# THE TEMPORAL VARIABILITY OF SOIL WETNESS AND ITS IMPACT ON CLIMATE *

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**Abstract.** The temporal variability of soil wetness and its interactions with the atmosphere were studied using a general circulation model of the atmosphere. It was found that time series of soil wetness computed by the model contain substantial amounts of variance at low frequencies. Long time-scale anomalies of soil moisture resemble the red noise response of the soil layer to white noise rainfall forcing. The dependence of the temporal variability of soil moisture on potential evaporation and precipitation is discussed.

Climatic variability is influenced by interactions between the atmosphere and its lower boundary. Interactions between the ocean and the lower atmosphere have been studied extensively. These interactions may be viewed in the light of the stochastic theory of Hasselmann (1976), in which the ocean acts as a long term integrator of white noise thermal forcing from the atmosphere, thus supplying a 'long memory' (red noise) component to the atmosphere-ocean system. A similar process may exist over land, whereby the soil acts as an integrator of white noise atmospheric forcing (precipitation), thus supplying a 'long memory' (red noise) component to the atmosphere-land surface system.

Mitchell (1964) and Gilman *et al.* (1963) were pioneers in showing that many geophysical variables possess the spectral properties of simple red noise. Mitchell (1964) pointed out that '...persistence in meteorological data can ordinarily be described very well by a first order linear Markov model'. This idea, described more than twenty years ago by Mitchell, is used in a current study of the temporal variability of soil moisture in a general circulation model. It is a privilege to be able to present our results on this occasion.

One of the motivations for such a study is that interactions between soil moisture and the atmosphere may make a substantial contribution to climatic variability. It is therefore important to understand the nature of the temporal variability of soil moisture, the physical mechanisms which control that variability, and the degree to which the temporal variability of soil moisture affects the atmosphere. In order to study these issues, a fifty year integration of a general circulation model (GCM) was performed, and the variability of that model was studied.

The model employed is similar to models used in previous climate studies as described in Manabe and Hahn (1981), or Manabe, Hahn and Holloway (1979). The dynamical component of the model is a derivative of the GFDL spectral model constructed by Gordon and Stern (1982). The model has nine levels in the vertical. Fields are represented by a limited number of spherical harmonics with

*Subsequent to the preparation of this manuscript, the detailed results of this study have been published elsewhere. See Delworth and Manabe (1988, 1989).

*Climatic Change* **16**: 185–192, 1990.

rhomboidal 15 truncation. One aspect of the model used in this study which is distinct from previously described GFDL models is that a finite difference scheme is used to compute the moisture field. Because the field of atmospheric moisture is characterized by small spatial scales, spectral truncation of that field frequently results in fictitious supersaturation and negative water vapor mixing ratios. These problems are substantially mitigated by the use of a finite difference scheme. This technique and the results of this study are discussed in greater detail in a separate publication (Delworth and Manabe, 1988).

Zonally uniform clouds are prescribed as a function of latitude and height. Carbon dioxide is constant everywhere. The diurnal cycle is omitted, but the seasonal cycle is included. The geographical and seasonal distributions of sea surface temperature and sea ice are prescribed. Precipitation is predicted whenever the relative humidity exceeds 100%. The budget of soil moisture is computed using the 'bucket method' (Manabe *et al.*, 1965).

The model's temporal variability has been studied by computing at each model grid point the spectra of the time series of soil moisture, precipitation (defined as rainfall plus snowfall), and the sum of rainfall plus snowmelt (RSNM). Unless otherwise stated, all analyses are performed on monthly mean data. It is the RSNM time series, and not the precipitation time series, which actually forces anomalies of soil moisture, as will be shown later in the definition of the soil moisture parameterization. After removing the annual cycle and its harmonics, these spectra were normalized by dividing each spectral value by the total variance of the time series at that grid point. The normalized spectra were then zonally averaged over land. Based on similarities of spectral shape, mean precipitation values, and mean soil moisture values, the zonally averaged spectra in the Northern Hemisphere were further composited into four broad bands defined in Table I. The composite spectra are shown in Figure 1.

