Observational evidence that soil moisture variations affect precipitation

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Land-atmosphere feedback, by which precipitation-induced soil moisture anomalies affect subsequent precipitation, may be an important element of Earth’s climate system, but its very existence has never been demonstrated conclusively at regional to continental scales. Evidence for the feedback is sought in a 50-year observational precipitation dataset covering the United States. The precipitation variance and autocorrelation fields are characterized by features that agree (in structure, though not in magnitude) with those produced by an atmospheric general circulation model (AGCM). Because the model-generated features are known to result from land-atmosphere feedback alone, the observed features are suggestive of the existence of feedback in nature. INDEX TERMS: 1818 Hydrology: Evapotranspiration; 1833 Hydrology: Hydroclimatoloy; 1866 Hydrology: Soil moisture; 3322 Meteorology and Atmospheric Dynamics: Land/atmosphere interactions; 3354 Meteorology and Atmospheric Dynamics: Precipitation (1854). Citation: Koster, R. D., M. J. Suarez, R. W. Higgins, and H. M. Van den Dool, Observational evidence that soil moisture variations affect precipitation, Geophys. Res. Lett., 30(5), 1241, doi:10.1029/2002GL016571, 2003.

1. Introduction

[2] Climate scientists have long speculated that anomalous wet periods may sustain themselves through land-atmosphere feedback, by which wetter-than-normal soil from a precipitation event maintains higher-than-normal evaporation in subsequent weeks, which in turn induces additional precipitation. Similarly, through feedback, an anomalous lack of rain may induce lower evaporation rates, which may reduce subsequent precipitation. Land-atmosphere feedback, if it exists and is well understood, could contribute to the skill of long-term weather forecasts, including forecasts of droughts or floods.

[3] The full feedback cycle (for convenience, discussed here in terms of wet anomalies) can be split into three parts: the wetting of the soil by precipitation, the enhancement of subsequent evaporation by the wetted soil, and the enhancement of precipitation by the evaporation. The first part is straightforward and intuitive; that it occurs in nature is indisputable. The second part, the increase of evaporation following a soil wetting, is also intuitive and is directly supported by various local evaporation measurements [e.g., Cahill et al., 1999]. It is indirectly supported by the presence of negative precipitation-temperature correlations that span much of the United States [Huang and Van den Dool, 1993], the argument being that wet soil induced by high precipitation leads to a higher surface latent heat flux (evapotranspiration) at the expense of the surface sensible heat flux. The lower sensible heat flux in turn induces cooler near-surface air temperatures.

[4] The third part of the cycle, the impact of evaporation (and thus soil moisture) on precipitation, is by far the most difficult to demonstrate with data. Observational evidence at the local scale is highly limited (e.g., Barnston and Schickedanz’s [1984] study of irrigation effects), and it can be subject to contradictory interpretation [Findell and Eltahir, 1997; Salvucci et al., 2003]. Observational evidence at the regional to continental scale simply does not exist. Although soil wetness anomalies definitely affect precipitation in atmospheric general circulation models (AGCMs) [e.g., Oglesby and Erickson, 1989; Dirmeyer, 2000], these studies beg an obvious question: does the simulated responsiveness of the atmosphere reflect reality, or is it just an artifact of the models?

[5] Because of the difficulty in observing the third part of the feedback cycle, definitive proof that the full cycle occurs in nature is still lacking. We are limited by a paucity of long-term, spatially extensive soil moisture and evaporation data and by the difficulty of identifying causality in a highly interconnected system. (Note that isolating the impact of feedback from background noise would be especially difficult if any existing feedback is inherently weak.) Providing such definitive proof is beyond the scope of this paper. Instead, we use AGCM results in conjunction with observations to provide some new, indirect evidence that the full cycle occurs in nature. The approach, reminiscent of that used by Huang and Van den Dool [1993] to study relationships between precipitation and surface temperature, is simple. Data from a pair of AGCM experiments, one in which feedback is allowed and one in which it is disabled, are compared to isolate a unique signature of feedback in the AGCM’s long-term precipitation record (section 2). The signature is then sought within a recently compiled comprehensive 50-year dataset of precipitation measurements over the United States (section 3).

