**
- **We have shown that to understand SM-ET coupling and interpret its changes under global warming, it is necessary to analyze the coupling of soil moisture with the different ET components: in particular, projected increases in SM-ET coupling in regions of precipitation increase actually reflect the greater role of canopy interception;**
- **We have shown that climate models broadly reproduce the Budyko Relationship in terms of land surface hydrology. This relationship doesn't change under climate change, reflecting competing effects of radiative and physiological CO2 forcing.**
- **We showed that root-zone soil moisture changes under global warming are more nuanced than surface moisture changes. We published a review on climate change and soil moisture drought based on the insights gained in the framework of the project, contributing to the growing debate in the climate/hydrology community regarding the evolution of land aridity under global warming, and the future of water resources and ecosystem health under climate change.**

- **As of the completion of this project, we are working to include the SM-ET coupling metric in the Model Diagnostic Task Force Diagnostic Package, along with an observational estimate of SM-ET coupling.**

Publications from the Project

Berg, A., B. Lintner, K. Findell, A. Giannini (2017a), Uncertain soil moisture feedbacks in model projections of Sahel precipitation, *Geophysical Research Letters*, 44, 6124-6133.

Berg, A., J. Sheffield, C. Milly (2017b), Divergent surface and total soil moisture projections under global warming, *Geophysical Research Letters*, 44, 236-244.

Berg A. and J. Sheffield (2018a), Soil moisture-evapotranspiration coupling in CMIP5 models: relationship with simulated climate and projections, *Journal of Climate*, 31(12), 4865-4878.

Berg A. and J. Sheffield (2018b), Global warming and drought: the soil moisture perspective, *Current Climate Change Reports*, 4(2), 180-191.

Berg, A. and J. Sheffield (2019a), Evapotranspiration Partitioning in CMIP5 Models: Uncertainties and Future Projections. *Journal of Climate*, 32, 2653–2671.

Berg, A., & Sheffield, J. (2019b), Historic and projected changes in coupling between soil moisture and evapotranspiration (ET) in CMIP5 models confounded by the role of different ET components. *Journal of Geophysical Research: Atmospheres*, 124. https://doi.org/10.1029/2018JD029807

Berg A. and J. Sheffield, Invariance of the Budyko Relationship to climate change, in prep. for *Geophysical Research Letters*.

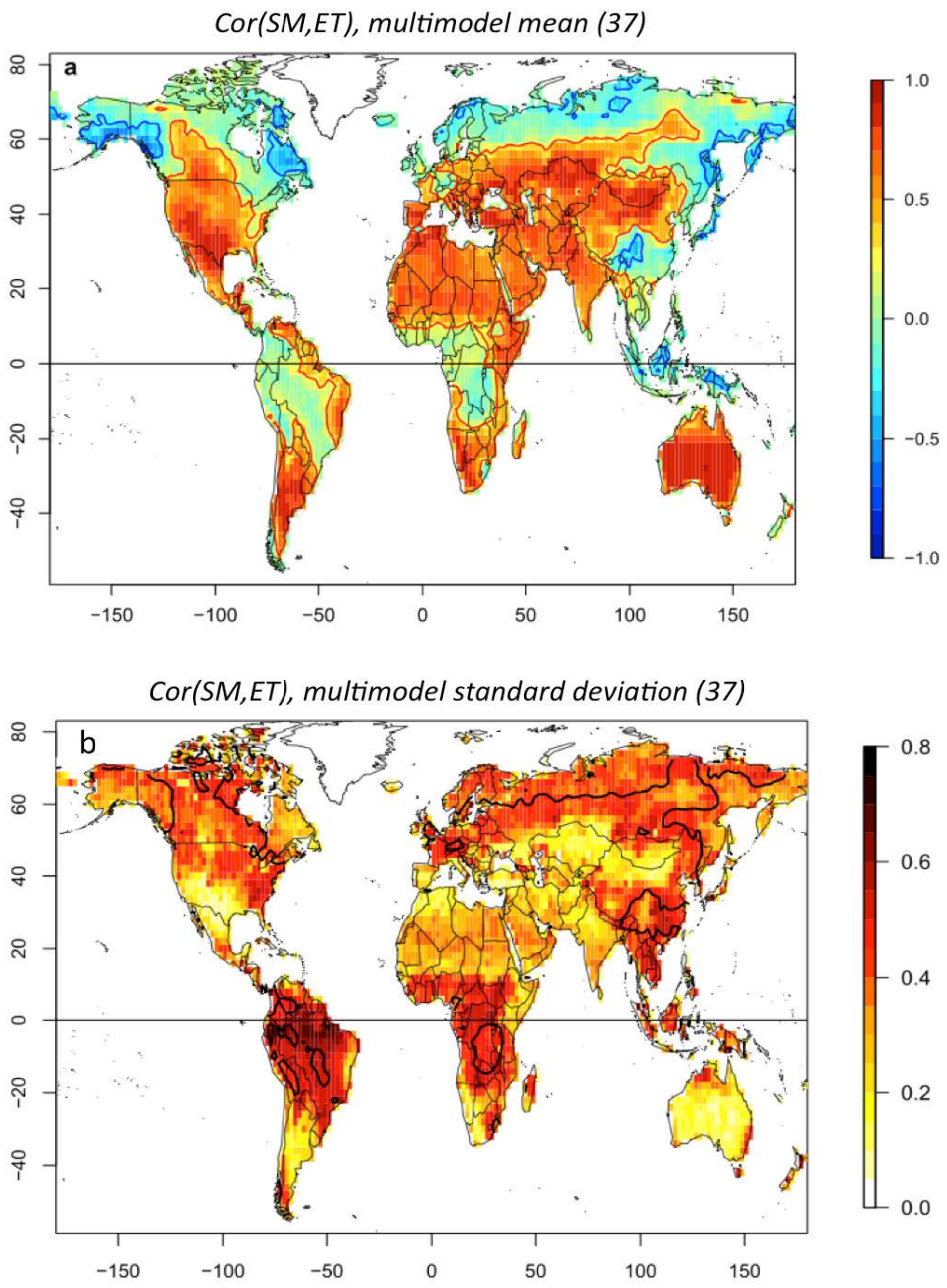


Figure 1: (a) Multimodel mean correlation between summertime-mean surface SM and ET over 1950–2005; JJA values are used in the northern hemisphere, DJF in the southern hemisphere; solid contour lines indicate correlations significant at the 5% level; (b) Standard deviation (across 37 CMIP5 models of the correlation between summertime-mean surface SM and ET over 1950– 2005. The black contour indicates where the mean multimodel mean correlation from (a) is nil.