The dominant feature of the soil moisture spectra is their resemblance to red noise. In contrast, the precipitation (denoted as RSNF in Figure 1) and RSNM spectra bear a resemblance to white noise. It should be noted that if daily data were analyzed, the precipitation and RSNM spectra would have more of a red noise character due to the serial correlation of daily rainfall. The monthly averaging process eliminates this feature. While the 'redness' of the soil moisture spectra increases with latitude, there is little variation with latitude in the precipitation or

TABLE I: Definitions of latitudinal bands used to average spectra of soil moisture, rainfall and snowmelt

| Latitude band | Range |
|---|---|
| Equatorial | 4 S–9 N |
| Subtropical | 9 N–31 N |
| Middle latitude | 31 N–54 N |
| High latitude | 54 N–76 N |

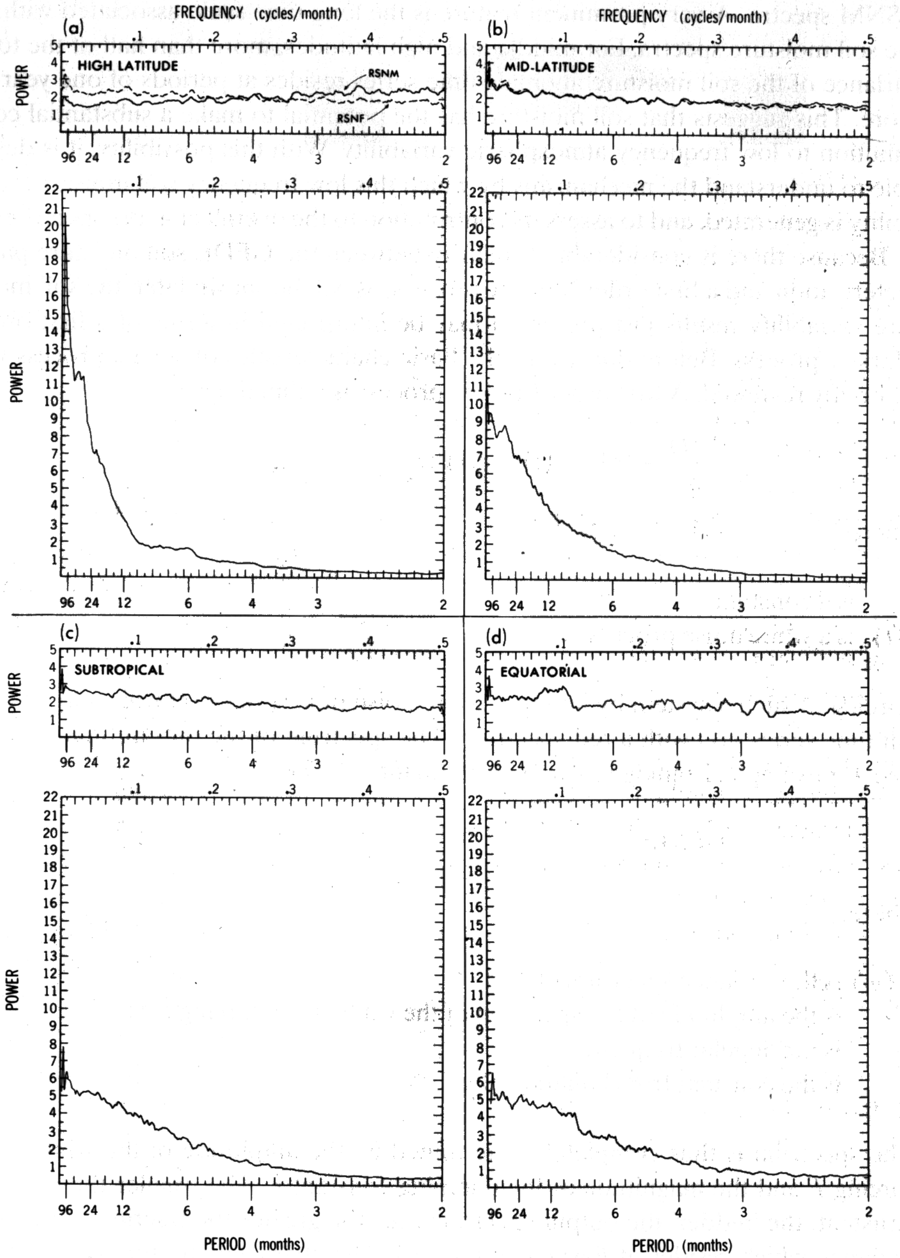


Fig. 1. Composite spectra of soil moisture (large boxes), rainfall plus snowmelt (solid lines in small boxes), and rainfall plus snowfall (dashed lines in small boxes). See text for details of compositing. (a) High Latitude band (defined in Table I). (b) Middle Latitude band. (c) Subtropical band. (d) Equatorial band.

RSNM spectra. A very prominent feature is the long time scale associated with all the soil moisture spectra. For middle and high latitudes, more than half of the total variance of the soil moisture anomaly time series resides at periods of one year or more. This suggests that soil moisture has the potential to make a substantial contribution to low frequency atmospheric variability. With this possibility, it is desirable to understand the mechanisms by which this low frequency soil moisture variability is generated, and to assess its contribution to the overall climatic spectrum.

Because there is considerable similarity between the GFDL soil moisture parameterization and a first order Markov process, as will be shown later, the soil moisture variability results just presented may be interpreted in terms of a first order Markov process. Before doing this, the basic characteristics of such a process will be briefly reviewed. A first order Markov process is defined by:

$$\frac{dy(t)}{dt} = -\lambda * y(t) + z(t) \tag{1}$$

where:

$\lambda$ is a constant
$z(t)$ is a white noise process.

