LETTER

doi:10.1038/nature11377

Afternoon rain more likely over drier soils

Christopher M. Taylor[1], Richard A. M. de Jeu[2], Fran⊠oise Guichard[3], Phil P. Harris[1] & Wouter A. Dorigo[4]

Land surface properties, such as vegetation cover and soil moisture, influence the partitioning of radiative energy between latent and sensible heat fluxes in daytime hours. During dry periods, soil-water deficit can limit evapotranspiration, leading to warmer and drier conditions in the lower atmosphere[1,2]. Soil moisture can influence the development of convective storms through such modifications of low-level atmospheric temperature and humidity[1,3], which in turn feeds back on soil moisture. Yet there is considerable uncertainty in how soil moisture affects convective storms across the world, owing to a lack of observational evidence and uncertainty in large-scale models[4]. Here we present a global-scale observational analysis of the coupling between soil moisture and precipitation. We show that across all six continents studied, afternoon rain falls preferentially over soils that are relatively dry compared to the surrounding area. The signal emerges most clearly in the observations over semi-arid regions, where surface fluxes are sensitive to soil moisture, and convective events are frequent. Mechanistically, our results are consistent with enhanced afternoon moist convection driven by increased sensible heat flux over drier soils, and/or mesoscale variability in soil moisture. We find no evidence in our analysis of a positive feedback—that is, a preference for rain over wetter soils—at the spatial scale (50–100 kilometres) studied. In contrast, we find that a positive feedback of soil moisture on simulated precipitation does dominate in six state-of-the-art global weather and climate models—a difference that may contribute to excessive simulated droughts in large-scale models.

Soil moisture influences precipitation across a range of scales in time and space[5]. In drought-affected continental regions, weak evapotranspiration leads to reduced atmospheric moisture content over a period of days, potentially suppressing subsequent precipitation[6]. When soil moisture anomalies are extensive, surface-induced perturbations to the atmospheric heat budget may modify synoptic-scale circulations[2], in turn affecting moisture advection from the oceans[7]. On smaller scales, the development of convective clouds and precipitation can be influenced by local surface fluxes over the course of the day[1,3]. Theoretical considerations[8,9] suggest that, in an undisturbed atmosphere, the likelihood and sign of a surface feedback will be determined by the atmospheric profiles of temperature and humidity. Thus, one might expect regional variations in the strength and sign of convective sensitivity to soil moisture[10,11]. Mesoscale variability in soil moisture can also influence the feedback through the development of daytime circulations[12], which provide additional convergence to trigger convection[13,14].

Several studies have examined the impact of the land surface on observed rainfall in different regions of the world. Analyses in Illinois[15] and West Africa[16] have indicated positive correlations between antecedent soil moisture and precipitation, consistent with a positive soil moisture feedback. A recent study[17] based on observationally constrained reanalysis data showed an increasing frequency of convective rainfall when evapotranspiration was higher across much of North America. On the other hand, examination of satellite cloud data has indicated locally enhanced afternoon precipitation frequency over surfaces with increased sensible heat fluxes, as a result of mesoscale circulations due either to soil moisture[18] or vegetation cover[19,20].

At the regional scale, climate models tend to agree on where feedbacks occur, these being constrained largely by where soil moisture limits evapotranspiration in the presence of convective activity[4]. But the spread in simulated feedback strength is large, highlighting both the uncertainty in surface flux sensitivity to soil moisture and the response of the planetary boundary layer and convection to surface fluxes[21,22]. Indeed, the feedback sign can change depending on model spatial resolution, with a strong influence of the convective parameterization likely to be responsible[23].

Until recently, there has been a lack of observations with which to evaluate feedbacks in large-scale models. We address that problem here, and focus on the least well understood aspect of the feedback loop between soil moisture and precipitation, namely, the response of daytime moist convection to soil moisture anomalies. In the past decade, global observational data sets of both surface soil moisture[24,25] and precipitation[26] have become available at a resolution of 0.25° × 0.25°, on daily and 3-hourly time steps respectively. We use these to analyse the location of afternoon rain events relative to the underlying antecedent soil moisture. In particular we examine whether rain is more likely over soils that are wetter or drier than the surrounding area. We then apply the same methodology to six global models used in reanalyses or climate projections.