2. Analysis of AGCM Precipitation

2.1. Structure of Statistical Fields

[6] Statistics from four parallel global simulations with the NASA Seasonal-to-Interannual Prediction Project AGCM, each simulation spanning the period 1948–1997, were averaged to produce the four plots in the top row of Figure 1. (The simulations differed only in their initial
conditions. Plots for the individual simulations, not shown, are similar.) The first and second plots show respectively the mean and variance of July precipitation. The third plot shows the variance field divided by the areal mean of the variance field across the continental United States. This plot highlights the spatial pattern of the variances, which will be helpful for later comparisons. The fourth plot in the top row shows the correlations between the precipitation in one pentad (5-day period) with the precipitation two pentads later. That is, it shows the average of the correlations between precipitation amounts in 1–5 and 11–15 July, between those in 6–10 and 16–20 July, between those in 11–15 and 21–25 July, and between those in 15–20 and 26–30 July. Presumably, if land-atmosphere feedback contributes to the prolongation of rainy periods and dry periods, then this prolongation should be reflected in the temporal correlations (and, as a result, in the monthly variances). We consider correlations between twice-removed pentads because correlations between adjacent pentads are overly influenced by storms that straddle them. The shading in the plot is tied to approximate significance levels, as determined by Monte Carlo analysis.

The AGCM runs examined in this study used a grid resolution of $2^\circ \times 2.5^\circ$. Because computed correlations depend in part on the spatial scale considered, each pentad $2^\circ \times 2.5^\circ$ precipitation field was smoothed with a three point filter in both the meridional and zonal directions prior to computing the correlations - the precipitation examined at each grid cell is actually a mix of that grid cell’s precipitation and the precipitation in immediately adjacent grid cells. If the raw AGCM data were analyzed without aggregation or smoothing, an impact of soil moisture on precipitation 300 km away would not be picked up by the correlation calculation, even though this remote impact fully constitutes feedback. The choice of a 3-point filter allowed us examine some non-local responses (up to a few hundred kilometers away) while still maintaining the broad spatial structure of the correlation field. For consistency between the plots, the monthly mean and variance fields were also computed from the smoothed data.

The patterns seen in the variance and autocorrelation plots are striking. In the variance plot (and in the normalized variance plot), a strong maximum is seen in the center of the country. In the correlation plot, a wide swath of high correlation begins at the Gulf Coast and continues up the center of the country, eventually veering west to the Pacific Northwest. Correlations in the east and southwest are very small.

An additional 50-year simulation was performed with the AGCM in which land-atmosphere feedback was artificially disabled. In this simulation, the evaporation efficiency (the ratio of evaporation to potential evaporation) at the land surface was prescribed from predetermined climatological seasonal cycles, following the approach of Koster et al.
[2000]. The prescription of evaporation efficiency in this simulation produced the same mean seasonal cycles of evaporation as were produced in the four control simulations without allowing wetter-than-usual soil to produce higher-than-usual evaporation rates. Potential violations of soil water balance are ignored, since this simulation focuses on the response of the atmosphere to surface conditions - in essence, the “control volume” for this experiment is the atmosphere itself, with the land acting as a prescribed boundary condition. Sea surface temperatures varied inter-annually, as they did in the control simulations.

[10] The normalized variance plot in the middle row of Figure 1 shows that the overall structure of the variance field for the no-feedback simulation is quite different from that of the control. The correlation fields are substantially different as well—the no-feedback simulation produced almost no significant precipitation correlations. The top and middle rows of Figure 1 provide proof that in the AGCM, a pronounced mid-country maximum of normalized variance and a swath of high correlation down the center of the country are unique “signatures” of land-atmosphere feedback. These features in the AGCM do not result from SST anomalies, internal atmospheric persistence, or other such factors.

