

A Role of the Soil Enthalpy in Land Memory*

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ABSTRACT

Recent studies have identified a connection between the summer monsoon rainfall in the southwest United States and anomalies of the antecedent winter precipitation and snowpack in the northwest United States. This connection shows a seasonal-scale predictability of the precipitation and indicates a seasonal predictability of the land–atmosphere system (the “land memory”) in the western United States. Although some efforts have been devoted to understanding this predictability, the physical processes constituting it remain unexplained. In this empirical study, a potential source, the soil enthalpy, and its role in land memory are examined for the recent epoch of a strong land memory (1961–90). The rationale is that the soil enthalpy variation has magnitudes comparable to the atmospheric enthalpy changes at various time scales, and the soil enthalpy anomaly in the top 20–50-cm soil column can persist for 2–3 months. As shown by the major results of this study, a persistent negative anomaly of the soil enthalpy in the northwest United States is related to negative anomalies of the surface and the lower-troposphere temperature in that region. Subsequently, the lower-troposphere temperature and related higher-atmospheric pressure anomalies in the northwest United States during late spring and the early summer months encourage a northward position of the lower-troposphere monsoon ridge in the western United States and, therefore, create a circulation that favors an above-average monsoon rainfall in the southwest United States. A weaker summer monsoon occurs when a sequence of opposite anomalies develops after a warm and dry winter in the northwest United States. In this regard, the soil enthalpy variations may serve to “record” the winter precipitation and temperature anomalies and “release” their effects on summer monsoon rainfall through interactions of soil enthalpy with the surface and lower-troposphere temperatures.

1. Introduction

Recent studies of the North American summer monsoon (July through September) have identified a connection between monsoon rainfall variation and the anomaly of the antecedent winter snow amount and accumulation in the western United States; an above-average winter snow in the northwest and below-average precipitation in the southwest United States correspond to above-average summer monsoon rainfall in the southwest United States, and a reversed anomaly pattern leads to a below-average summer monsoon rainfall (Gutzler and Preston 1997; Higgins et al. 1998; Hu and Feng 2002). This relationship indicates that some land processes could have “recorded” winter season anomalies in atmospheric circulation and precipitation and “released” their effects on the monsoon rainfall in the following summer, highlighting a predictability of inter-

seasonal scale in the land–atmosphere system of the western United States. These yet-to-be-discovered land processes and their constituted predictability have been coined “land memory.”

In understanding the land memory, most studies have focused on the roles of winter snow anomaly and related spring and summer soil moisture and surface water flux variations (Higgins and Shi 2000; Entin et al. 2000; Lo and Clark 2002; Robock et al. 2003). Indeed, soil moisture variation can affect the local hydrological cycle and cause variations in the surface albedo, energy budget, and atmospheric circulation of various spatial scales (e.g., Pielke and Zeng 1989). However, those anomalies develop almost simultaneously with changes of the soil moisture—quite different from the case of land memory, in which the monsoon circulation anomaly appears several months after the antecedent winter precipitation anomaly. To have such a lagged response in monsoon rainfall, the winter precipitation anomaly would have to sustain its effect into the summer season (Bamzai and Shukla 1999). Recent investigations have found that the soil moisture anomaly in the top 1-m soil column could persist up to 1.8 months after the spring snowmelt (in April)—a persistency that is too short to account for land memory (Entin et al. 2000; Robock et al. 2003).

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A more intriguing finding has been made by Robock et al. (2003), who show that the soil moisture anomalies in the Eurasian region had virtually no correlation with the winter snow amount, possibly because snowmelt occurred before the top soil layer thawed and snow water could have been lost in surface runoff. A similar result would be expected in the high-elevation regions in the western United States. These results show a rather weak connection of spring and summer soil moisture anomaly with winter snow anomaly. Thus, the soil moisture may not play a substantial role in the land memory. This leads to the proposition that the land memory contains additional sources of land process linking the antecedent winter precipitation anomaly in the western United States with summer monsoon rainfall variation in the southwest United States.