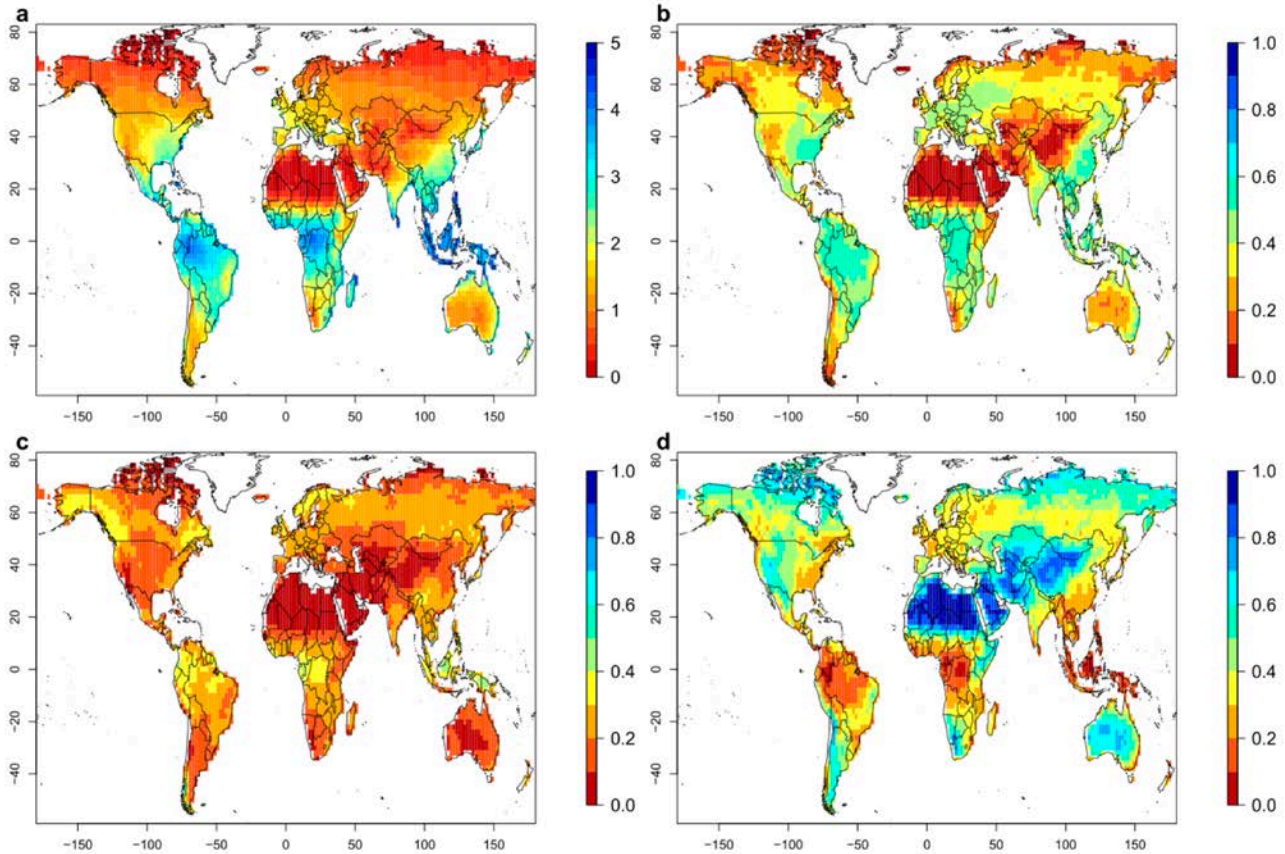


Figure 2: Multimodel mean annual mean values over 1950–2005 of (a) ET (mm/day) and fractions of (b) transpiration, (c) canopy interception, and (d) soil evaporation in total ET. A total of 32 models with full ET partitioning are used.

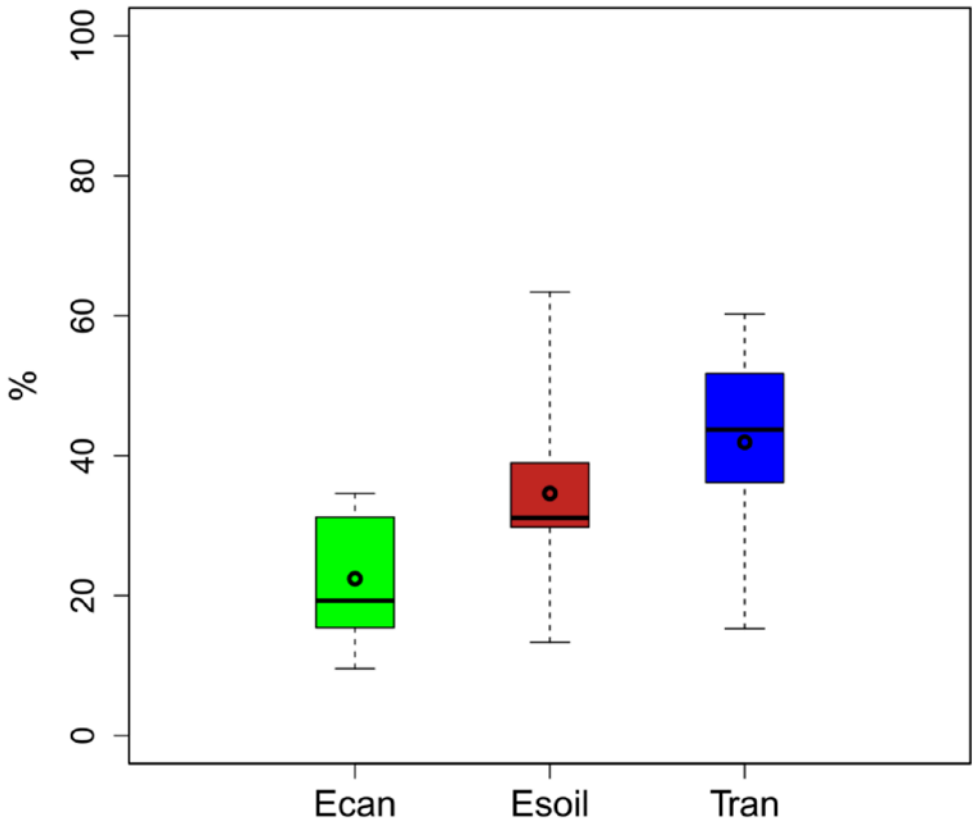


Figure 3: Mean value and spread across CMIP5 models of the global fraction of each ET component (% of total ET). Ecan: canopy interception; Esoil: soil evaporation; Tran: transpiration; 32 models with full ET partitioning are used. The thick line represents the median of the distribution, the central dot the mean, and the edges of the box the 25% and 75% quantiles. Whiskers represent the total model range.