2.2. Partial Explanation of Statistical Fields

[11] The location of the correlation swath can be explained, at least in part, by considering the second part of the feedback cycle: the modification of evaporation by soil moisture. Clearly, if the sensitivity of evaporation to variations in soil moisture is small, then the feedback cycle would be disrupted. A map of diagnosed sensitivity (using an approach outlined by Koster and Suarez [2001]) shows that it is indeed relatively small in both the eastern and southwestern United States, fully consistent with the low correlations seen in these two regions in the top row of Figure 1.

[12] The low sensitivities in the eastern and southwestern United States, by the way, are not unexpected. In the east, evaporation is limited by the atmosphere’s ability to receive water rather than by soil water availability; evaporation there is “atmosphere-controlled”. Thus, in the east, a small soil water anomaly does not affect the evaporation rate. In the southwest, evaporation sensitivity to soil moisture, particularly deeper soil moisture, which can retain anomalies from week to week, is limited by an absence of transpiration caused by sub-wilting moisture levels and minimal vegetation cover.

[13] The third part of the feedback cycle, the modification of precipitation by evaporation, also affects the correlation fields. A map of convective available potential energy (CAPE) indicates, as expected, low values of CAPE in the southwestern United States and higher values elsewhere. The low values imply a stable atmosphere that is not likely to promote convection when the near-surface air is modified by evaporation. Thus, in the southwest, feedback and the associated temporal correlations in precipitation are further inhibited.

[14] As for the precipitation variance in top row of Figure 1, note that the monthly variance of any quantity will typically increase with both an increase in the mean and an increase in sub-monthly temporal correlation [Van den Dool and Cher-
[20] Other potential contributors to the observed signal are worth considering. To examine the impact of a potential long-term trend in the precipitation data, we repeated the observational analysis above using detrended data, i.e., data in which the linear temporal trend (as determined from a least-squares regression analysis) was removed from the precipitation time series at each grid cell. Results (not shown) are essentially the same as those shown in the bottom row of Figure 1. Determining the relevance of other contributors, such as monsoon dynamics, is not as straightforward; nevertheless, we can say that if these other contributors produce the observed statistical structures without help from feedback, then any agreement seen between the top and bottom rows of Figure 1 is entirely coincidental.

[21] AGCM-generated correlations in June (not shown) are weak, and those in August are fairly strong, though not as strong as in July. Correlations inherent in the “no-feedback” simulation and in the observational data are essentially negligible in both June and August. Thus, on one hand, the June and August results further support the conclusion that the AGCM overestimates the strength of land-atmosphere feedback. On the other hand, though, we note that July is the period of maximum correlation for both the AGCM and the observations. The agreement in the timing of the maximum is either an additional piece of evidence for feedback in nature or is yet another coincidence.

4. Discussion

[22] Given the potential importance of land-atmosphere feedback for improving short- and long-term weather predictions, a demonstration of the existence of feedback in nature would be of tremendous value. The evidence presented in the two rightmost columns of Figure 1 is not conclusive and is even subjective. Furthermore, it does not address the potential for remote impacts (farther than a few hundred kilometers) of land moisture on precipitation. Nevertheless, the evidence is intriguing, as it is the first to support, with observations, the existence of land-atmosphere feedback at continental scales. The evidence is particularly suggestive because the position of the variance and correlation structures in the observational data make intuitive sense in the context of what controls feedback (section 2.2). The desired definitive evidence may need to wait several decades for the design and implementation of programs to amass large-scale soil moisture and evaporation data. Alternatively, definitive evidence of feedback might be obtained sooner through a detailed analysis of the impact of accurate soil moisture initialization on the skill of short- or long-term precipitation forecasts.

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References


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