Forcing of such a system by an input white noise time series $z(t)$ will yield an output time series $y(t)$ with a red spectrum. The spectrum of the output time series is (see, for example, Frankignoul and Hasselmann, 1977):

$$G(\omega) = \frac{F}{\omega^2 + \lambda^2} \tag{2}$$

where:

$G(\omega)$ is the variance spectrum of $y(t)$
$F$ is the amplitude of the spectrum of the white noise forcing $z(t)$
$\omega$ is the angular frequency
$\lambda$ is the constant from equation (1).

The spectrum is thus completely determined by the amplitude of the white noise forcing $F$ and the magnitude of the damping constant $\lambda$. The smaller the damping constant, the 'redder' the output spectrum (i.e., the greater the fraction of the total variance which resides at lower frequencies). The characteristic time scale of the white noise forcing ($z(t)$) is much shorter than the characteristic time scale of the output time series ($y(t)$).

The temporal variability of a red noise process is often characterized by its decay time scale. This quantity, defined as $(1/\lambda)$, is the *e*-folding time for the damping of anomalies in the absence of forcing. The longer the decay time scale, the redder the spectrum, and the longer the inherent time scale of the process. A 'separation time scale' may be defined as the decay time scale multiplied by $2\pi$. For a first order Markov process, approximately half of the total variance of the time series resides at periods longer than the separation time scale. For example, a decay time scale of two months implies, for a first order Markov process, that half of the total variance of the process is at periods of one year and longer.

The similarity between a first order Markov process and the GFDL soil moisture parameterization may be seen from the definition of that parameterization:

$$\frac{dw(t)}{dt} = -E_p * f\left(\frac{w(t)}{w_{FC}}\right) + \text{RSNM}(t) - \text{Runoff}(t) \tag{3}$$

where:

$w(t)$ is the time series of soil moisture
$w_{FC}$ is the field capacity (= 15 cm)

$$f\left(\frac{w}{w_{FC}}\right) = \begin{cases} \dfrac{w}{0.75 * w_{FC}} & \text{when } w < 0.75 * w_{FC} \\ 1 & \text{when } w > 0.75 * w_{FC} \end{cases}$$

RSNM$(t)$ is the time series of rainfall plus snowmelt
Runoff$(t)$ is the time series of model runoff
$E_p$ is the potential evaporation rate (cm $d^{-1}$).