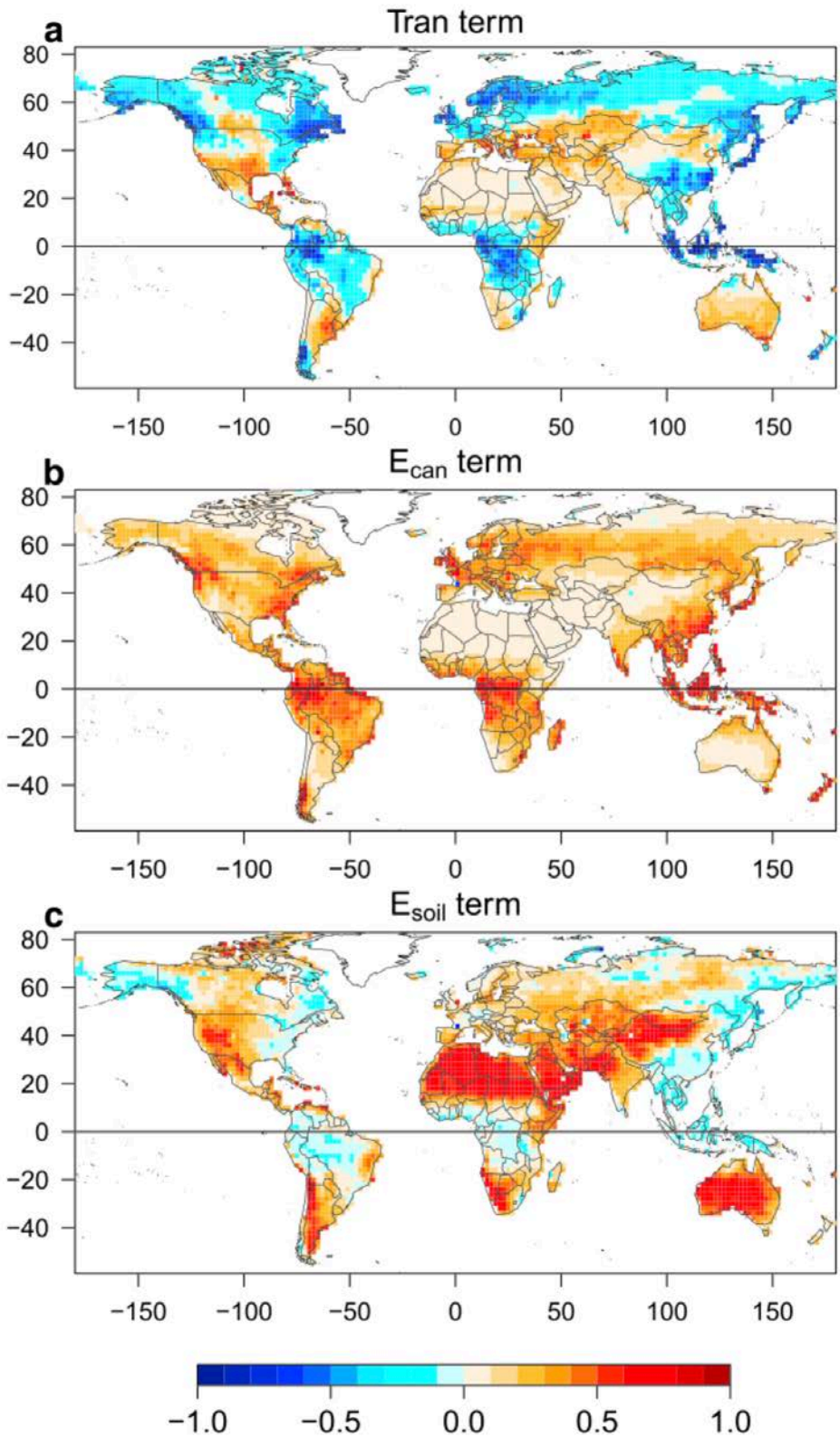


Figure 4: (a–c) Multimodel mean components of soil moisture-evapotranspiration coupling (defined on Figure 1a) attributable to transpiration, canopy interception, and soil evaporation, respectively.

