# Influence of Soil Moisture Anomaly on Temperature in the Sahel: A Comparison between Wet and Dry Decades

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ABSTRACT

The influence of the Sahelian drought and resultant soil moisture deficit on air temperature is explored, using a simple water balance model that was validated with multiyear observations of the root-zone soil moisture. A comparison between wet soil years in the 1950s to 1960s and dry soil years in the 1970s to 1980s demonstrated a series of processes by which precipitation anomalies during the rainy season of a few months influence the time-lagging temperature through soil moisture. These processes were clearly seen only during the beginning 1 or 2 months of the dry season, and then both the concurrent soil moisture and temperature anomalies disappeared. Thus, the timescale of the drying up of root-zone soil moisture anomalies was determined to be approximately 1.5 months. This suggests that the root-zone soil moisture does not act as a memory of rainfall anomaly into the following rainy season and is not related to the long-term persistence of the drought.

## 1. Introduction

The Sahel, the semiarid region located south of the Sahara desert, experienced recurring droughts during the twentieth century, including a long-term persistent drought during the late 1960s into the 1980s. In particular, the recent multidecadal decline in the rainfall is a unique phenomenon in the worldwide perspective that draws much scientific attention. Since the 1970s, a large number of observational and numerical simulation studies have been conducted on the causes of such a long-term decline in the rainfall. These studies have examined large-scale sea surface temperatures (SSTs; e.g., Folland et al. 1986; Wolter 1989; Hastenrath 1990; Shinoda and Kawamura 1994; Rowell 1996; Janicot et al. 1996) and regional land surface conditions (e.g., Charney 1975; Entekhabi et al. 1992; Xue and Shukla 1993; Zeng et al. 1999; Wang and Eltahir 2000). The latter factor has long been examined, previously by investigating sensitivity to prescribed land surface changes with atmospheric general circulation models (AGCMs; Charney 1975; Xue and Shukla 1993) and recently with new models coupling interactive vegetation and atmosphere (Zeng et al. 1999; Wang and Eltahir 2000). Simulations by the coupled models suggested that the interactive vegetation, as a component of land surface conditions, acts to enhance the interdecadal variations including the recent long-term drought. Compared with these modeling approaches, very few observational studies have, however, been made of the land surface–atmosphere interaction over the Sahel (Lare and Nicholson 1994; Taylor et al. 1997; Shinoda and Gamo 2000), especially on the interdecadal scale. With this background in mind, we present observational evidence of the influence of soil moisture on the overlying air temperature in relation to the interdecadal drought.

From a climatological point of view, soil moisture acts as a memory of anomalies in the land surface water budget and, in turn, it has a delayed and durable influence on the overlying atmosphere through the land surface fluxes of heat and moisture. The model calculation of the monthly surface water balance (Lare and Nicholson 1994) showed that the interdecadal changes in evapotranspiration, and hence latent heating over the Sahel during the rainy season were sufficiently large to alter the latitudinal thermal pattern of the overlying atmosphere over West Africa. As for the United States, a number of investigations have been made to present observational evidence of strong negative correlation between the model-computed soil moisture and surface air temperature for the warm season, particularly over inland, nonarid areas (Walsh et al. 1985; Karl 1986; Chang and Wallace 1987; Williams 1992; Georgakakos et al. 1995; Huang et al. 1996; Durre et al. 2000).

The above-mentioned studies for the Sahel and United States focused primarily on the relationships between the soil moisture/evapotranspiration and temperature for

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specific seasons such as the rainy and warm seasons. When considering mechanisms causing such a multiyear drought, we, first, have to examine the existence of soil moisture anomalies acting as a memory of rainfall anomalies from a rainy season, through the dry season, to the following rainy season. Thus, a detailed soil moisture time series including the rainy and dry seasons on the interdecadal timescale is produced, based on the 4-yr soil moisture observations and modeling in the Sahelian Niger. Second, using the time series, we investigate the processes by which the soil moisture anomaly affects the overlying air temperature. These are central problems of the present study.

In section 2, we describe hourly soil moisture observations at a Sahelian station. (These original observations are partly shown in Fig. 4c.) In section 3, we examine the continental-scale correlation between precipitation and temperature on a monthly basis. The monthly data is used here because this is available widely over Africa. In section 4, we outline a simple soil moisture model that was proposed for climate-change studies and drought monitoring (Yamaguchi and Shinoda 2002). (Although this model calculation was conducted on a daily timescale, the monthly averages are presented in Figs. 2 and 3d to highlight a general interannual tendency.) In section 5, to determine detailed timings of occurrence of soil moisture and temperature anomalies, we produce the time series on a 10-day basis.

## 2. Study area and soil moisture observations

Detailed soil measurements have been performed as the soils program of the Hydrological Atmospheric Pilot Experiment in the Sahel (HAPEX-Sahel) in Niger mainly during a limited intensive observation period of August–October 1992 (Cuenca et al. 1997). The soil moisture observations of this program were used for validating the water balance model (Lare and Nicholson 1994) that was applied on daily timescales (Nicholson et al. 1997).