We focus on the development of precipitation events during the afternoon, when the sensitivity of convection to land conditions is expected to be maximized. An event is defined at a 0.25° × 0.25° pixel location (L_{max}) with a maximum in afternoon rainfall, centred in a box measuring 1.25° × 1.25° (see Methods Summary and Supplementary Fig. 3). Each L_{max} is paired with one or more pixels in the box where afternoon rainfall is at a minimum (L_{min}). We compute the difference in pre-rain-event soil moisture, ΔS_e, between L_{max} and L_{min} having first subtracted a climatological mean soil moisture from both locations. We quantify the strength of the soil moisture effect on precipitation using a sample of events, and assess how unexpected the observed sample mean value of ΔS_e is, relative to a control sample, ΔS_c, from the same location pairs on non-event days. More precisely, we examine the difference in ΔS between the event and control samples, $\delta_e = \text{mean}(\Delta S_e) - \text{mean}(\Delta S_c)$, expressed as a percentile of typical δ values (see Methods Summary). Mountainous and coastal areas are excluded because of their effects on mesoscale precipitation, and we are unable to analyse the observations in tropical forest regions, owing to the limitations of soil moisture retrievals beneath dense vegetation.

The map in Fig. 1 shows regions of the world where afternoon precipitation is observed more frequently than expected over wet (blue) or dry (red) soils, based on analysis of δ_e at a scale of 5°. Globally, 28.9% of the grid cells analysed have percentile values, P, less than 10, as compared to an expected frequency (assuming no feedback) of 10%, and just 3.4% with $P > 90$. Clusters of low percentiles are found in semi-arid and arid regions, most notably North Africa, but also in Eastern Australia, Central Asia and Southern Africa. These clusters indicate a clear preference for afternoon rain over drier soils

[1]NERC Centre for Ecology and Hydrology, Maclean Building, Benson Lane, Crowmarsh Gifford, Wallingford OX10 8BB, UK. [2]Vrije Universiteit Amsterdam, Earth and Climate Cluster, Department of Earth Sciences, Faculty of Earth and Life Sciences, De Boelelaan 1085, 1081 HV Amsterdam, The Netherlands. [3]CNRM-GAME (CNRS and Me¨te¨o-France), 42 avenue Coriolis, 31057 Toulouse Cedex, France. [4]Institute of Photogrammetry and Remote Sensing (I.P.F.), Vienna University of Technology, Gusshausstraþe 27-29, 1040 Vienna, Austria.

