The temporal variability of soil moisture and surface hydrological quantities

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Land surface models (LSMs) provide the connection between the atmosphere and the underlying land surface in general circulation models (GCMs) via fluxes of energy, moisture, and momentum. Soil moisture is a dominant characteristic affecting these fluxes and many researchers have investigated the role of soil moisture in influencing near-surface atmospheric variability and the effect of soil moisture anomalies on atmospheric circulation. Few studies have focused on the nature and causes of soil moisture variability itself.

Here we analyze the variability of land surface hydrological quantities in an AMIP 2 simulation made with the Canadian Centre for Climate Modelling and Analysis (CCCma) third-generation general circulation model (AGCM3). The land surface parameterization in this model is the comparatively sophisticated Canadian Land Surface Scheme (CLASS). Arora and Boer (2002) analyze, and compare with observations, the first order statistics of moisture budget quantities from the AMIP 2 simulation. Here, second order statistics namely variances and covariances, of surface hydrological quantities are assessed by comparison with observation-based estimates and related to soil moisture variance and the persistence time-scales of soil moisture anomalies.

Table 1: Comparison of globally averaged values of variances of AGCM3 precipitation $(mm/day)^2$, evapotranspiration $(mm/day)^2$, and soil moisture in the top 1 m layer (mm^2) over land with observation-based and other estimates.

	AGCM3	Other estimate
Precipitation	1.65	1.59 (Xie and Arkin, 1996)
Evapotranspiration	0.19	0.15 (ECMWF reanalysis)
Soil Moisture	376	382 (VIC-2L hydro. model)

The variance of simulated monthly precipitation values is compared with the observation-based estimates of Xie and Arkin (1996) in Figure 1a. In the absence of an observation-based evapotranspiration data set, model evapotranspiration variance is compared with estimates obtained from ECMWF reanalysis (not shown). Globally averaged values over land are compared in Table 1. Model values of precipitation and evapotranspiration variance compare reasonably well with observation-based and reanalysis estimates, respectively. Figure 1b compares soil moisture variance estimates (for the top 1 m soil layer) with those simulated by the VIC-2L hydrological model. Model estimates are qualitatively similar but generally somewhat larger than the VIC-2L estimates, although the globally averaged values compare well (Table 1).

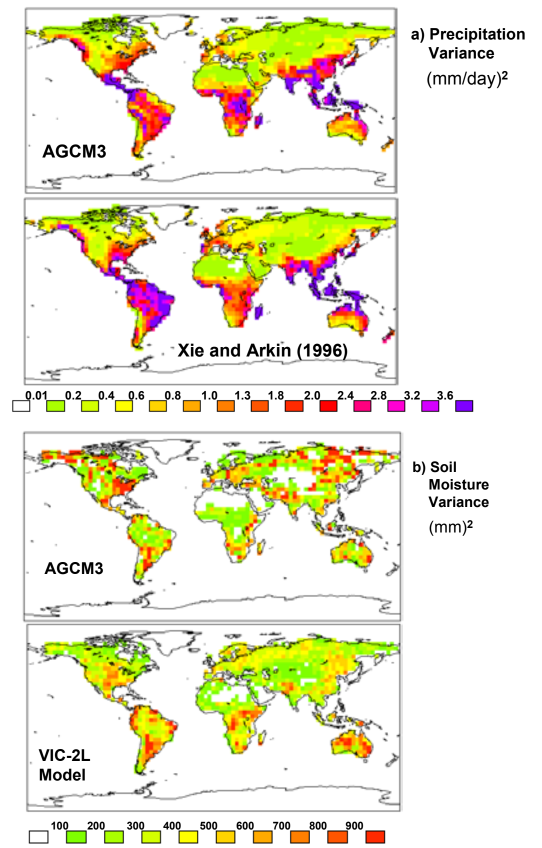

Figure 1: Comparison of AGCM precipitation variance with observed estimates of Xie and Arkin (1996) (a) and soil moisture variance with estimates from VIC-2L hydrological model (b).

We attempt to gain insight into the causes of soil moisture variability via a budget equation for the variances. The equation for soil moisture (W) is,

$$\frac{dW}{dt} = G - E - R \quad (1)$$

where G is the moisture input into the soil (including precipitation, leaf drip, and snow melt), E is evapotranspiration, and R is runoff. Eqn. (1) can also be written in terms of deviations of the monthly hydrological quantities from their mean annual cycle as,

$$\frac{dW'}{dt} = \frac{W'_{t+n} - W'_t}{n} = G' - E' - R' = S' \qquad (2)$$

where n=30 days, and W'_{t+n} and W'_t are the daily soil moisture values at the end and beginning of each month. Squaring both sides of eqn. (2) and averaging yields,