We made a field measurement of hourly volumetric water content at the meteorological observation site of the Japan Green Resources Cooperation (JGRC) of Magou (13°07′N, 1°44′E), located about 75 km southwest of Niamey (Fig. 1), from July 1995 to the present (Iwashita et al. 1999; Shinoda et al. 2002). (The original data are displayed in Fig. 4c.) This area is located in the sandy lowlands, covered mainly with *Guiera senegalensis* L. shrubs and cultivated rainfed millet. In our previous study, we used the measurements from 1996 to 1999 for the soil moisture modeling (Yamaguchi and Shinoda 2002).

The soil moisture (W) measurement has been conducted, automatically every hour, at 20- and 40-cm depths, based on the time domain reflectometry (TDR) principle. The near-surface soil layer for the measurement coincides with that of the major root zone of the vegetation representing this area (Hanan and Prince 1997). This soil layer exhibits a marked seasonal cycle (Cuenca et al. 1997) and most likely interacts with the overlying atmosphere. The soil in the layer is comprised of similar grain-size compositions of 84% sand, 8% silt, and 8% clay, and is classified as loamy sand under the U.S. Department of Agriculture (USDA) system (Soil Survey Staff 1962) and as luvic Arenosol in the United Nations Food and Agriculture Organization (FAO) system (FAO-UNESCO 1977). This type of surface soil is widely distributed over the Sahel and is representative of this region.

## 3. Correlation between precipitation and temperature

Figure 1a shows simultaneous correlations of temperature (T) and precipitation (P) for September. The data source is the Global Historical Climatology Network version 2 [see Vose et al. (1992) for version 1]. The details of the temperature dataset are found in Peterson and Vose (1997). On a climatological basis, in the Sahel, P is concentrated on the major rainy months of June–September and T exhibits a yearly maximum around May and a secondary maximum around October. These months correspond to the end and beginning of the dry season, respectively. In the present study, we highlighted the ending month of the rainy season, September, because the T for this month tends to be substantially influenced by soil moisture anomalies accumulated during the preceding rainy months.

As shown in Fig. 1a, there are significant negative correlations with an east–west-oriented axis covering the Sahelian zone. A similar pattern with a high significance is also observed between the T for September and P for the preceding months of July–August (Fig. 1b). Note that Niamey, on which our analysis is focused later, is located in the central zone with the significant negative correlations in Figs. 1a,b (see arrows). These results suggest that the Sahelian T for a rainy month may be influenced by the real-time and time-lagging effects of P. The former is likely to include a simultaneous albedo effect of clouds that reflect incoming solar radiation. That is, increased (decreased) P is associated with increased (decreased) clouds, leading to decreased (increased) incoming solar radiation and T. On the other hand, both the real-time and time-lagging effects may be owing, in part, to the soil moisture that functions as a memory of the preceding P anomaly and affects the overlying air temperature through heat fluxes at the ground surface. From the time-lagging effects, we can rule out an apparent effect of an autocorrelating nature of P anomaly between July–August and September, because we observe no significant autocorrelations covering the entire Sahel (Fig. 1c).

## 4. Soil moisture modeling

The elucidation of the time-lagging processes requires an estimate of actual soil moisture over decades that