A potential source is the soil heat content, which affects the surface heat flux and also interacts with soil moisture to affect surface water flux. The role of soil heat content and soil enthalpy in regional climate variations is revealed in a scale analysis in Tang (1989). Using long-term soil temperature data from a station in St. Paul, Minnesota, Tang analyzes the variations of the soil enthalpy (soil heat content per unit mass), $\int c_p T \rho dz$, where T is soil temperature, c_p is the soil specific heat capacity at constant pressure, ρ is soil density, and z is the depth in a soil column. He shows that the amplitude of the variations in average annual soil temperature in a soil column from the surface to 5 m below is 11.3 K. This change corresponds to an annual soil enthalpy variation of $1.1 \times 10^4 \text{ J cm}^{-2}$ in the soil column [using average soil density of 2.0 g cm^{-3} and constant specific heat capacity of 1.0 J (g K)^{-1}], close to the annual enthalpy change of the entire atmospheric column, $1.5 \times 10^4 \text{ J cm}^{-2}$, and indicating the soil enthalpy as a considerable energy source for variations of atmospheric temperature in land areas. Additional evidence provided in Tang and Reiter (1986) and in Retnakumari et al. (2000) also suggests that the soil enthalpy could be an important source that affects the regional atmospheric circulation and climate.

A few recent studies have further illustrated a lagged effect of the spring season surface heat flux anomaly on the following summer rainfall variation. For example, Zhao and Chen (2001) and Chen et al. (2003) showed that in the Tibetan Plateau, the late spring surface heat flux anomaly could initiate variations in the surface and lower-troposphere temperatures. Different anomalies in the surface heat flux and temperature proceeded to distinct summer circulation and rainfall anomalies not only in downstream eastern China but also in the Indian summer monsoon region, a result illuminating a role of the land surface processes in extending the winter and spring surface conditions and circulation anomalies to influence the summer rainfall in local and adjacent regions.

Because the variation of the surface heat flux is related to heat flow in the soils, these previous results

suggest that the soil enthalpy anomaly could have affected the surface heat flux and influenced the summer rainfall. However, little is known about the specific connections and interactions between variations of the winter and spring soil enthalpy and surface and atmospheric temperatures and rainfall in the following summer. These connections and the role of the soil enthalpy in the land memory are examined in this empirical study for the western United States and the North American summer monsoon region. Because the intensity of the land memory has been varying in the last century, strong memory was observed in the epochs 1921–30 and 1961–90, whereas weak memory or no memory effect was observed in the epochs 1931–60 and the recent years since 1990 (Hu and Feng 2002), we will focus on the recent epoch from 1961 to 1990, which possesses a strong land memory. In addition, because of data limitations, particularly a lack of quality surface heat and moisture flux data, we will use reliable data to determine 1) the persistence of the soil enthalpy anomaly, 2) the relationship between variations of the soil enthalpy and the surface and lower-troposphere temperatures in spring and early summer, and 3) the connection of these variations with the summer monsoon rainfall in the southwest United States. From these analyses, we will provide the essential evidence showing the role of the soil enthalpy in constituting the land memory.¹

After resulting from winter precipitation and temperature anomalies, the soil enthalpy anomaly affects the surface temperature through heat exchange at the surface. This exchange becomes elevated after the snowmelt or after the cold season's rainy period ends in the low-elevation regions of the northwest United States. In the heat exchange, either the upward soil heat flows or soil heat anomaly creates a heat "resistance" to prevent the downward heat flow from the surface to deep soils. The heat flow interacts with the other energy components, for example, the surface radiation, to affect the surface temperature. If the soil enthalpy anomaly persists for several months, this effect can continue over the same period. In that period, the accumulated effect of soil enthalpy anomalies on the surface temperature also could initiate lower-troposphere temperature and associated atmospheric pressure anomalies, which could

¹ A concern may arise on the subject of whether the SST variations in the tropical and North Pacific as well as the SST variations associated with the El Niño–Southern Oscillation could have influenced the roles of soil enthalpy in land memory. Our investigation of this question has indicated that the SST did affect the southwest U.S. summer monsoon rainfall, but the effect was significant only in those epochs when the land memory was weak or could not be observed (1931–60 and the recent years after 1990). In other words, the land memory and associated soil enthalpy and land process effects on the summer monsoon rainfall were deemed to be secondary in the epochs when the SST effect was strong. In the other epochs (1921–30 and 1961–90), however, the SST effect was weak. With a weak SST effect, the land processes became important (see Hu and Feng 2004 for details), and the soil enthalpy anomaly played a major role in the summer monsoon rainfall variation and the land memory.