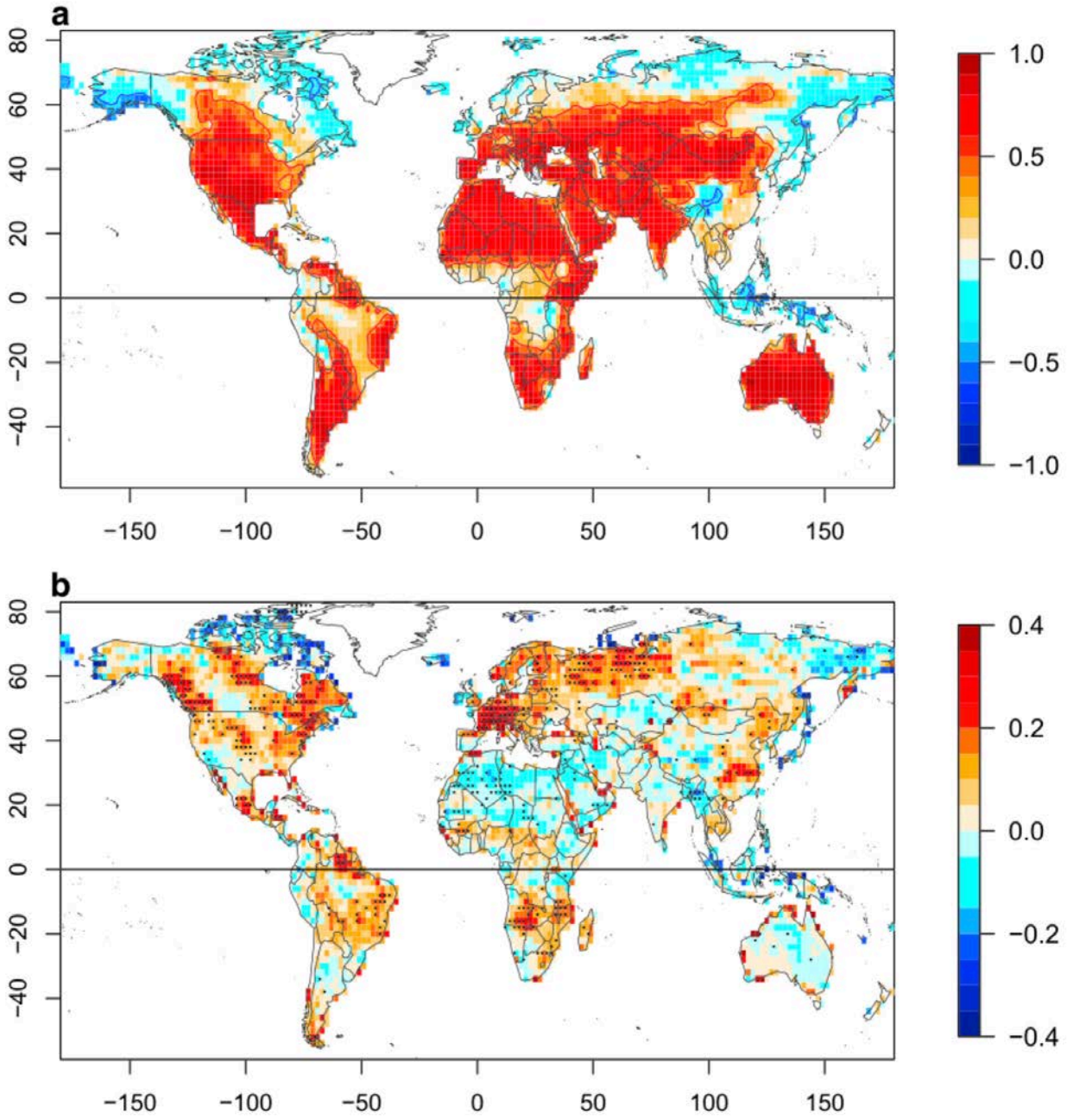


Figure 5: (a) Multimodel mean correlation between summertime-mean surface soil moisture and evapotranspiration over 2071–2100; red and blue contour lines indicate positive and negative correlations significant at the 5% level. (b) Multimodel mean change from 1950–2005 (note the different scale from (a)). Stippling indicates where more than three quarters of the models agree on the sign of the projected changes. Twenty-three models with full evapotranspiration partitioning and soil moisture available in the future (and present) scenarios are used.

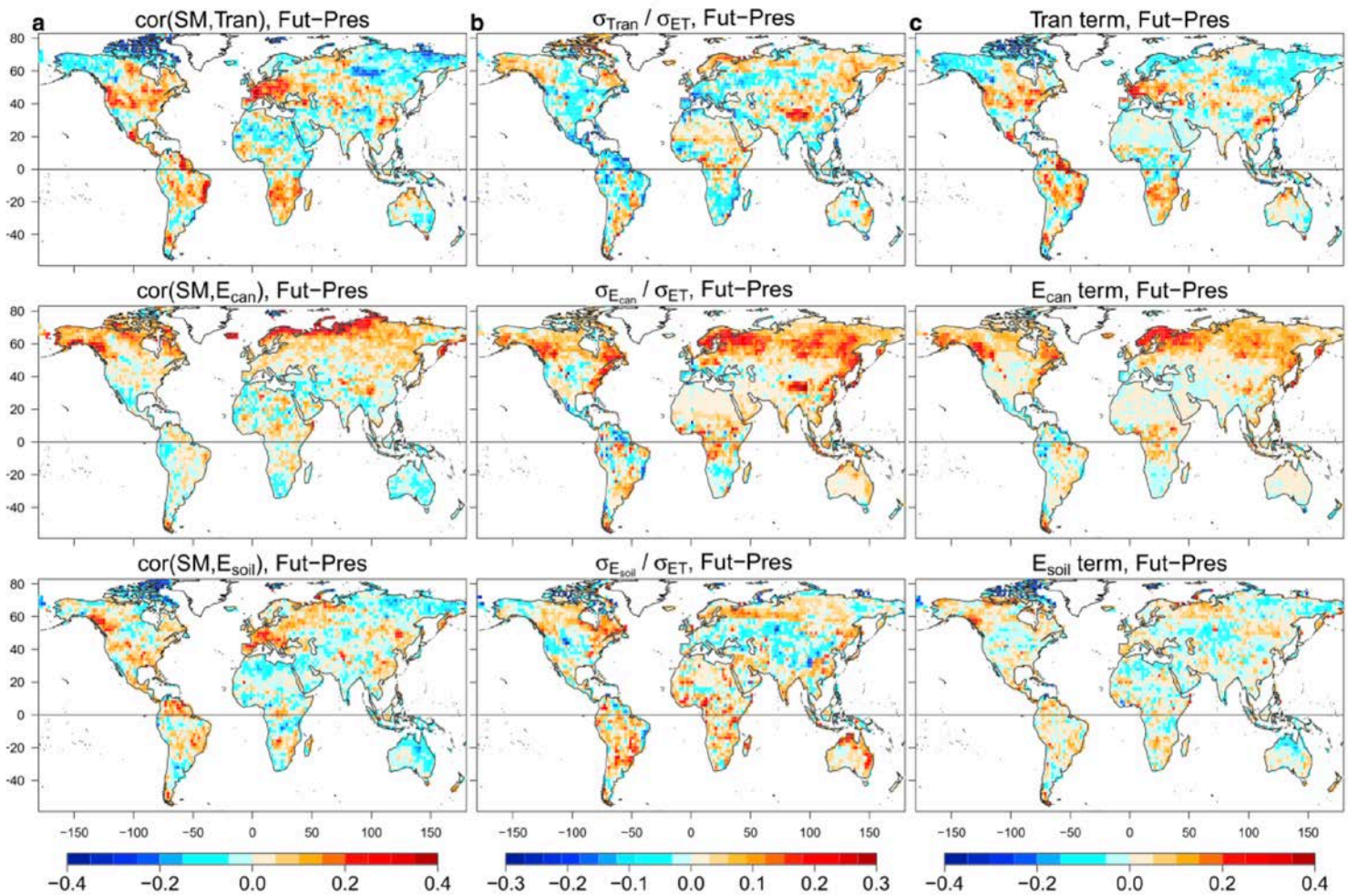


Figure 6: Multimodel mean change, from 1950–2005 to 2071–2100, in (a) the correlation of each ET component with soil moisture; (b) the ratio of interannual variability of each ET component to ET variability; (c) the full component of SM-ET coupling attributable to each ET component, for (from top to bottom) transpiration, soil evaporation, and canopy interception. Note the difference in scale between (a), (b), and c). Twenty-three models with full ET partitioning and soil moisture available in the future (and present) scenarios are used. SM = soil moisture; ET = evapotranspiration.