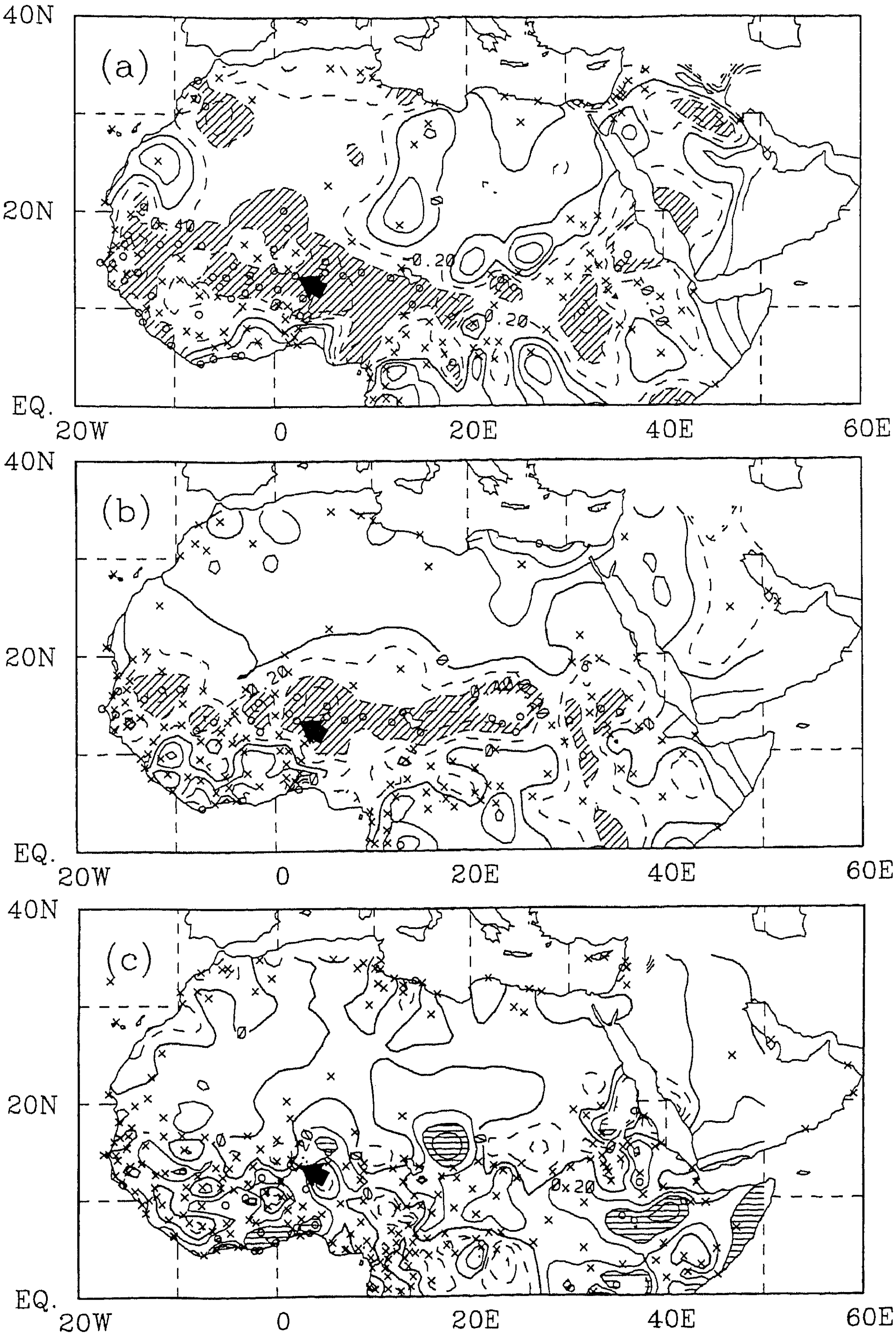

FIG. 1. Correlations of monthly temperature (T) for Sep with (a) precipitation (P) for the same month and (b) P for the preceding Jul–Aug during 1961–90. (c) Auto/lag correlations of P for Sep with P for the preceding Jul–Aug. The solid lines denote positive correlations and dashed lines, negative correlations. The contour interval is 0.2. The horizontal (oblique) hatching denotes correlations above 0.4 (below −0.4). The circles (crosses) indicate observational stations with correlations significant (not significant) at the 5% level. Niamey in Niger is indicated by arrows.

has not been observed operationally. For this purpose, we proposed a simple water balance model having one layer for climate-change studies and drought monitoring (Yamaguchi and Shinoda 2002). This model calculates absolute soil moisture amounts using only daily P and T data. Similar approaches have been made for the United States, as were found in some of the studies cited in the introduction. The studies, focusing on long-term climate changes, do not necessarily require a soil moisture model incorporating a variety of complex land surface processes. This is because the complex models require a detailed meteorological dataset as various input variables that has not usually been available for decades. We prefer the simplicity in the modeling for our purpose. The model used here is expressed in the following equation:

$$\frac{dW(t)}{dt} = P(t) - E(t) - R(t) \tag{1}$$

$$\begin{aligned} R(t) &= W(t) - W_{\mathrm{fc}} \qquad && W(t) > W_{\mathrm{fc}}, \\ R(t) &= 0, && W(t) \leq W_{\mathrm{fc}}, \end{aligned} \tag{2}$$

where $W$, the plant-available soil moisture, is expressed as the equivalent depth of liquid water (mm) that exists from the surface to a 50-cm depth and $t$ is the time in days; $P$, $E$, and $R$ are the daily precipitation, evapotranspiration, and runoff. Here, the daily maximum values are used as the observed $W$ in order to extract a peak in response to intensive rainfall in the Sahel (Shinoda et al. 1999). The soil is assumed to have one layer that has a field capacity ($W_{\mathrm{fc}}$). For this model, if $W$ exceeds $W_{\mathrm{fc}}$, the excess is assumed to be runoff ($R$). The evapotranspiration ($E$) varies with $W$ such that

$$E(t) = \overline{E}\frac{W(t)}{\overline{W}} = \frac{W(t)}{\tau}, \tag{3}$$

where $\tau$ is interpreted as a residence time or turnover period that signifies the time required for a volume of water equal to the annual mean of exchangeable $W$ to be depleted by $E$. The actual value of $\tau$ is a function of the soil properties, including the wilting point ($W_{\mathrm{wp}}$), field capacity ($W_{\mathrm{fc}}$), and the potential evapotranspiration rate (PET). The PET was calculated on a daily interval through the Thornthwaite (1948) formula in the following equation (Mintz and Walker 1993):

$$\mathrm{PET} = \begin{cases} 0, & T < 0^\circ\mathrm{C} \\ \left[0.553\left(\dfrac{10T}{I}\right)^{a}\right]\dfrac{h}{12}, & 0 \leq T \leq 26.5^\circ\mathrm{C}, \\ (-13.86 + 1.075T - 0.0144T^2)\dfrac{h}{12}, & T > 26.5^\circ\mathrm{C} \end{cases}$$

$$I = \sum_{1}^{12} i, \qquad i = \left(\frac{T_m}{5}\right)^{1.514}, \qquad i_{\min} = 0,$$

$$a = (6.75 \times 10^{-7} I^3) - (7.71 \times 10^{-5} I^2) + (1.79 \times 10^{-2} I) + 0.492, \tag{4}$$

where $T$ is the daily mean air temperature; $T_m$ the monthly mean air temperature; $h$ (h) the length of daylight; $I$ the annual heat index. In this formula, the PET is dependent only on temperature; thus this simple method is applicable to the past decades when detailed meteorological observations were not performed. The Thornthwaite PET coincided fairly well with the Penman (1963) potential evaporation during the months excluding the middle dry season when the PET estimate has significance in calculating soil moisture (Yamaguchi and Shinoda 2002).