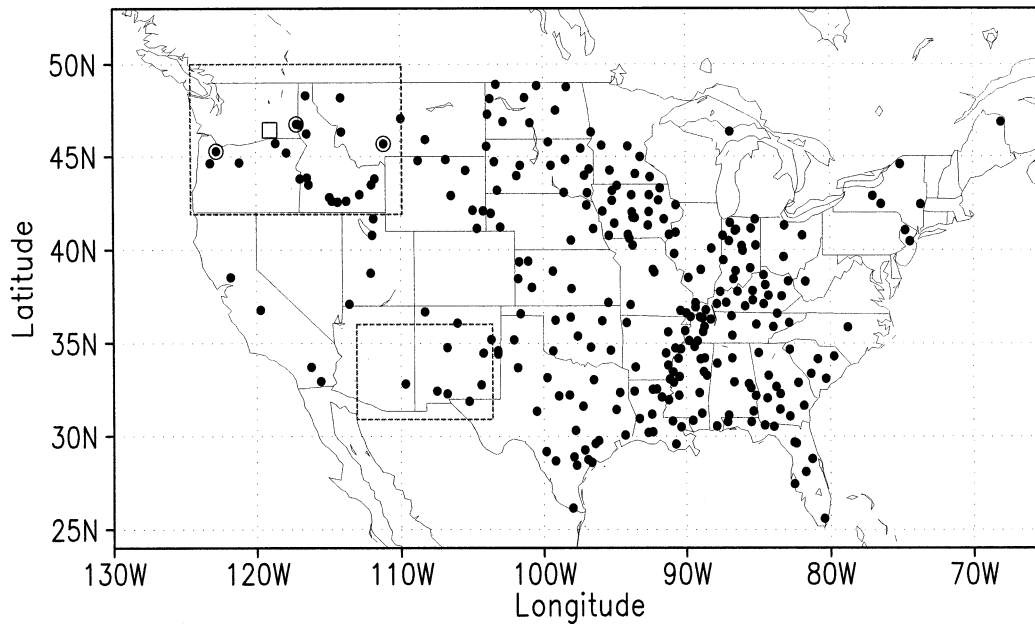


FIG. 1. Geographical distribution of the 292 soil temperature stations whose data are used in this study. The three circled stations in the northwest have daily soil temperature data that qualify and are used for the phase analysis presented in section 3b. The square in southeast Washington marks the location of the Lind station in the U.S. Department of Agriculture (USDA) Soil Moisture–Soil Temperature (SM–ST) Network (Hu et al. 2002). Soil moisture observations at Lind are used later in Fig. 4a. The two boxed regions are the northwest (42° – 50° N, 110° – 125° W) and southwest (31° – 36° N, 104° – 113° W) United States, which are used in analyses and discussions presented in this article.

further affect the summer monsoon circulation and rainfall.

This hypothesis is examined in this study through the following steps: First, we evaluate the persistency of the soil enthalpy anomaly in soil columns of different thickness. (This persistency is compared to that of the soil moisture anomaly in the same column.) Second, we examine the relationship between the variations among anomalies of the soil enthalpy and the surface temperature and determine if the soil enthalpy variations occur prior to changes of the surface temperature in spring and early summer. A leading-phase relationship of the soil enthalpy variation would indicate an effect of the soil enthalpy on the surface temperature. Third, we evaluate the relationship of the surface temperature and the lower-troposphere geopotential height and temperature to examine any connection of the latter with the soil enthalpy. Fourth, if such a connection exists, we use it and additional evidence to articulate the role of the soil enthalpy in the summer monsoon rainfall and thus in the land memory.

The data and methods used in this study are described in the next section. Because we focus on the epoch of 1961–90, we use data for the same period in our statistical analyses except when stated otherwise. Major results of these analyses are presented and discussed in section 3. Section 4 contains a summary of the study and some remarks on the results and future work.

2. Data and methods

a. Data

For this study, we used soil temperature data from 1967 to 1990 at 292 stations in the contiguous United States and snow cover data for the same period in the western United States. The 292 soil temperature stations are shown in Fig. 1. Their data have been quality controlled (Hu and Feng 2003; Hu et al. 2002), and include daily soil temperatures at multiple depths: 5, 10, 20, 50, and 100 cm. However, not all of these depths have temperatures measured at every station. For example, only 43 of the 292 stations have data at a 100-cm depth. Additionally, the length of the soil temperature records also varies among the stations and can be different at different depths for the same station. In spite of such variations, these 292 stations are selected because they have at least 10 yr of soil temperature data at more than one depth during 1967–90.

When using the daily data to calculate monthly mean soil temperature at a depth, we first check for missing daily values in a particular month. A monthly mean value is calculated for that month if 1) its daily data has fewer than 10 missing values and the missing values are scattered in the month, and 2) its daily series has less than 5 consecutive missing values. Otherwise, the monthly mean value is considered missing. The monthly temperatures are then used to calculate monthly soil

enthalpy. The monthly soil enthalpy data are used to calculate the anomalies of monthly soil enthalpy after the annual cycle is removed from the data. When removing the annual cycle from the monthly data, we subtract the long-term mean monthly enthalpy value from the same month's enthalpy in the time series. In the analyses that require daily soil temperature and enthalpy data, we use those stations that have no missing daily observations of soil temperature. Daily soil enthalpy anomalies are calculated from the daily enthalpy data after the annual cycle is removed using the method detailed in Jones et al. (1999). (In section 3, the soil enthalpy anomaly refers to the enthalpy anomaly series without the annual cycle.)

