Reconciling spatial and temporal soil moisture effects on afternoon rainfall

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Soil moisture impacts on precipitation have been strongly debated. Recent observational evidence of afternoon rain falling preferentially over land parcels that are drier than the surrounding areas (negative spatial effect), contrasts with previous reports of a predominant positive temporal effect. However, whether spatial effects relating to soil moisture heterogeneity translate into similar temporal effects remains unknown. Here we show that afternoon precipitation events tend to occur during wet and heterogeneous soil moisture conditions, while being located over comparatively drier patches. Using remote-sensing data and a common analysis framework, spatial and temporal correlations with opposite signs are shown to coexist within the same region and data set. Positive temporal coupling might enhance precipitation persistence, while negative spatial coupling tends to regionally homogenize land surface conditions. Although the apparent positive temporal coupling does not necessarily imply a causal relationship, these results reconcile the notions of moisture recycling with local, spatially negative feedbacks.
L and climate interactions play an important role in the climate system, in particular in transitional climate regions, where soil moisture influences the partitioning of the energy available at the land surface into sensible and latent heat fluxes. Surface turbulent fluxes may influence precipitation directly via moisture input to the atmosphere (moisture recycling), as well as indirectly, via boundary-layer dynamics and mesoscale circulations. Moisture recycling is expected to lead to a positive feedback, that is, more precipitation induced by wet conditions. The indirect effect via mesoscale circulations, on the other hand, may lead to a negative effect. Finally, the indirect effect via boundary-layer dynamics can theoretically lead to feedbacks of both signs depending on atmospheric conditions. Studies in the 1990s and 2000s have mostly identified positive coupling mechanisms using models or reanalyses. However, ref. 11 has recently suggested a strong dominance of negative coupling mechanisms in observations contrasting with a strong positive coupling in Global Climate Models. This negative coupling could be consistent with negative indirect effects via soil-moisture induced mesoscale circulations or boundary-layer dynamics. The apparent contradiction between these latter results and previous studies has led to a recent debate on the dominant sign of soil moisture–precipitation feedbacks.

Since the sign of the feedback exhibited by climate models has been shown to be sensitive to the parameterization of convective available from resampling.

Results

Analysis of precipitation events. In this study, a precipitation event domain is defined as a 5 × 5 grid cell (0.25° × 0.25° each, that is, 1.25° × 1.25° in total) centred at a location of local afternoon precipitation maximum (Lmax) with at least 4 mm of accumulated rain. The event domain is denoted Levıt, while Lmin is the location of precipitation minimum within Levıt. Events that occur in days with morning precipitation are excluded from the analysis, as our focus is on the triggering of new rainfall events. Similarly, events located over fixed features that may influence precipitation location such as complex topography or water bodies are excluded, and only months when convective conditions dominate are retained for the analysis (see Methods). For each event, morning temporal soil moisture anomalies S relative to the mean seasonal cycle are analysed at various locations or combinations of these. More precisely, we define three metrics based on three combinations (Y0, Y1 and Y2) of S at locations Lmax, Lmin and/or Levıt: a spatial metric, defined as Y0 = ΔS = Smax - Smin, which compares soil moisture at location of precipitation maximum versus precipitation minimum; a temporal metric, defined as Y1 = Smax, which quantifies anomalies of soil moisture at the event locations relative to the seasonal cycle (or, alternatively, using either Smax, Smin instead of Smax, see Supplementary Discussion); and a heterogeneity metric, defined as Y2 = σ(Smax) (the spatial s.d. of the 25 S values within Levıt), which quantifies spatial soil moisture heterogeneity.

The method to quantify the strength of a relationship between a variable Y and precipitation events follows ref. 11 (therein, Y = Y0), and is applied for fixed 5° × 5° boxes. For each event, we compute Y and denote it as Ye. Then we define a control sample based on data for non-event days, Yc (using the same locations on non-event days). All values of Ye and Yc within a 5° × 5° box are pooled together, and we compute the difference in Y values between the event and control sample, δY = (mean(Ye) − mean(Yc)). We then compare δY to typical values of δ(Y) obtained from bootstrapping (see Methods Summary) by displaying the quantile of typical values corresponding to δY. In other words, we compare Y from event days with non-event days and measure the strength of this difference with expectations from resampling.