As shown in Fig. 2, the efficiency of this model is validated by a comparison with the 4-yr W observations. For this comparison, the monthly interval is used to examine a general interannual tendency. Moreover, interdecadal trends are also investigated on the monthly timescale in section 5. In general, the model simulates the variations on the seasonal and interannual timescales reasonably well. The correlation coefficient between the observed and estimated Ws on the monthly basis is 0.95, being highly significant, and the root-mean-square error is 9.2 mm. The 4 yr of W observations include the second wettest (1999) and ninth driest (1997) years from 1963 to 1999 (with the respective normalized anomalies of +1.9 and −0.8) at the nearest station, Torodi. Although the observational period was only 4 yr, this period provided an opportunity to investigate a wide range of climate changes that occurred on an interdecadal scale.

## 5. Interdecadal time series

Figure 3 represents the interdecadal time series of T and P for Niamey that is located in the zones of climatic, vegetation, and soil types similar to those at Magou. It is clearly seen that the annual T revealed an increasing

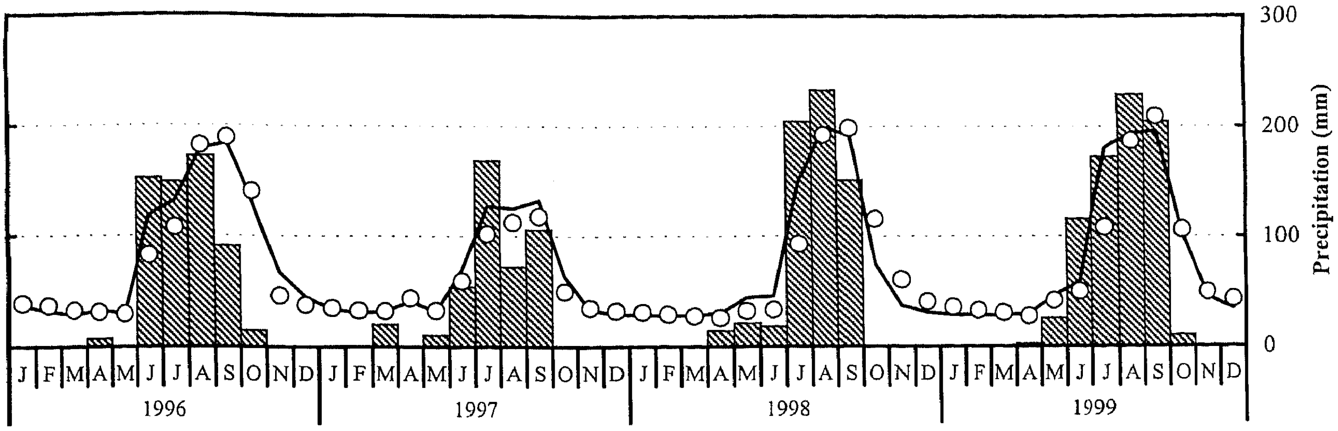

FIG. 2. Monthly based time series (1996–99) of P (mm; bar) and observed soil moisture (W) (mm; circle) at Magou, along with W calculated based on a water balance model (solid curve). The W is expressed as the equivalent depth of liquid water (mm) that exists from the surface to 50-cm depth with a constant value of daily maximum volumetric water content averaged at 20- and 40-cm depths. The daily W values were averaged over a monthly interval.

trend during the recent five decades (Fig. 3a), in conjunction with the decreasing trend in the annual P (Fig. 3b). Focusing on the end of the rainy season, September, the T and P exhibited trends (Figs. 3c,d) similar to those on the annual basis (Figs. 3a,b). The correlation coefficients between T and P on the annual basis and for September during 1950–94 are 0.67 and 0.57, respectively. What should be considered here is the mechanism correlating the T and P trends on the interdecadal scale. We described these time series as interdecadal trends. On the other hand, they can be regarded as regime shifts from the wet to dry mode that occurred as abrupt changes around 1970 (Wang and Eltahir 2000; Nicholson and Grist 2001). This problem is beyond the scope of the present study.

Figure 4 shows the time series of solar radiation ratio, air T, ground surface T, P, and observed W at the 20-cm depth. The daily solar radiation ratio is defined as the ratio of daily total global solar radiation to the maximum value within the period analyzed that occurred on 9 June. This ratio is used here to identify a fine weather day. The figure illustrates how the air and ground surface Ts responded to the W variation on a fine weather day prior to and following a rainfall event during the early rainy season. The W exhibited a sharp increase in response to the first heavy precipitation exceeding 40 mm on 24 June. This led to drastically reduced air and ground surface Ts. These were manifested specifically in the daily maximum values, compared with the daily minimum. The amplitudes of diurnal variations in the air and ground surface Ts were also reduced after the rainfall event. An additional analysis for the rainy season revealed that the correlation of the W with the daily maximum air T is stronger than those with the daily minimum and amplitude of diurnal variation. Thus, focus is placed on the daily maximum air T in the following analysis.