$$\sigma^2_{daily} = \frac{n^2}{[1-r(30)]}\left(\begin{matrix}\overline{G'^2} + \overline{E'^2} + \overline{R'^2} - 2\overline{G'R'} \\ -2\overline{G'E'} + 2\overline{E'R'}\end{matrix}\right) = \frac{n^2}{[1-r(30)]}\overline{S'^2} \qquad (3)$$

where σ^2_{daily} is the daily variance of soil moisture and $r(30)$ is the lag 30-day soil moisture auto-correlation. Equation (3) can also be written in terms of monthly soil moisture variance (σ^2_w) since

$$\sigma^2_w = \sigma^2_{daily}\frac{(1+C)}{n}; \; C = 2\sum_{\alpha=1}^{n-1}\left(1-\frac{\alpha}{n}\right)r(\alpha) \qquad (4)$$

where $r(\alpha)$ is lag α-day auto-correlation, as

$$\sigma^2_w = \frac{n(1+C)}{2(1-r(30))}\left(\overline{S'^2}\right). \qquad (5)$$

Eqn. (5) illustrates how the variance and covariance terms of the moisture budget quantities $\left(\overline{S'^2} = \overline{G'^2} + \overline{E'^2} + \overline{R'^2} - 2\overline{G'R'} - 2\overline{G'E'} + 2\overline{E'R'}\right)$ and the "transfer function" [$n(1+C)/2(1-r(30))$] are connected to soil moisture variance σ^2_w. High values of soil moisture variance result when values of the transfer function and/or values of $\overline{S'^2}$ are high. The transfer function is essentially a measure of soil moisture persistence via the auto-correlation terms (eqn. 4) as seen by comparing it to the persistence estimated using monthly soil moisture anomaly time series in Figure 2. Soil moisture persistence is estimated as the average length of series of months with the same anomaly sign. Soil moisture persistence time-scales and the values of the transfer function are smaller in the tropics and larger at high-latitudes, consistent with the latitudinal dependence of soil moisture persistence on potential evaporation found in earlier studies.

AGCM3 estimates of monthly soil moisture variability are shown in Figure 3b and the variance and covariance term $\overline{S'^2}$ in Figure 3a. Model results indicate that soil moisture variability in the tropics is driven mainly by the variability of surface hydrological quantities, in particular precipitation (Figure 1) and runoff (not shown). In the tropics, although the persistence of soil moisture anomalies is short and values of the transfer function small (due to higher potential evaporation rates), higher values of soil moisture variance are still obtained because of high precipitation variability. At high-latitudes, however, higher soil moisture variability is linked to long persistence of soil moisture anomalies. Here, the variability of precipitation and other moisture budget quantities is low (Figure 3a); but since the persistence time scales are longer and hence transfer function values are higher, the resulting soil moisture variance is high. As expected, soil moisture variance is low in regions with low precipitation such as the Sahara Desert, south-western U.S., and the Middle East.

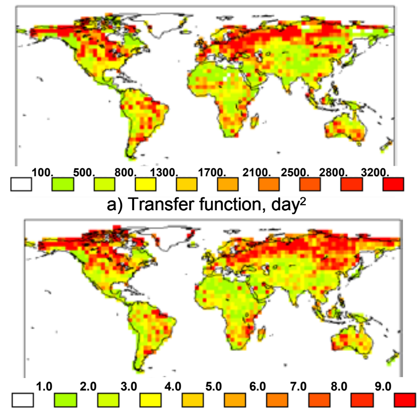

Figure 2: Transfer function (a) and persistence time scales of soil moisture anomalies (b).

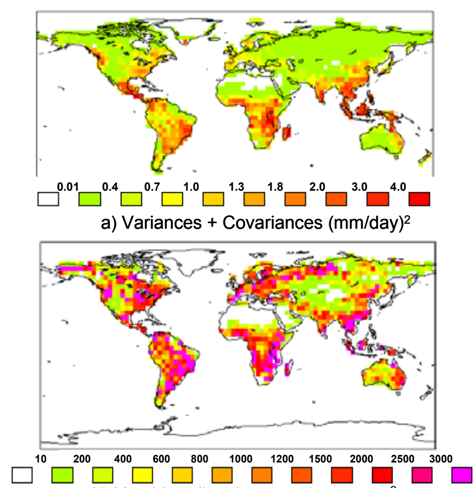

Figure 3: The sum of variances and covariances of moisture budget quantities (a) and AGCM3 simulated soil moisture variance (b).

References

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Xie, P., and P.A. Arkin, 1997, Global precipitation: a 17-year monthly analysis based on gauge observations, satellite estimates, and numerical model outputs. Bull. Ame. Meteorol. Soc., 11(78), 2539-2558.

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