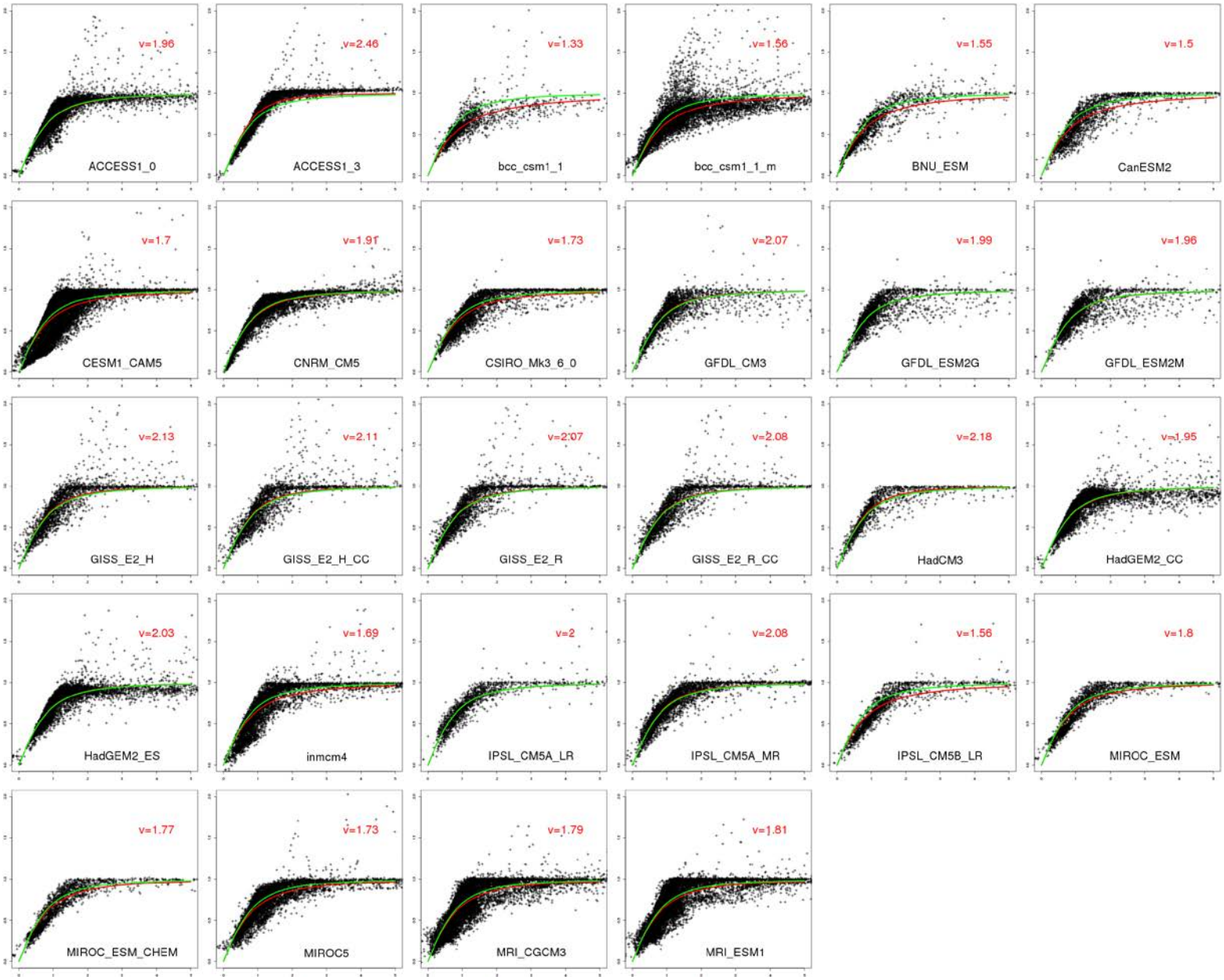
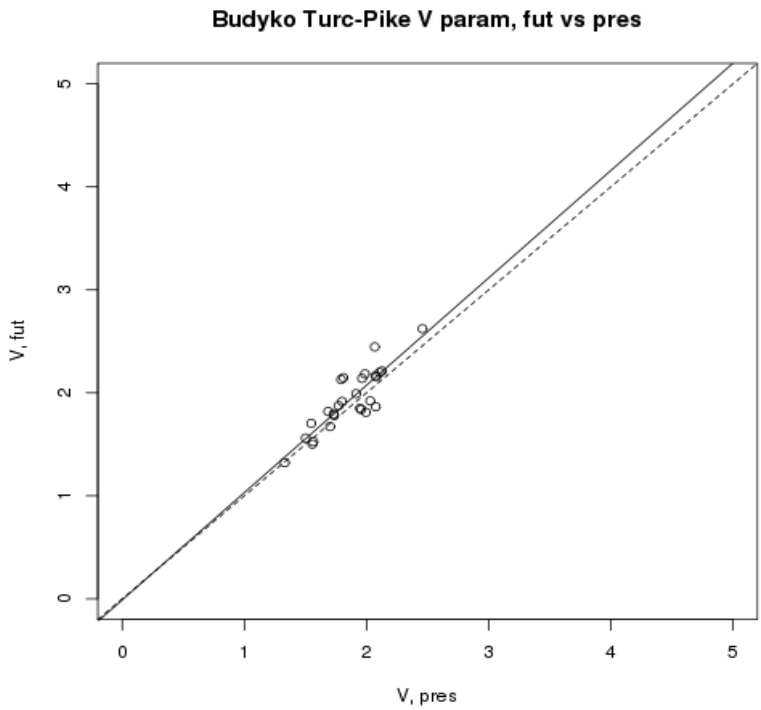


Figure 7: Budyko Relationship in CMIP5 models. For each model (panel), x-axis is mean Net Radiation/P and y-axis is mean ET/P, using annual climatological means over 1950-2005 from the historical simulations. Each point represents one land pixel in the model. In red is represented the best fit over all land pixels using the Turc-Pike formulation, with the value of the parameter v given in each panel. In green is the same curve in each panel, based on observations (v=2; based on Milly and Dunne (2002)).