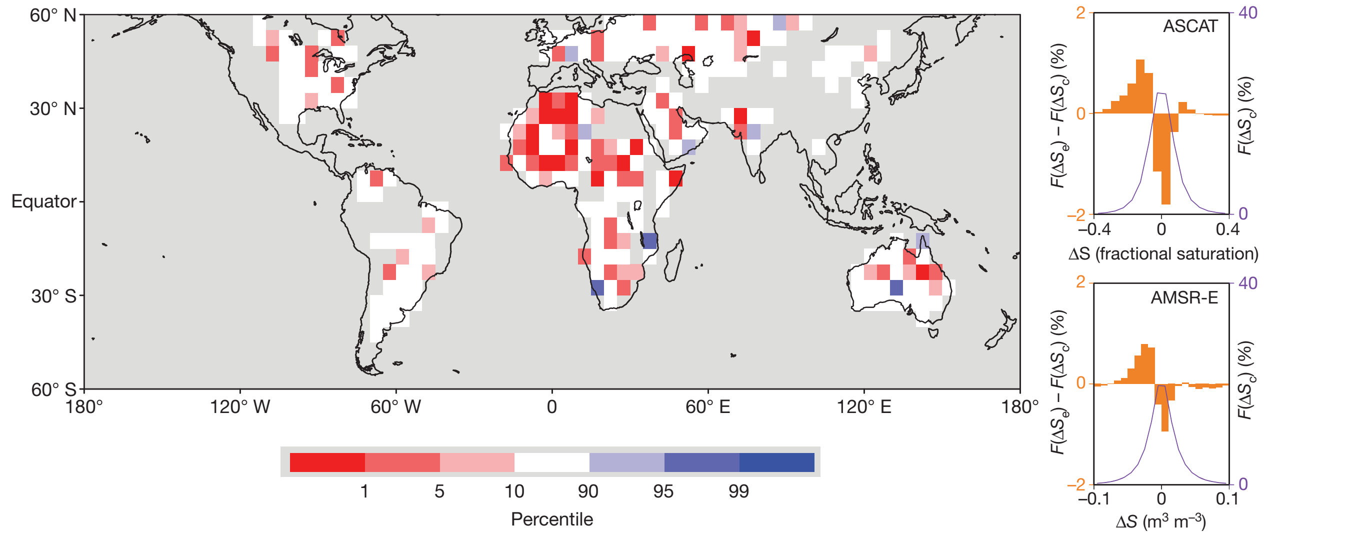

Figure 1 | Preference for afternoon precipitation over soil moisture anomalies. Percentiles of the observed variable $\delta_e = \text{mean}(\Delta S_e) - \text{mean}(\Delta S_c)$ for each $5^\circ \times 5^\circ$ box under a null assumption that no feedback exists. Null sampling distributions of δ values were estimated for each box by re-sampling without replacement from the combined set of event and non-event ΔS values. Low (high) percentiles indicate where rainfall maxima occur over locally dry (wet) soil more frequently than expected. Grey denotes $5^\circ \times 5^\circ$ cells containing fewer than 25 events. The map is based on a merging of two separate analyses using either ASCAT or AMSR-E soil moisture. For each $5^\circ \times 5^\circ$ cell, the relative quality of the two data sets is tested independently to determine which product is used (Supplementary Figs 5, 6). Insets: frequency histograms $F(\Delta S_c)$ of soil moisture difference in the global control sample (purple), and the difference $F(\Delta S_e) - F(\Delta S_c)$ between the histograms of the global event and global control samples (orange shading). The total number of events (n_e) is 29,729 for ASCAT and 73,623 for AMSR-E. Note the different units for ΔS for ASCAT (fractional saturation) and AMSR-E ($m^3\ m^{-3}$).

in those regions, consistent with a previous study over the Western Sahel[18]. This signal is also evident when computing δ_e from all events across the world (Fig. 1 insets). Further analysis (Supplementary Information and Supplementary Tables 3 and 4) demonstrates that this signal is statistically significant at the 99% level over all continents and in all climate zones, with the exception of tropical forests, where accurate soil moisture retrievals are unavailable. We repeated the analysis after degrading the spatial resolution from 0.25° to 1.0° . This produced only about one-tenth of the number of events identified in the 0.25° data, but a statistically robust preference for rain over drier soil was still found across the tropics, and in particular over parts of North Africa and Australia (Supplementary Fig. 10; Supplementary Tables 3, 4).

Using two alternative precipitation data sets, we found the same global preference for rain over drier soil, and similar regions contributing to that signal (Supplementary Fig. 8; Supplementary Tables 3, 4). Although all of the satellite-derived data sets are subject to errors at the event scale, analysing the data over many events should yield more accurate estimates of δ_e. Furthermore, our approach exploits an aspect of rainfall that is relatively well captured by satellite, that is, its spatial structure. Additional analysis (Supplementary Fig. 4) indicates a strong degree of mutual consistency in the spatial variability of soil moisture and rainfall in our independent data sets, providing further evidence to support our methodology.