Comparison between fine weather days prior to and following the rainfall event suggests that the reduced daily maximum air T is due to increased W, and thus increased latent heat flux from the ground surface to the atmosphere and decreased sensible heat flux during the daytime. With this regard, we used the daily maximum value of air T as a proxy of the daytime sensible heating of the atmosphere from the ground surface for the following interannual analysis. The solar radiation is not a determinant for the reduced T, because the solar radiation for a fine weather day did not differ substantially prior to and following the rainfall event (Fig. 4a).

Figure 5 displays a comparison of seasonal changes in T, P, and estimated W on the 10-day basis between the wet and dry soil years for Niamey. These 8 yr are chosen from Fig. 3d in terms of large above- and below-normal W anomalies without substantial P anomalies in September, in order to eliminate the simultaneous albedo effect of clouds as described earlier. In this context, we did not choose very wet soil years such as 1952 and 1967, because these years also had extremely large rainfall. If we include those years for the wet soil composite, it becomes difficult to distinguish the effects of the wet soil and large rainfall (namely, large amount of clouds) on temperature. The wet and dry years are selected so as to be concentrated on the 1950s to 1960s and 1970s to 1980s, respectively, for examining the interdecadal changes. This analysis was conducted to answer questions about how long the W anomalies, occurring on the interdecadal timescale, lasted from September to the following dry season and how those anomalies influenced the overlying air T.

Magou and Niamey are located in the similar soil zone; the same soil parameters used for Magou ($W_{fc}$ and $W_{wp}$) were applied to the W calculation for Niamey (Fig. 5b). Interestingly, marked differences between wet and dry years in daily maximum T emerged during late July (Fig. 5a), in conjunction with the simultaneous appearances of substantial P and W differences (Fig. 5b), and they disappeared as the W differences did so during the early dry season of late October. The maximum T dif-

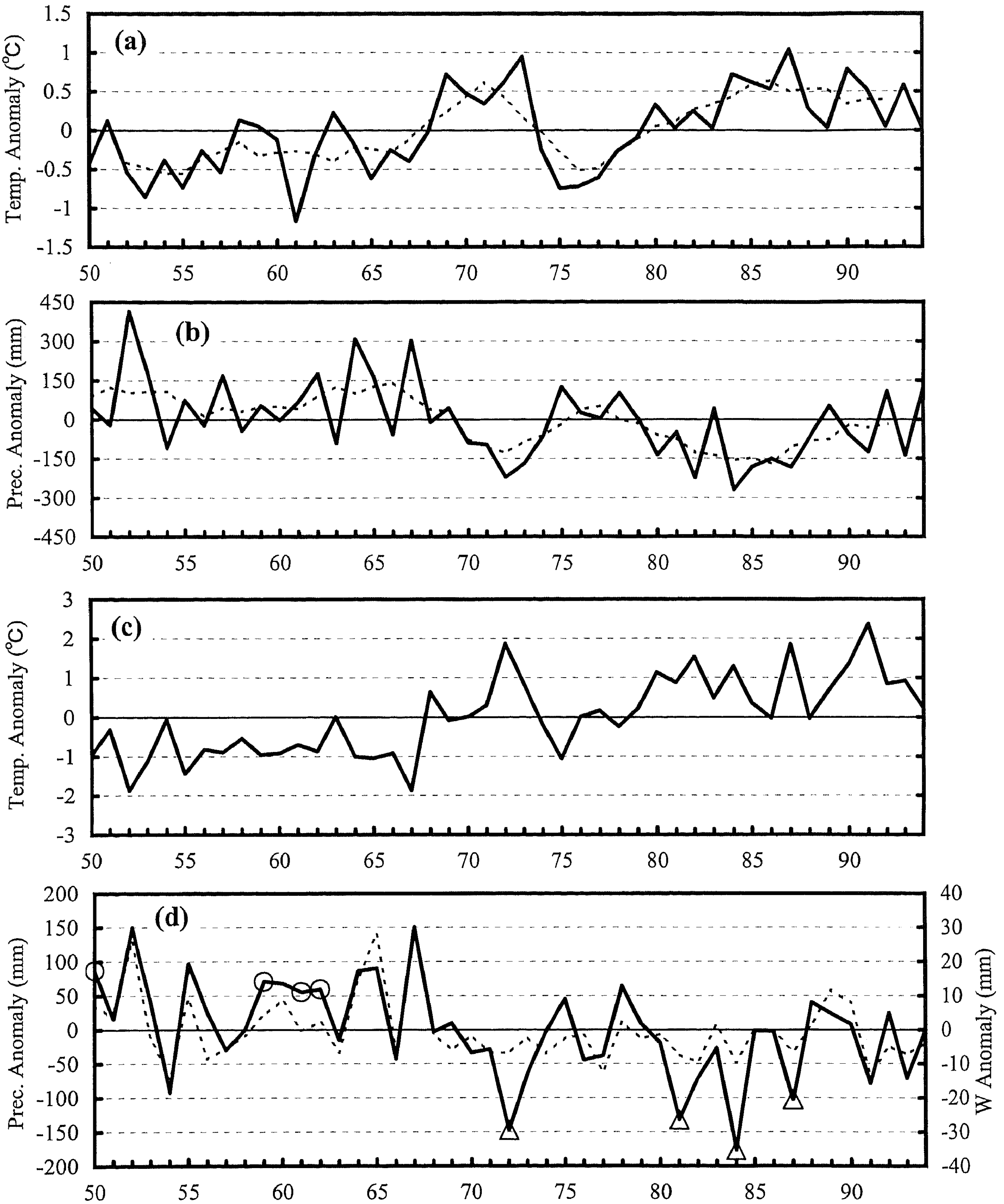

FIG. 3. Interannual time series (1950–94) of anomalies of (a) annual mean T, (b) annual total P, (c) monthly mean T, and (d) monthly total P (mm; dashed curve) and monthly mean W (mm; solid curve) for Sep at Niamey. The dashed curves in (a) and (b) denote 5-yr running means. The circles and triangles in (d) indicate the respective wet and dry soil years used for the composite analysis in Fig. 5.