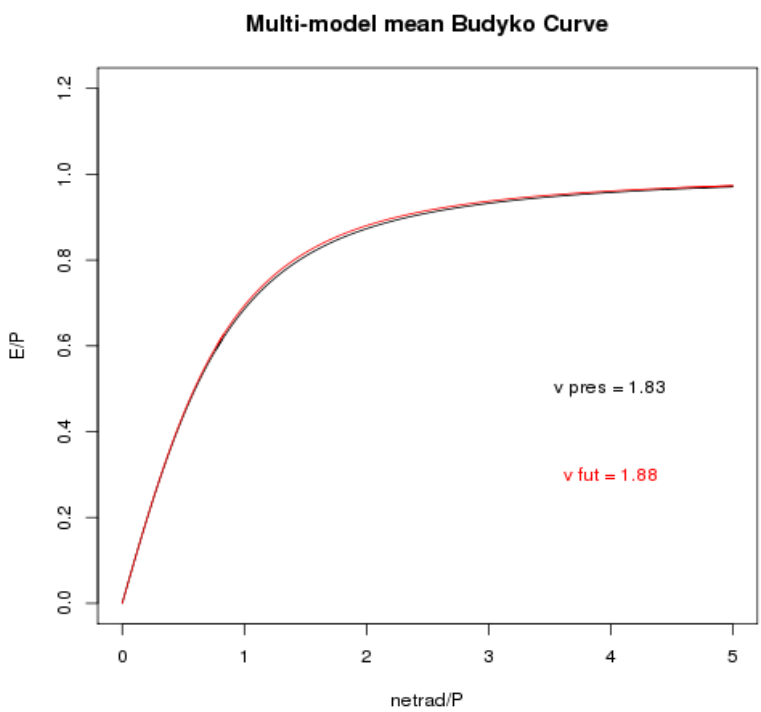


Figure 8: (top) changes in the v parameter in CMIP5 climate models, between 1950-2005 (x-axis) and 2071-2100 (y-axis; RCP8.5 scenario). Each dot represents one model. The full line is the 1:1 line and the dotted line is a regression line. (Bottom): multi-model mean Budyko Curve from CMIP5 models in the present (black) and the future (red), with corresponding v parameter values given on the plot.