We now consider whether the observed preference for rain over drier soil is consistent with land surface feedback. For a soil moisture feedback on precipitation, soil water deficit must limit evapotranspiration. This regime is found only in certain seasons and regions of the world[4], where water stress coincides with convective activity. Low percentiles in Fig. 1 occur in areas that are relatively dry, and originate from seasons with convective storms (Supplementary Fig. 9). Using data from across the globe, the sensitivity of δ_e to the areal-mean ($1.25^\circ \times 1.25^\circ$) soil moisture is explored in Fig. 2a. The most negative values (rain over drier soil) are found for the driest mean conditions, and the signal loses significance at the 95% level above $0.20\ m^3\ m^{-3}$. This behaviour is consistent with soil moisture feedback, as the sensitivity of sensible and latent heat fluxes to soil moisture increases as mean soil moisture decreases. Also, the use of surface soil moisture

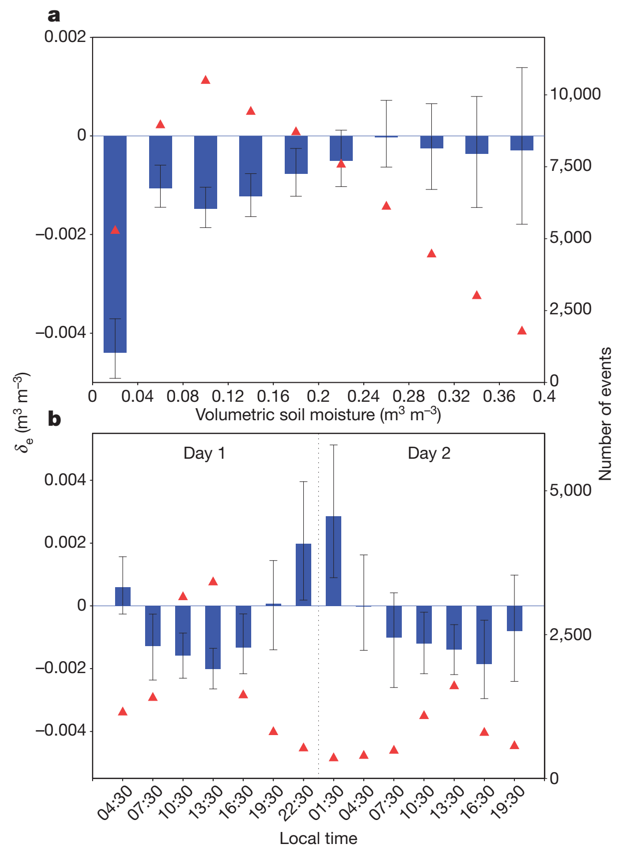

Figure 2 | Sensitivities of pre-rain-event soil moisture to mean soil moisture and time of day. Blue bars denote the anomalous pre-rain-event soil moisture difference, δ_e, averaged over every event globally, as a function of pre-event soil moisture averaged over $1.25^\circ \times 1.25^\circ$ (**a**), and time of first precipitation (at least 1 mm over 3 h), following a soil moisture measurement at 1:30 on day 1 (**b**). Negative values of δ_e indicate a preference for precipitation over drier soil, and error bars show 90% confidence limits. Red triangles denote the number of events used for each δ_e average.

as a proxy for surface flux variability should be most effective for dry and sparsely vegetated surfaces.

A land feedback requires a strong diurnal sensitivity in the observed signal. We repeated our analysis, this time detecting the onset of precipitation at varying lag times after a soil moisture observation at 1:30 (all times are local time). The values of δ_e (Fig. 2b) exhibit a pronounced diurnal cycle, still evident 36 hours after the observation. The most negative values occur during daytime, in particular between 12:00 and 15:00. By contrast, between 21:00 and 3:00 the opposite signal emerges; that is, events are more likely to be found over wetter soils. The early afternoon minimum is consistent with a negative soil moisture feedback on convective initiation, when the effects of surface properties on the planetary boundary layer, convective instability and mesoscale flows are all maximized. Mechanisms to explain the reverse signal in the hours around midnight may be more subtle. The effects of thermals and daytime surface-induced flows are likely to be relatively short-lived after dusk. On the other hand, nocturnal humidity anomalies may persist for longer, depending on the spatial scale of the surface features and wind conditions. From detailed examination of individual events, it appears that, overnight, there is an increasing influence of pre-existing, fast-moving convective systems in our sample, particularly in the Sahel. Distinct mechanisms will be involved in the surface interaction with organized convective systems, which may favour a positive feedback[16].