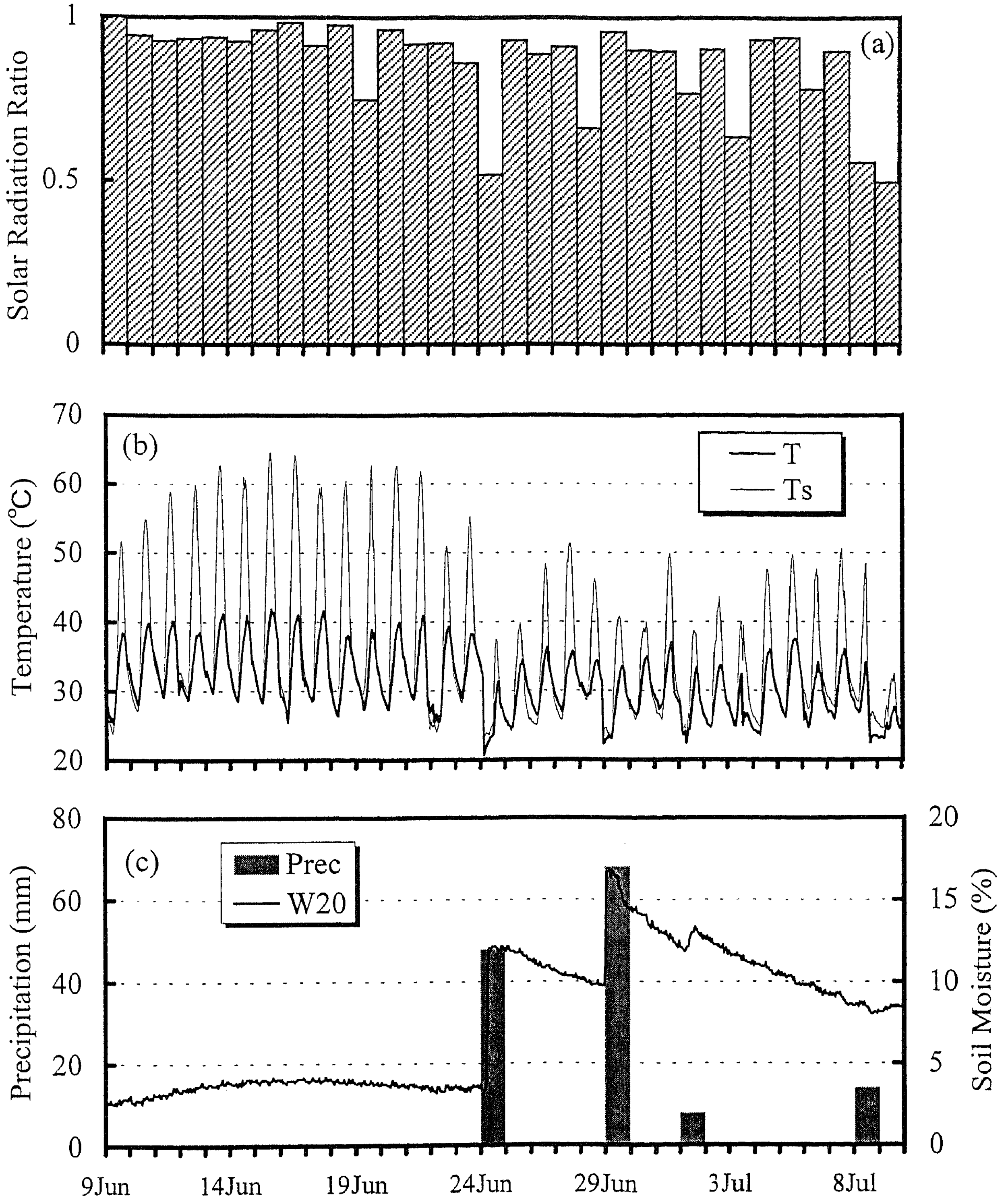

FIG. 4. Time series of (a) daily solar radiation ratio, (b) hourly air (T, thick curve) and ground surface ($T_s$, thin curve) Ts (°C), and (c) daily P (mm) and observed hourly W at the 20-cm depth ($W_{20}$) in volumetric water content (%) for the Magou site during the early rainy season of 1999.

ference (4.1°C) occurred during mid-August. Also, the daily mean T exhibited differences similar to those of the daily maximum, although the amplitude of the differences was smaller. A substantial P difference occurred last in mid-September and then the W differences of the same sign remained about 1.5 months. In other words, the W acted as a memory of the P anomalies during the early dry season. Then, the W anomalies attenuated toward the middle dry season when no precipitation occurs.