Spatial relationships. The results of the spatial analysis are displayed in Fig. 1a (see also Supplementary Figs 1 and 2). Clearly, values of δY lie on the lower tail of the null distribution (low quantile values) at more locations than they lie on the upper tail (for example, 23% of the analysed boxes lie below 0.1, while only 10% lie above 0.9 as expected by chance). This indicates that afternoon rain falls preferentially over soils that are drier than their surrounding consistently with the findings from ref. 11 (see also Supplementary Fig. 1a), with small differences in the regional patterns likely due to various factors (soil moisture data, precipitation data set version, months used for the analysis and so on). Hence, results from ref. 11 do not depend on the use of shallow surface soil moisture therein, as we reproduce these results when considering soil moisture over the entire region and season. These results demonstrate the coexistence of positive temporal and negative spatial relationships within the same region and based on the same data. Although a positive temporal correlation does not necessarily imply a causal relationship, our results potentially reconcile the notions of positive temporal soil moisture–precipitation coupling with local, spatially negative feedbacks. We further propose physical mechanisms by which these apparently contradictory processes could coexist.
Temporal relationships. The temporal analysis based on $Y^t$ provides information about the soil moisture state on the morning of an event compared with the expectation, by computing $\delta_t(Y^t) = \text{mean}(S'_{\text{max},t}) - \text{mean}(S'_{\text{min},t})$. While this approach is likely to be impacted by externally forced precipitation persistence at various time scales\cite{15}, it provides a temporal perspective that complements the spatial approach inherent to the metric by ref. 11. We find that afternoon rain does not occur preferentially on days with drier soil conditions: Fig. 1b (see also Supplementary Figs 3 and 4) highlights that the analysed precipitation events occur for most locations when soils are wetter than usual at $L_{\text{max}}$ (that is, positive temporal relationship; 51% of analysed grid boxes above 0.9 versus 10% below 0.1). Exceptions are the Central United States, Western Amazonia and parts of the Sahel and Equatorial Africa, where precipitation events tend to occur when soils are dry. We find similar results using $L_{\text{min}}$ instead of $L_{\text{max}}$ (Supplementary Figs 5 and 6; Supplementary Discussion), indicating that this correlation may be driven by soil moisture on a larger scale. Together, the spatial and temporal analyses highlight that, for most regions, precipitation events generally occur when soils are wet, but where soils are drier relative to larger-scale regions (as illustrated in Fig. 2).

Possible mechanisms. One possible explanation for the diagnosed temporal relationships\textsuperscript{5,14,15} is that the atmosphere can sustain persistent large-scale features that favour sequences of dry (or wet) days, regardless of soil moisture state. On the other hand, if the above relationships indicate causality, our results imply that soil moisture–precipitation coupling interacts in two ways: the positive temporal coupling might enhance precipitation persistence, while the negative spatial coupling leads to an homogenization of moisture on land. However, these two simultaneous processes are likely to be interdependent, first of all because the required soil moisture heterogeneity for the presence of a spatial coupling may be temporally related to precipitation. To assess whether precipitation events indeed present a preference for heterogeneous soil moisture conditions, we compute our third metric based on $Y^h$ and thereby compare spatial heterogeneity in the morning of event versus non-event days. The results (Fig. 1c; Supplementary Figs 7 and 8) clearly indicate that precipitation is triggered preferentially over heterogeneous soil moisture conditions.

Taken together, our results suggest that—if our metrics do not only reflect atmospheric persistence—the negative spatial coupling could lead to a positive temporal feedback at a larger scale, as precipitation-induced soil moisture heterogeneity might help generating further precipitation events via spatial coupling mechanisms\textsuperscript{5}, although with a spatial shift related to previous events. In addition, the rain over drier parcels might enhance evaporation in more water-stressed patches, thereby increasing total evaporation over a larger region. These two effects, in turn could contribute to a positive temporal feedback at larger scales. Note that a positive temporal coupling would not need to occur locally but could also affect areas downwind via moisture recycling\textsuperscript{6}. This view is also consistent with the fact that land evaporation is overall an important source of moisture for precipitation on land\textsuperscript{1,16}. Nonetheless, a negative temporal effect might also be generated by spatial coupling, which tends to homogenize land wetness and thereby might reduce the occurrence of heterogeneity-induced precipitation events. These possible mechanisms are consistent with our results; their existence and relevance, however, depend on the relative contributions of soil moisture versus atmospheric persistence to the computed statistical relationships.

Discussion

Our findings potentially reconcile a number of studies on soil moisture–precipitation feedback, as illustrated in Fig. 2. Indeed, we demonstrate the compatibility of a positive temporal correlation\textsuperscript{6,10,15,17,18} with a negative spatial correlation\textsuperscript{5,11}. We show that the apparent contradiction in the sign of the soil
spatial context plays a crucial role in the resulting sign of the relationship. Temporally, we find the dominance of an apparent positive relationship, that is, rain occurring more often in wet conditions, which might enhance precipitation persistence. Spatially, we find a dominant negative relationship, that is, rain occurring more often over soils that are drier than the surrounding areas, which might lead to an homogenization of moisture availability on land. If representative of causal relationships, these results would be consistent with the notion of moisture recycling, as well as the existence of soil moisture-induced mesoscale circulations. Improvements in models, in particular with respect to the representation of convection, as well as studies of the feedback with models that explicitly resolve convection, are becoming increasingly crucial to help disentangling the observed positive temporal relationship from atmospheric persistence.