Finally, we repeat our analysis using 3-hourly diagnostics from six global models, ranging in horizontal resolution from 0.5 to 2.0°. Our results (Fig. 3) indicate a strong preference for rain over wet soils for large parts of the world, in contrast to the observations. Only one model (Fig. 3e) produces more than the expected 10% of grid cells with $P < 10$, largely due to contributions at mid-latitudes. The cross-model signal favouring precipitation over wet soil, particularly across the tropics (Supplementary Table 3), demonstrates a fundamental failing in the ability of convective parameterizations to represent land feedbacks on daytime precipitation. This is likely to be linked to the oft-reported phase lag in the diurnal cycle of precipitation; that is, simulated rainfall tends to start several hours too early[27], and is possibly amplified by a lack of boundary-layer clouds in some models. This weakness has been related to the crude criteria used to trigger deep convection in large-scale models[28]. The onset of convective precipitation is overly sensitive to the daytime increase of moist convective instability, which is typically faster over wetter soils[3], favouring a positive feedback. Early initiation limits the effect of other daytime processes on triggering convection in the models. In contrast, our observational analysis points to the importance of dry boundary-layer dynamics for this phenomenon over land.

The observed preference for afternoon rain over locally drier soil on scales of 50–100 km is consistent with a number of regional studies based on remotely sensed data[18–20]. Our failure to find areas of positive