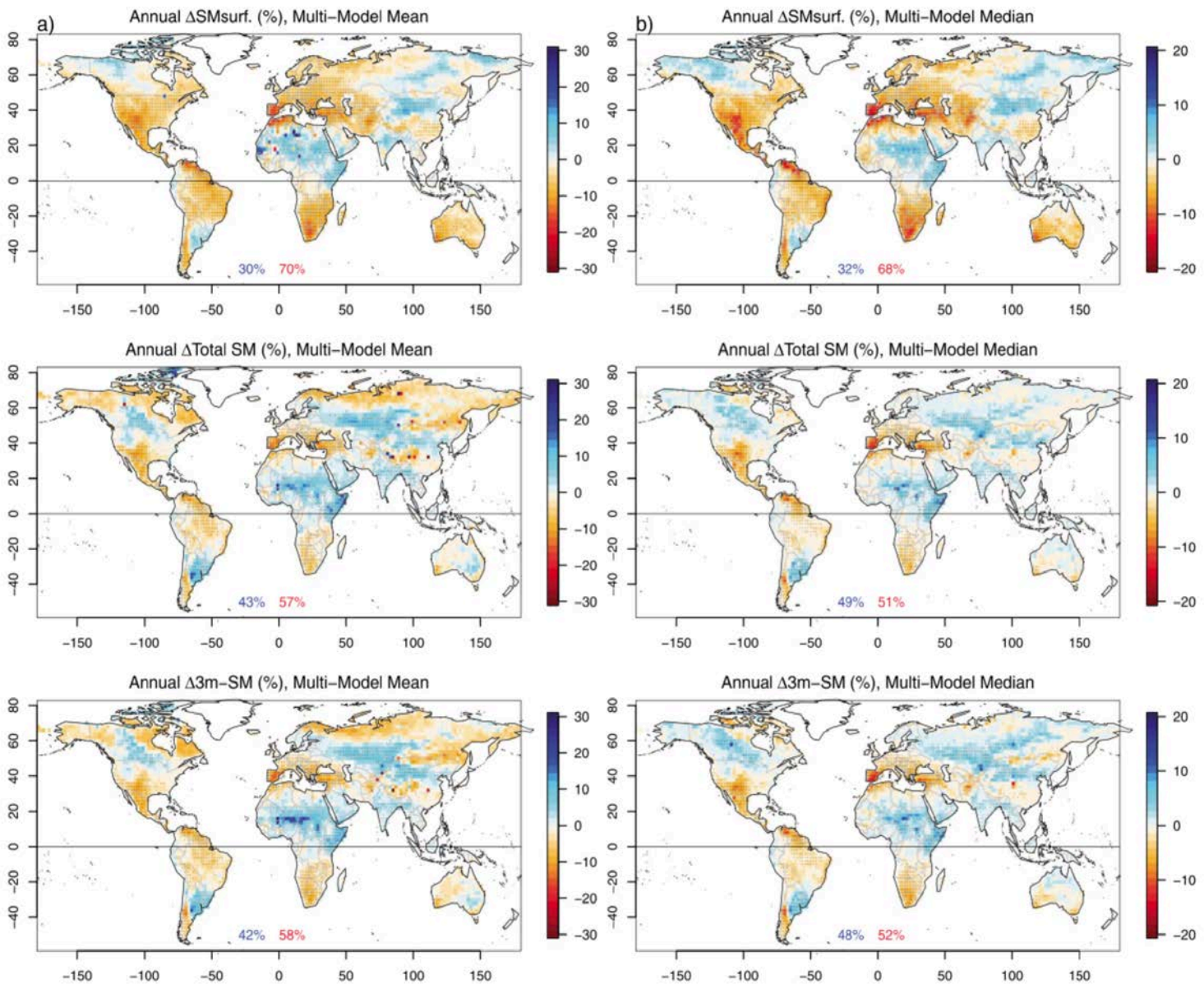


Figure 9 : (a) Multimodel annual mean change between 1976–2005 and 2070–2099 (using RCP8.5 scenario) of (top to bottom) surface (upper 10 cm) soil moisture (SM), total SM, and SM integrated down to 3 m. Values are percentages of simulated present-day values. (b) Same as in Figure 1a with multimodel median. On all plots, the numbers indicate the share of the land surface with positive (blue) or negative (red) changes. The stippling indicates where more than three quarters of the models agree on the sign of the projected change.

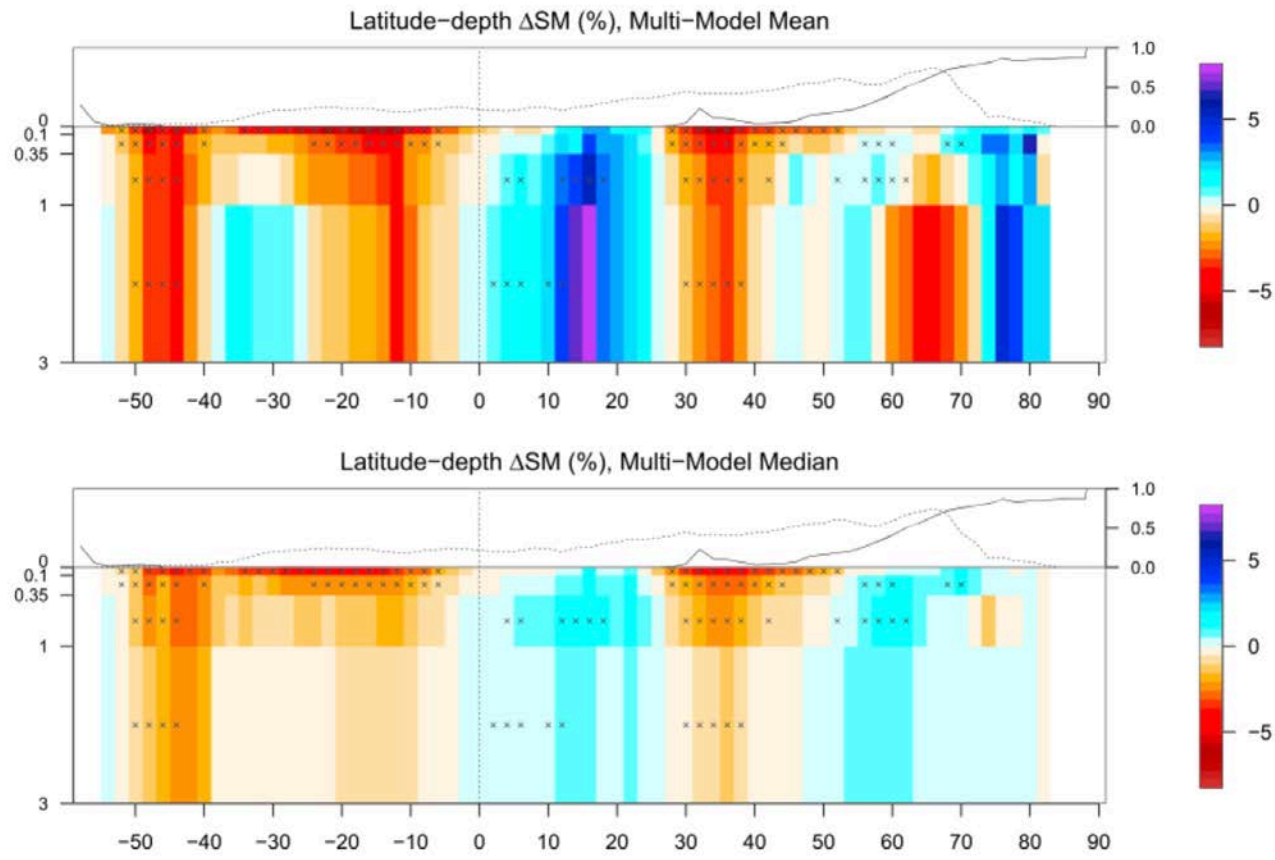


Figure 10: Multimodel (top) mean and (bottom) median relative change (%) in volumetric soil moisture between 1976–2005 and 2070–2099 as a function of depth (left-hand y axis (m)) and latitude (x axis). The stippling indicates where more than three quarters of the models agree on the sign of projected changes. The full line represents the multimodel mean ratio of frozen over total soil moisture; the dotted line represents the global fraction of land by latitude (for both lines, values are on the right-hand y axis).