Since we chose the wet and dry soil years for the composite analysis as explained above, there were small

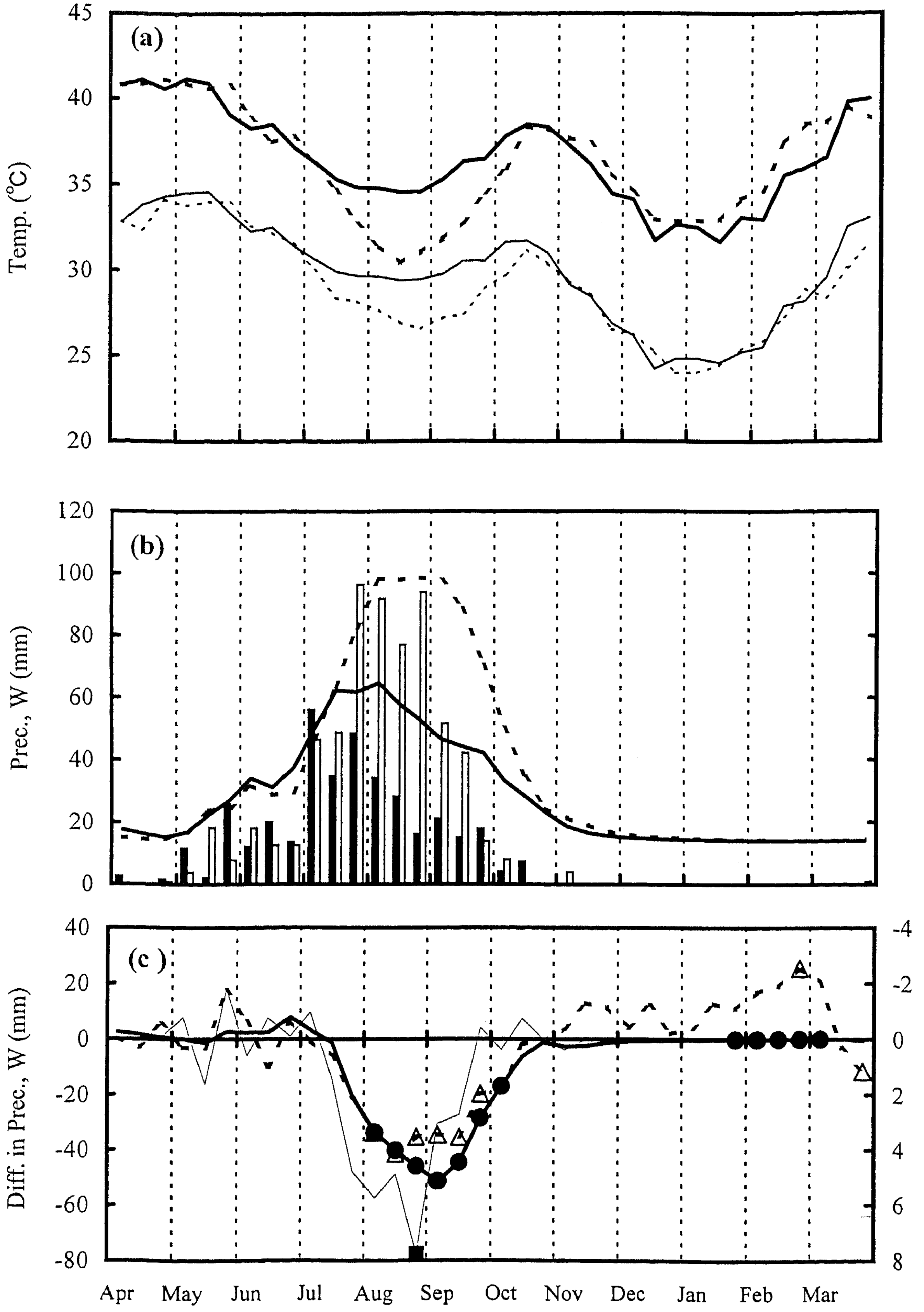

FIG. 5. The 10-day-based seasonal changes in (a) daily maximum and daily mean Ts (°C) and (b) precipitation P (mm)(10-day)$^{-1}$ and estimated W (mm); comparison between the composites of 1950, 1959, 1961, 1962 (wet soil years, dashed curves and white bars) and 1972, 1981, 1984, 1987 (dry soil years, solid curves and black bars), and (c) their differences. The differences in P, estimated W, and daily maximum T are denoted by the thin solid, thick solid, and dashed curves in (c), respectively. The square, circle, and triangle symbols indicate the 5% significance of the differences for the P, W, and T, respectively.

differences in P in September. Thus, during September and October, both differences for W and T are significant, but not that for P (Fig. 5c). The correlation between W and T lasted into the dry season until the end of October. This indicates that not only the substantial soil moisture anomaly but also its effect on T remained about 1.5 dry months following the rainy season. The T and estimated W are not necessarily independent here, because the estimated W is, in part, a function of T through the calculation of the Thornthwaite PET. Nevertheless, as explained in Fig. 4, we highlighted a different aspect of temperature (the daily maximum value) that is more directly related to the daytime sensible heating than the daily mean value used for the PET calculation. That is, dry (wet) soil led, likely through increased (decreased) sensible heating and simultaneously decreased (increased) latent heating, to high (low) daily maximum T, occurring during the daytime.