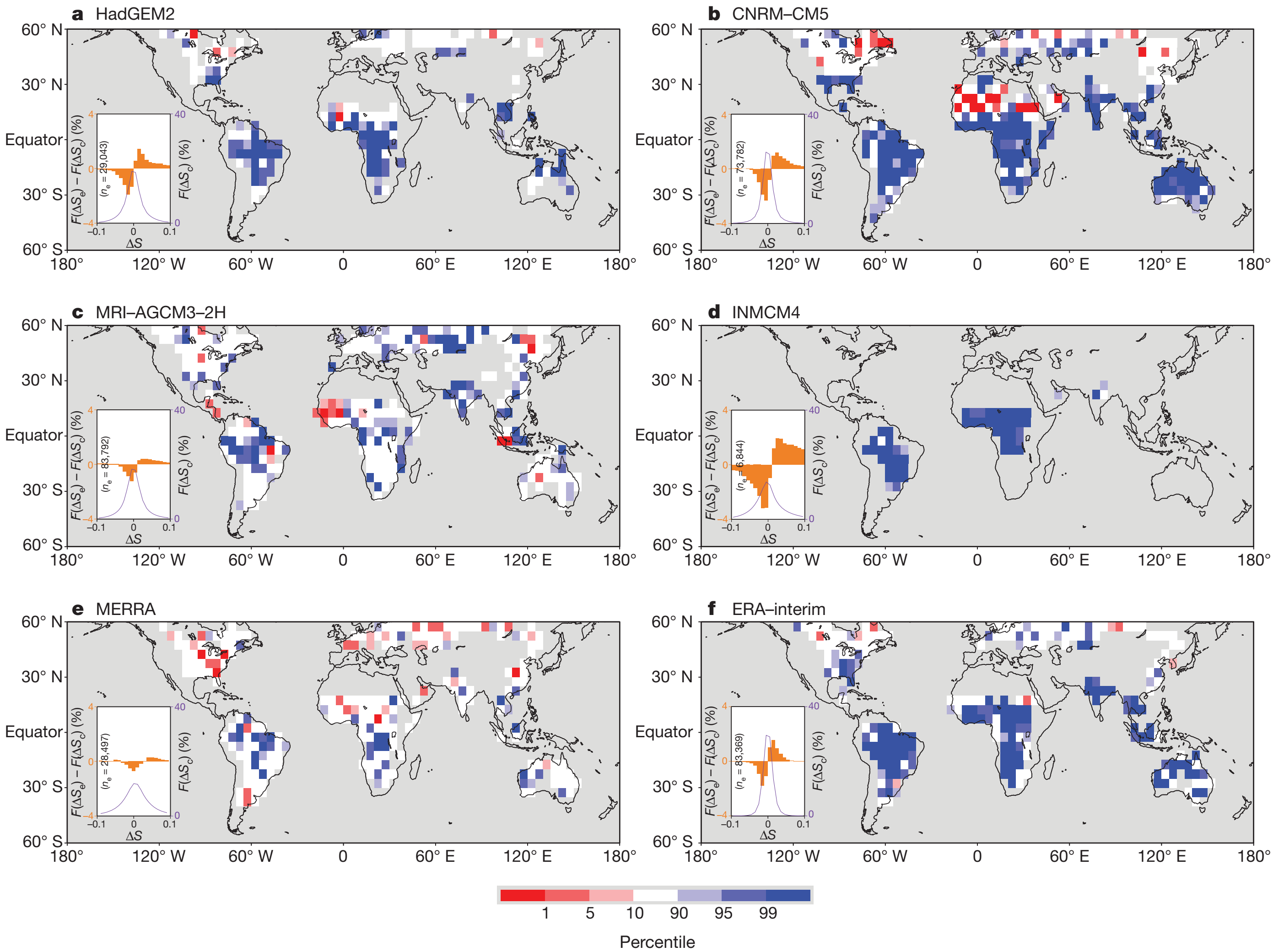

Figure 3 | Simulated preference for afternoon precipitation over soil moisture anomalies. As for Fig. 1 but using diagnostics from integrations by four climate models (**a**–**d**) and two atmospheric reanalysis models (**e**, **f**). Blue (red) shading indicates convective precipitation more likely over wetter (drier) soils. The models used are: **a**, HadGEM2; **b**, CNRM-CM5; **c**, MRI-AGCM3-2H; **d**, INMCM4; **e**, MERRA; and **f**, ERA-Interim. Inset as for Fig. 1, with ΔS in $m^3\,m^{-3}$. Further details of the models are in Supplementary Information, with maps of the number of events in each model in Supplementary Fig. 11.

feedback may indicate the importance of surface-induced mesoscale flows in triggering convection[18], although the coarse spatial resolution of our data sets prevents us from drawing firm conclusions on this issue. Equally, mixing processes in the growth stage of convective clouds before precipitation[23,29] may play an important role. Neither of these processes is captured in existing one-dimensional analyses[8]. Furthermore, our results raise questions about the ability of models reliant on convective parameterizations to represent these processes adequately. Although the coarser-resolution models analysed here (HadGEM2, CNRM-CM5 and INMCM4) cannot resolve mesoscale soil moisture structures, nor their potential impacts on convective triggering[18], all the models have a strong tendency towards rain over wetter soils, for which we find no observational support. Our study does not, however, imply that the soil moisture feedback is negative at temporal and spatial scales different from those analysed here. The multi-day accumulation of moisture in the lower atmosphere from a freely transpiring land surface may provide more favourable initial (dawn) conditions for daytime convection than the equivalent accumulation over a drought-affected region. Equally, the large-scale dynamical response to soil moisture may dominate in some regions. However, the erroneous sensitivity of convection schemes demonstrated here is likely to contribute to a tendency for large-scale models to `lock-in' dry conditions, extending droughts unrealistically, and potentially exaggerating the role of soil moisture feedbacks in the climate system[30].

METHODS SUMMARY

Surface soil moisture retrievals are used between 60° S and 60° N from the Advanced Microwave Scanning Radiometer for EOS (AMSR-E; June 2002 to October 2011)[24], and the MetOP Advanced Scatterometer (ASCAT; 2007–11)[25]. They have typically one overpass per pixel per day at either 1:30 or 13:30 (AMSR-E), and 9:30 or 21:30 (ASCAT). Additional soil moisture quality control procedures are described in Supplementary Information. The CMORPH[26] 3-hourly precipitation data set is based on data from a combination of satellites.

Locations of afternoon events, L_{max}, are defined within a box measuring 5×5 pixels by the maximum accumulated precipitation (12:00–21:00) that exceeds 3 mm. We exclude pixels with more than 1 mm rain in the preceding hours, and apply an additional filter to remove cases close to active precipitation when using soil moisture data for 13:30. These steps ensure that the soil moisture measurement precedes the rainfall. Locations where topographic height variability exceeds 300 m are excluded, along with regions containing water bodies or strong climatological soil moisture gradients.