The inputs to the parameterization are the value of potential evaporation ($E_p$), and the RSNM time series. Outputs consist of time series of soil moisture and runoff. Runoff is generated whenever the computed soil moisture value exceeds the field capacity (15 cm). The excess moisture is called runoff, and is removed from the system. The soil moisture value is then set equal to the field capacity.

Most of the components of the parameterization have analogs in a first order Markov process. The RSNM time series is analogous to the white noise forcing time series $z(t)$ of (1). The spectra of the RSNM time series, shown in Figure 1, are close to white at all latitudes, demonstrating that the RSNM time series behaves similarly to white noise forcing for monthly mean data. It is important to note that the characteristic time scale of the RSNM time series is much shorter than that of the output soil moisture time series. The potential evaporation term ($-E_p * f(w(t)/w_{FC})$) is analogous to the damping term ($-\lambda * y(t)$) in (1). This term determines the rate at which anomalies of soil moisture are evaporatively damped. As a result of this analogy, one would expect that smaller values of potential evaporation should correspond to longer soil moisture decay time scales, and to generally redder soil moisture spectra.

These ideas may be used to interpret the spatial variability of soil moisture decay time scales shown in Figure 2. The decay time scales were derived at each grid point by fitting a first order Markov process to the time series of soil moisture com-

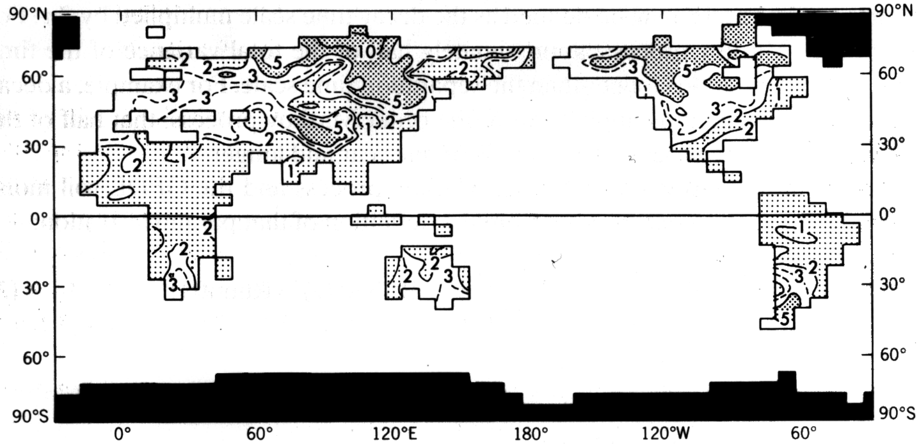


Fig. 2. Soil moisture decay time scales. Computed from model soil moisture data. (Units are months).

puted by the GCM. It is seen in Figure 2 that decay time scales show a substantial increase with latitude. This feature may be understood largely in terms of the above mentioned dependence of soil moisture decay time scales on potential evaporation. At low latitudes, an abundance of radiational energy available for evaporation leads to large potential evaporation values, rapid evaporative damping of soil moisture anomalies and short decay time scales. At high latitudes, the small amounts of radiational energy available for evaporation lead to small potential evaporation values, slow evaporative damping of soil moisture anomalies and long decay time scales. The mean increase with latitude of soil moisture decay time scales is therefore largely determined by the mean decrease with latitude of potential evaporation (and net radiation).

There are also longitudinal variations in decay time scales which are explicable in terms of longitudinal variations in potential evaporation. For example, small potential evaporation values over the Tibetan plateau, consistent with the relatively cool surface temperatures found there, account for that region's long decay time scales.