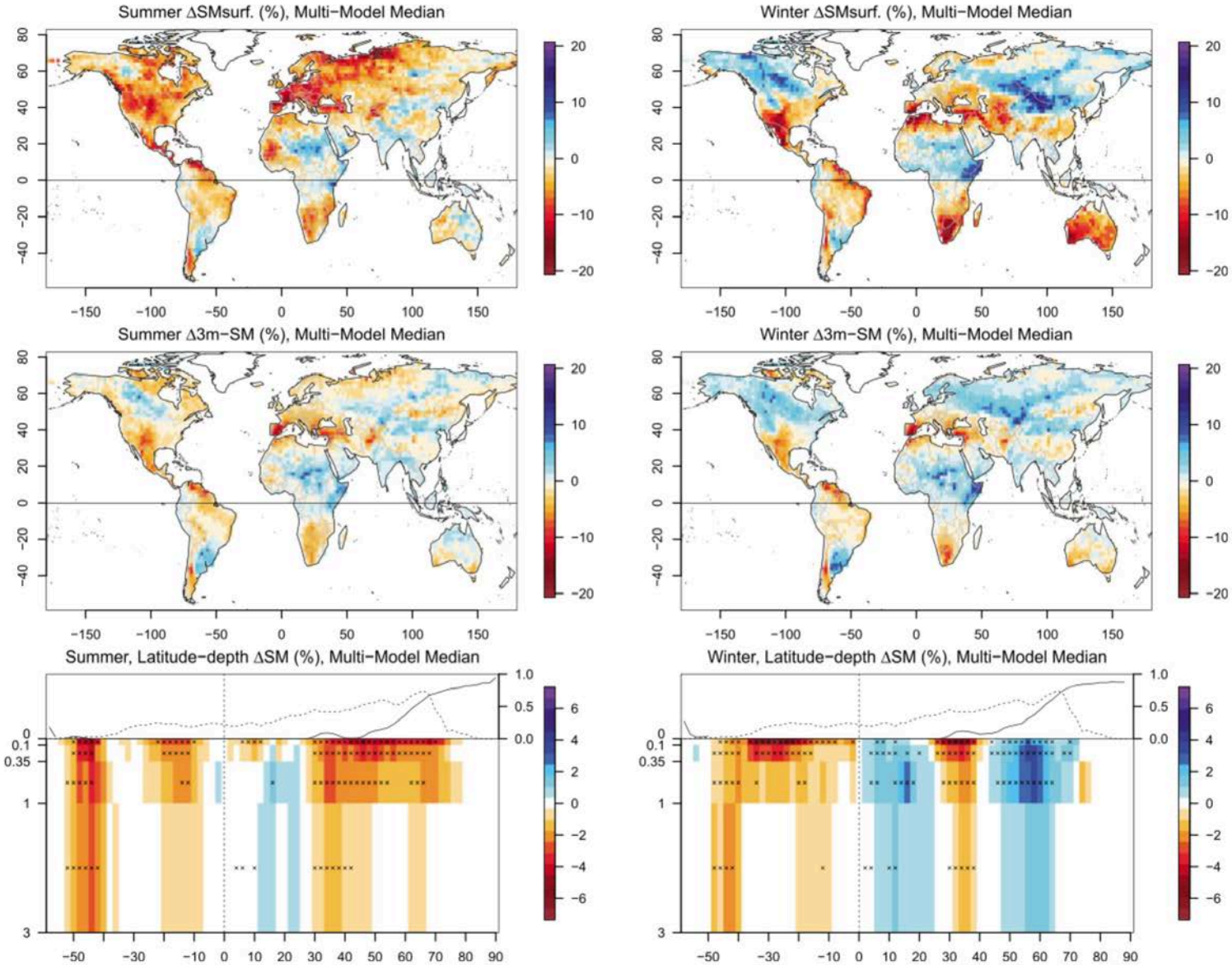


Figure 11: Multimodel median relative change (%) in (left) summer and (right) winter (top row) surface soil moisture, (middle row) 3 m soil moisture, and zonal-depth soil moisture. Summer is JJA in the Northern Hemisphere and DJF in the Southern Hemisphere and vice versa for winter. (bottom) Similar as in Figure 10, but for summer/winter.

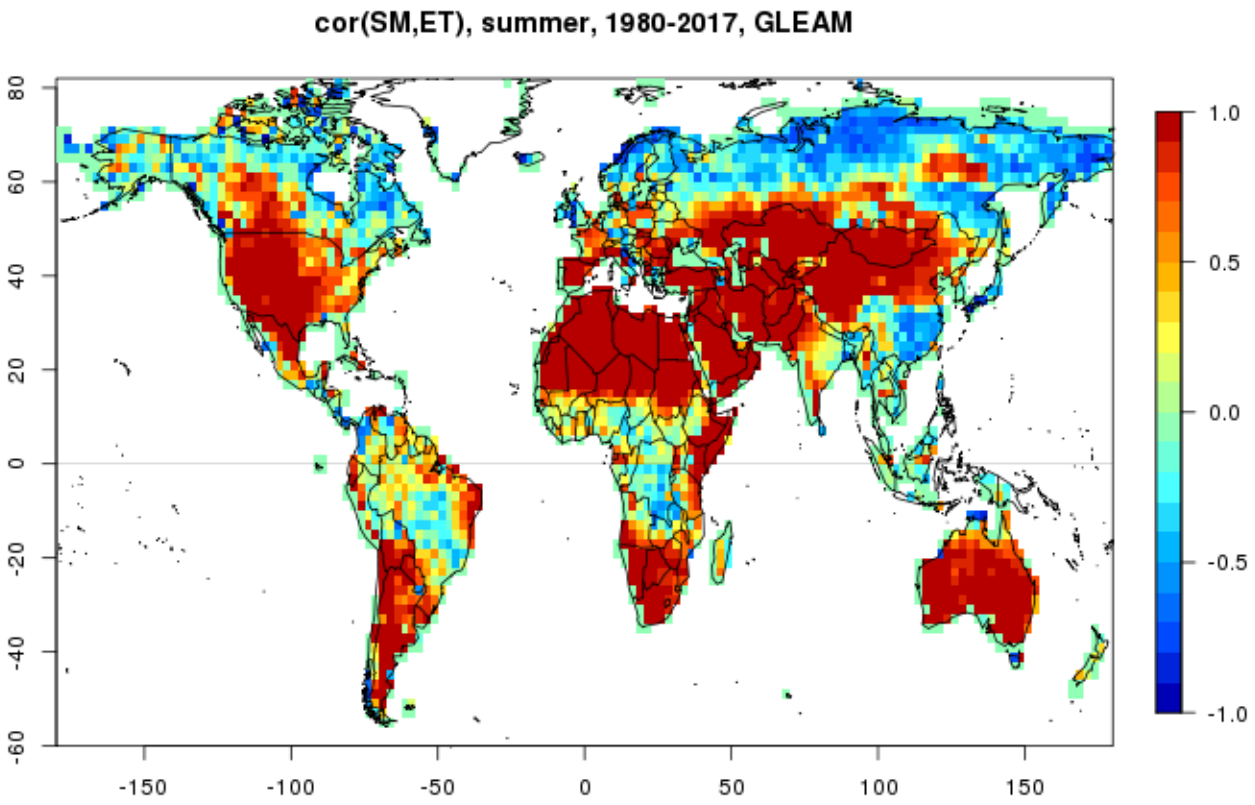


Figure 12: SM-ET coupling in the GLEAM dataset, defined similarly as in Figure 1a: correlation between summertime-mean surface SM and ET, but over 1980–2017; JJA values are used in the northern hemisphere, DJF in the southern hemisphere.