The control sample, ΔS_c, is constructed from daily soil moisture differences between locations L_{max} and L_{min}, using data for the same calendar month but from non-event years. This quantifies typical (non-event) soil moisture differences between the locations. Each value in samples ΔS_e and ΔS_c has an individual climatological mean ΔS subtracted, which is calculated from ΔS values in the same calendar month in non-event years. For the models, soil moisture and rainfall accumulations are available every 3 h (universal time). Because of the models' lower spatial resolution (0.5–2.0°), the event box is reduced to 3×3 pixels and the local time window between 6:00 and 8:59 adopted to calculate ΔS. Convective rain is accumulated in the subsequent 9 h, several hours in the day earlier, to account for diurnal phase bias in model precipitation.

Received 19 March; accepted 29 June 2012.
Published online 12 September 2012.

1. Betts, A. K. & Ball, J. H. FIFE surface climate and site-average dataset 1987–89. *J. Atmos. Sci.* **55,** 1091–1108 (1998).
2. Fischer, E. M. *et al.* Soil moisture-atmosphere interactions during the 2003 European summer heat wave. *J. Clim.* **20,** 5081–5099 (2007).
3. Eltahir, E. A. B. A soil moisture-rainfall feedback mechanism. 1. Theory and observations. *Wat. Resour. Res.* **34,** 765–776 (1998).
4. Koster, R. D. *et al.* Regions of strong coupling between soil moisture and precipitation. *Science* **305,** 1138–1140 (2004).
5. Goessling, H. F. & Reick, C. H. What do moisture recycling estimates tell us? Exploring the extreme case of non-evaporating continents. *Hydrol. Earth Syst. Sci.* **15,** 3217–3235 (2011).
6. van der Ent, R. J., Savenije, H. H. G., Schaefli, B. & Steele-Dunne, S. C. Origin and fate of atmospheric moisture over continents. *Wat. Resour. Res.* **46,** W09525 (2010).
7. Webster, P. J. Mechanisms of monsoon low-frequency variability - surface hydrological effects. *J. Atmos. Sci.* **40,** 2110–2124 (1983).
8. Findell, K. L. & Eltahir, E. A. B. Atmospheric controls on soil moisture-boundary layer interactions. Part I: framework development. *J. Hydrometeorol.* **4,** 552–569 (2003).
9. Ek, M. B. & Holtslag, A. A. M. Influence of soil moisture on boundary layer cloud development. *J. Hydrometeorol.* **5,** 86–99 (2004).
10. Findell, K. L. & Eltahir, E. A. B. Atmospheric controls on soil moisture-boundary layer interactions. Part II: feedbacks within the continental United States. *J. Hydrometeorol.* **4,** 570–583 (2003).
11. Ferguson, C. R. & Wood, E. F. Observed land–atmosphere coupling from satellite remote sensing and reanalysis. *J. Hydrometeorol.* **12,** 1221–1254 (2011).
12. Ookouchi, Y., Segal, M., Kessler, R. C. & Pielke, R. A. Evaluation of soil moisture effects on the generation and modification of mesoscale circulations. *Mon. Weath. Rev.* **112,** 2281–2292 (1984).
13. Cheng, W. Y. Y. & Cotton, W. R. Sensitivity of a cloud-resolving simulation of the genesis of a mesoscale convective system to horizontal heterogeneities in soil moisture initialization. *J. Hydrometeorol.* **5,** 934–958 (2004).
14. Anthes, R. A. Enhancement of convective precipitation by mesoscale variations in vegetative covering in semi-arid regions. *J. Clim. Appl. Meteorol.* **23,** 541–554 (1984).
15. Findell, K. L. & Eltahir, E. A. B. An analysis of the soil moisture-rainfall feedback, based on direct observations from Illinois. *Wat. Resour. Res.* **33,** 725–735 (1997).
16. Taylor, C. M. & Lebel, T. Observational evidence of persistent convective-scale rainfall patterns. *Mon. Weath. Rev.* **126,** 1597–1607 (1998).
17. Findell, K. L., Gentine, P., Lintner, B. R. & Kerr, C. Probability of afternoon precipitation in eastern United States and Mexico enhanced by high evaporation. *Nature Geosci.* **4,** 434–439 (2011).