There are regions, however, where the relationship between potential evaporation and soil moisture decay time scale breaks down. For example, the northeast of Siberia is an area characterized by both low potential evaporation values (not shown) and short decay time scales. Such differences occur primarily in regions where the ratio of annual mean potential evaporation ($E_p$) to annual mean precipitation ($Pcp$) is less than one. Under such conditions, evaporation is insufficient to balance precipitation in the climatic mean, necessitating frequent runoff. The effect of runoff is to prevent large positive anomalies of soil moisture by removing excess precipitation when the soil is saturated. By preventing potentially long lasting positive soil moisture anomalies, soil moisture values are more rapidly returned to their mean, thereby shortening decay time scales. Through the mechanism of runoff, decay time scales in regions where the value of $E_p/Pcp$ is less than one are considerably shorter than decay time scales one would expect based only on potential evaporation. Additional areas which are strongly affected by this process are the coastal regions of Alaska and Newfoundland.

The effect on the temporal variability of soil moisture of spatially varying field capacity, a common feature of more complicated soil moisture parameterizations, was not considered in this study. Varying the field capacity would be similar to varying the damping constant in (1). It may be theorized, however, that the principal effect of such an added feature would be a shortening of the time scales of soil moisture temporal variability in arid regions, where such time scales are already short. This would occur as a result of the small field capacities associated with desert soils.

The overall impact of interactive soil wetness on the variability of the model climate was assessed by performing a second 25 year integration of the GCM. The second experiment is referred to as the 'noninteractive' case, while the first experiment is referred to as the 'interactive' case. In the noninteractive case, the annual cycles of soil wetness and surface albedo were prescribed using data from the first experiment. In this manner, the interaction between soil moisture and the atmosphere was removed.

The variances of monthly mean surface air temperature were computed at each grid point for the two experiments using data from only the Northern Hemisphere summer months (JJA). The zonal means over land are shown in Figure 3. It is clear that interactive soil moisture can substantially increase the variance of summer surface air temperature over continental regions. In particular, the variance of surface

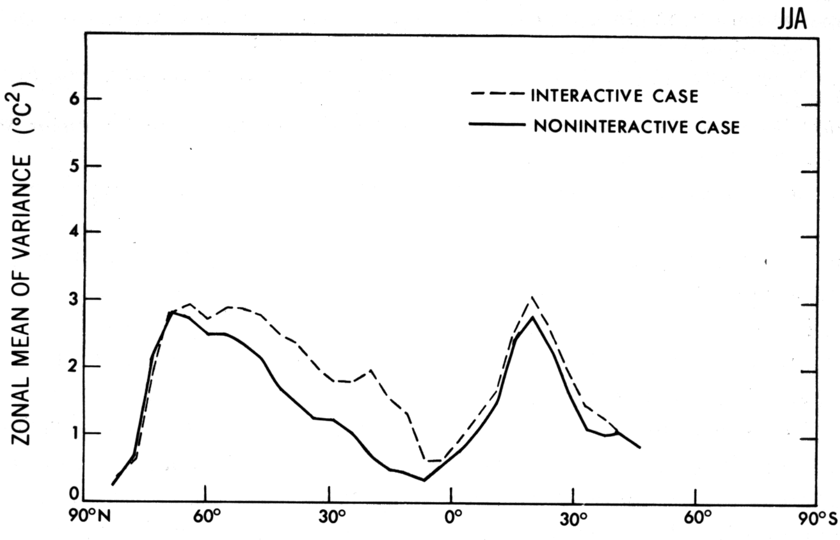


Fig. 3. Zonal means over land of the variance of monthly mean surface air temperature for the interactive and noninteractive experiments. The variances were computed using data from the Northern Hemisphere summer months (JJA) only.

air temperature seems to be more sensitive to the inclusion of interactive soil moisture at low latitudes than at high latitudes. This is a consequence of the fact that potential evaporation is larger at low latitudes than at high latitudes.

In summary, the temporal variability of soil moisture is largely controlled by the climatic values of potential evaporation and precipitation. Time series of soil moisture possess large amounts of variance at low frequencies, suggesting that interactions between soil moisture and the atmosphere have the potential to make substantial contributions to low frequency atmospheric variability. This possibility is supported by the results of a second GCM integration, documenting the effect of interactive soil moisture on the variance of surface air temperature.

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