A statistical test indicated significant W differences for late January to early March having the same sign as that found in the preceding rainy season. This means that during the period, all the W values for 4 yr of the wet soil composite are systematically larger than those for 4 yr of the dry composite. However, the amplitude of the differences between the composites is only in the range of 0.02–0.2 mm, that is, 0.004%–0.04% in volumetric water content of the top 50-cm layer. These W values appear to be negligibly small, not having a substantial influence on the overlying air T. In fact, during late January to early March, the W–daily maximum T correlation is positive; daily maximum T is larger when W is larger and vice versa. This relationship is the opposite of that observed during the rainy season. The statistical significance occurred because during the middle dry season—when no precipitation forcing exists—slightly higher daily mean (not daily maximum) Ts (Fig. 5a) and thus higher PET [see Eq. (4)] resulted in lower W, and vice versa. At late February and late March, two significant differences of daily maximum T, having opposite signs, appeared sporadically. Considering that no substantial W differences occurred at the periods, those T differences may be attributed to factors other than land surface conditions such as atmospheric advection.

## 6. Conclusions and discussion

The present study showed observational evidence of the influence of the Sahelian drought and resultant soil moisture deficit on air temperature. The timescale of the drying up of root-zone soil moisture anomalies was determined as approximately 1.5 months. For the soil moisture calculation, we proposed a new water balance model that runs with input of only daily P and T. The model development was based on the unique multiyear observations of the root-zone soil moisture. Although our analyses were limited to two stations (Niamey and Magou), they are considered to represent the Sahelian zone in terms of the P–T correlations (Fig. 1) and the climatic/vegetation/soil characteristics as mentioned earlier. Moreover, the water balance model used here is applicable to other Sahelian stations for deriving large-scale soil moisture, if we know the two soil parameters (the field capacity and wilting point), along with daily P and T data.

Evidence demonstrated a series of processes—by which the precipitation anomaly influences the time-lagging temperature anomaly through soil moisture—that has previously been suggested by GCM studies, but not confirmed based on observations for the Sahel. That is, increased (decreased) P is accumulated as increased (decreased) soil moisture with a time lag, leading to decreased (increased) sensible heating and simultaneously increased (decreased) latent heating and finally to low (high) daily maximum T. For the United States, previous studies have provided similar observational evidence that soil moisture anomalies correlate strongly with summer surface air temperature and, in particular, daily maximum temperature in inland regions (Williams 1992; Georgakakos et al. 1995; Huang et al. 1996; Durre et al. 2000).

Comparison between the wet and dry decades revealed that the processes described were clearly seen only during the beginning 1 or 2 months of the dry season, and then both the concurrent soil moisture and temperature anomalies disappeared during the middle dry season. Thus, the soil moisture anomaly does not act as a memory of rainfall anomaly into the following rainy season. The drying-up timescale of 1.5 months for the root-zone (50 cm) soil moisture in the tropical semiarid Sahel is shorter than the decay timescale of 2–3 months related to the atmospheric forcing for the top 1-m soil moisture in the extratropics (Vinnikov and Yeserkepova 1991; Vinnikov et al. 1996; Entin et al. 2000). The latter timescale was measured as the lag at which the autocorrelation function reduces to $1/e$, as first theorized by Delworth and Manabe (1988). The quick drying-up for the Sahel is attributable to high evapotranspiration during the early dry season with relatively high temperatures. The low persistence of soil moisture anomaly for the Northern Hemisphere summer season was also simulated by AGCMs coupled with a bucket model (Delworth and Manabe 1989) and a more complex land surface model (Koster and Suarez 2001). In addition to high evapotranspiration, small field capacity, occurring in arid areas due to the poorly developed root zone of vegetation, contributes to the short soil moisture memory (Koster and Suarez 2001).

We can, therefore, conclude that the root-zone soil moisture may not have a direct effect on the long-term persistence of the Sahelian drought through the soil moisture/precipitation recycling. This conclusion was based on the composite analysis for the wet and dry soil years in section 5 that excluded a year having substantial precipitation during the late rainy season. However, even during the dry season, occasional rains may occur due to the equatorward invasion of a rain-bearing extratropical disturbance. In this case, the rains function as an external forcing and create a new land surface anomaly with more vegetation (Shinoda and Gamo 2000). This land surface anomaly is possibly accompanied by more soil moisture.

Despite the above conclusion, we do not rule out possible effects of land surface conditions on the long-term persistent drought. Soil moisture at depths deeper than 1 m continues to decrease during the entire dry season (Gaze et al. 1998), providing a basis for the survival of deep-rooted perennial plants of dry ecosystems. A comprehensive review paper on the soil moisture–atmosphere interaction by Entekhabi et al. (1996) pointed out the importance in consideration of the depth of soil moisture that interacts with the atmosphere. This is because there are sharp vertical gradients in soil moisture near the surface, especially in the semiarid region such as the Sahel.

A coupled vegetation–atmosphere model simulated the phenomenon that the underground structures of perennials in the Sahel remain alive during the dry season, providing a multiyear memory of climate anomaly (Wang and Eltahir 2000). Thus, it is likely that the deep-layer soil moisture and perennial plants would act as a memory of rainfall anomalies. Nevertheless, our observations of the root-zone soil moisture strongly suggested that the annual plants and near-surface soil moisture do not have a memory of rainfall anomalies. In addition, as stated above, the large-scale SST pattern is a potential external cause of the interdecadal drought.

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