18. Taylor, C. M. *et al.* Frequency of Sahelian storm initiation enhanced over mesoscale soil-moisture patterns. *Nature Geosci.* **4,** 430–433 (2011).
19. Wang, J. F. *et al.* Impact of deforestation in the Amazon basin on cloud climatology. *Proc. Natl Acad. Sci. USA* **106,** 3670–3674 (2009).
20. Carleton, A. M. *et al.* Synoptic circulation and land surface influences on convection in the Midwest US ``corn belt'' during the summers of 1999 and 2000. Part II: role of vegetation boundaries. *J. Clim.* **21,** 3617–3641 (2008).
21. Santanello, J. A., Peters-Lidard, C. D. & Kumar, S. V. Diagnosing the sensitivity of local land–atmosphere coupling via the soil moisture–boundary layer interaction. *J. Hydrometeorol.* **12,** 766–786 (2011).
22. Guo, Z. C. *et al.* GLACE: The Global Land-Atmosphere Coupling Experiment. Part II: analysis. *J. Hydrometeorol.* **7,** 611–625 (2006).
23. Hohenegger, C., Brockhaus, P., Bretherton, C. S. & Schar, C. The soil moisture-precipitation feedback in simulations with explicit and parameterized convection. *J. Clim.* **22,** 5003–5020 (2009).
24. Owe, M., de Jeu, R. & Holmes, T. Multisensor historical climatology of satellite-derived global land surface moisture. *J. Geophys. Res.* **113,** F01002 (2008).
25. Bartalis, Z. *et al.* Initial soil moisture retrievals from the METOP-A Advanced Scatterometer (ASCAT). *Geophys. Res. Lett.* **34,** L20401 (2007).
26. Joyce, R. J., Janowiak, J. E., Arkin, P. A. & Xie, P. CMORPH: a method that produces global precipitation estimates from passive microwave and infrared data at high spatial and temporal resolution. *J. Hydrometeorol.* **5,** 487–503 (2004).
27. Dai, A. Precipitation characteristics in eighteen coupled climate models. *J. Clim.* **19,** 4605–4630 (2006).
28. Guichard, F. *et al.* Modelling the diurnal cycle of deep precipitating convection over land with cloud-resolving models and single-column models. *Q. J. R. Meteorol. Soc.* **130,** 3139–3172 (2004).
29. Zhang, Y. & Klein, S. A. Mechanisms affecting the transition from shallow to deep convection over land: inferences from observations of the diurnal cycle collected at the ARM southern Great Plains site. *J. Atmos. Sci.* **67,** 2943–2959 (2010).
30. McCrary, R. R. & Randall, D. A. Great Plains drought in simulations of the twentieth century. *J. Clim.* **23,** 2178–2196 (2010).

Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

Acknowledgements This research was partly funded by the European Union (FP6) WATCH Integrated Project (contract 036946), the UK National Centre for Earth Observation and the European Space Agency STSE Water Cycle Multi-mission Observation Strategy (WACMOS) project (ESRIN/contract number 22086/08/I-EC. We thank A. Beljaars, S. Seneviratne and D. Parker for discussions on this topic. We also thank the CMORPH, TRMM, PERSIANN and GPROF teams for the provision of their precipitation data, the World Climate Research Programme's Working Group on Coupled Modelling, and the centres who provided modelling data in Figure 3.

Author Contributions C.M.T. and R.A.M.d.J. conceived the study, C.M.T. performed the analysis and wrote the paper, R.A.M.d.J. and W.A.D. provided expertise on soil moisture data sets, F.G. interpreted the convective responses in models and observations, and P. P.H. devised statistical tests. All authors discussed the results and edited the manuscript.

Author Information Reprints and permissions information is available at www.nature.com/reprints. The authors declare no competing financial interests. Readers are welcome to comment on the online version of this article at www.nature.com/nature. Correspondence and requests for materials should be addressed to C.M.T. (cmt@ceh.ac.uk).