### Methods

**Precipitation data.** We use three precipitation data sets that merge measurements from a number of satellites to produce quasi-global, consistent data sets at a high spatial (0.25° × 0.25°) and temporal (3 h) resolution: CMORPH (the Climate Prediction Center morphing method) and PERSIANN (Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks), available from 60°S to 60°N and TRMM3B42 (from the Tropical Rainfall Measuring Mission), available from 50°S to 50°N and hereafter referred to as TRMM. These products provide us with at least partly independent databases for our investigation of land–precipitation coupling. Here we choose CMORPH as our main data set because of the more physically based algorithm employed, and we only show results with this data set in Fig. 1. Results with other precipitation data sets are provided in the Supplementary Information (Supplementary Figs 1–8).

All three products are primarily based on data from passive microwave sensor overpasses, which provide high-quality precipitation estimates, but are available typically only several times a day. These are combined with data from infrared sensors onboard geostationary satellites, which are available at a high temporal resolution over most of the globe. The products rely on different algorithms to convert the raw measurements to consistent precipitation data.

CMORPH propagates passive estimates using motion vectors derived from infrared sensors. We use version 1.0 of CMORPH, where the whole archive was reprocessed using a fixed algorithm and using inputs of the same versions. TRMM uses data from the passive microwave sensors, incorporates radars on the TRMM satellites and fills the gaps with infrared data calibrated at the monthly time scale before scaling estimates to monthly rain gauge observations. We use version 7 of the 3B42 product. PERSIANN is based on roughly the same input satellite data but uses a neural network approach to estimate precipitation. These products have been validated and used in numerous studies. Generally, a good agreement is found with other products, but the quality decreases at high latitudes and over water bodies, complex terrain or coastal areas. Nonetheless, our analysis does not consider areas with complex topography and water bodies. In addition, precipitation occurrence, which is at the basis of our precipitation detection analysis, was shown to be of good quality. Before conducting our analyses, the 3-h precipitation data was adjusted to local time (based on longitude) by taking the closest 3-h Coordinated Universal Time-based time step.

**Soil moisture data.** We use two main soil moisture data sets based on satellite observations: surface soil moisture from AMSR-E (NASA-LPRM algorithm) and total evaporative stress from GLEAM (‘Global Land Evaporation: the Amsterdam Methodology’). We choose GLEAM as our primary data set, used in Fig. 1, because of two major advantages over satellite-based surface moisture estimates: it includes the whole root zone (in addition to surface soil moisture; limited to the top few cm for AMSR-E), and its variability is limited to when soil

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**Figure 2 | Representation of various perspectives on soil moisture–precipitation coupling.** Traditionally in the literature, temporal approaches (a) suggest that rain is more likely in wet conditions, while spatial approaches (b) emphasize rain over locally drier patches. The joint perspective presented here (c) highlights that both are valid, and thereby rain is more likely in overall wet conditions but is located over drier (less wet) patches. Shown here are typical soil moisture conditions preceding afternoon rainfall events but do not necessarily imply causal relationships.
To ensure that events are generated in the analysed afternoon, grid cells with morning (06:00 – 12:00) precipitation > 1 mm are filtered out. Grid cells with fixed features that may influence the precipitation field are also excluded: grid cells with a range of topographic height within a box of 1.25° extending 300 m, as well as grid cells where water bodies cover over 5% of the area are removed as in ref. 11, using the data sets therein. Supplementary Figure 10 illustrates the event definition and the filtering applied with an example day over West Africa. To concentrate on the convective season, results in Fig. 1 are presented for May–September latitudes North of 23° N, November–March latitudes South of 23° S, and including all months in the tropics where convection is the dominant process of precipitation generation 14. Results for individual seasons are available in Supplementary Fig. 11.

Typical (Y) values are computed by pooling both samples (Y1 and Y2) together and taking 1,000 bootstrap samples of a size equal to the size of Y. The quantile of the null distribution of δ(Y) to which the actual δ(Y) corresponds is a measure of the significance of the relationship. Note that we have chosen to include rainfall from 12:00 to 24:00 in our analysis, while ref. 11 uses 12:00 – 21:00. This might lead to some different detected locations if events are propagated. However, a direct comparison between the two definitions of afternoon shown in Supplementary Fig. 13 highlights the robustness of our results to this aspect of the analysis.

Applying a temporal metric from the literature 13,15 to our data yields regions of positive and negative δ values in our temporal metric δ(Y) shown in Fig. 1b (see Supplementary Discussion; Supplementary Figs 14 and 15).

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B.P.G., B.O. and S.I.S. initiated the study. B.P.G. mainly performed the analysis and wrote the manuscript. D.G.M. contributed to the analysis. All authors participated in the design of the experiments, discussion of the results and writing of the paper.

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