Daily precipitation and surface temperature data for 1961–90 are obtained from New et al. (2000) covering North America from 15° to 60°N. These data have a spatial resolution of 0.5° × 0.5°. Another independent winter precipitation dataset is the snow data. They include daily snow cover thickness, which also describes changes in snow depth and is used to monitor snowmelt in the spring season. The snow data extend over the period 1961–90 and were used in several previous studies (Frei et al. 1999; Clark et al. 2001), which have shown the adequate data quality for this study. Lower-troposphere geopotential height and temperature data are from the NCEP–NCAR reanalysis dataset with a spatial resolution 2.5° × 2.5° and for the period 1961–90.

b. Methods

Soil enthalpy of a column from the surface to a depth, Z , is calculated from (DeGaetano et al. 1996; Beltrami 2001)

$$Q = \int_0^Z C_h T(z) dz, \quad (1)$$

where T is soil temperature and z is the depth (positive downward). The specific heat capacity at constant volume, C_h , of the frozen and unfrozen soil is assumed to be constant and has the values of $1.4 \times 10^6 \text{ J m}^{-3} \text{ K}^{-1}$ and $3.0 \times 10^6 \text{ J m}^{-3} \text{ K}^{-1}$, respectively (Oke 1988; DeGaetano et al. 1996). Because there was no soil moisture measurement at the stations measuring soil temperatures, we have to ignore variations of C_h with respect to soil moisture. The soil enthalpy in (1) is computed numerically using the trapezoidal formula. Because there was no soil temperature measured at the surface (0 cm) and the soil temperatures were measured at separate depths beneath the surface, (1) is integrated using soil temperatures at 5, 10, 20, . . . 100 cm.

We use the following method to measure the persistence of soil enthalpy anomalies: First, we assume that the temporal variation of the soil temperature follows the first-order Markov process, as the soil moisture variation does (Delworth and Manabe 1988; Vinnikov et

al. 1996; Entin et al. 2000). Then, we verify this assumption using results from comparisons of soil temperature variations at all available stations to the behavior of a variable obeying the first-order Markov process, which is characterized by the variable's autocorrelation, r , satisfying

$$r(\delta t) = \exp\left(\frac{-\delta t}{S}\right). \quad (2)$$

In (2), δt is the time lag, and S is the scale of the autocorrelation or the e -folding time of the lagged correlation. Taking the natural log on both sides of (2) and rearranging, we can get $\delta t = -S \ln[r(\delta t)]$, which describes a straight line in the two-dimensional domain of δt and the natural log of autocorrelation, r . This straight line is the "characteristic" of the variable obeying the first-order Markov process. Following this procedure, we calculate autocorrelations of monthly soil enthalpy anomalies at time lags from 1 to 4 months at the individual stations and plot their average autocorrelations in the $\delta t - \ln[r(\delta t)]$ domain. After confirming that the soil enthalpy variation satisfies the Markov process, we calculate the persistence of the soil enthalpy anomaly as the negative inverse of the slope of the characteristic lines (Entin et al. 2000). While the results show the persistence of soil enthalpy anomalies, they also depict the differences from the persistence of the soil moisture anomalies reported in previous studies (Vinnikov et al. 1996; Entin et al. 2000).

When soil heat/enthalpy anomalies persist, anomalies of heat gain or loss in soils in a season could remain and cause anomalies of the heat exchange at the surface in subsequent season(s). This possible mechanism underlies an effect of the soil enthalpy on the surface energy budget and interseasonal variations in regional circulation and rainfall. Moreover, in the heat exchange between the soil, the surface, and the atmosphere, if the soil enthalpy change leads the variation of the surface and lower-troposphere temperatures, it is justified to say that the soil enthalpy anomaly affects the temperature variations through the heat exchange at the surface. Hence, phase differences in the variations of the soil enthalpy and surface temperature can help disclose how the former may have affected the latter, or vice versa, and in which spectrum of frequency in their variations and season such effect is the most significant.

The relationship of the variations in the soil enthalpy and the surface temperature anomalies is examined using the cross-wavelet spectrum analysis (Torrence and Webster 1999). Its unique feature, which justifies the application of this method in this study, is that the method measures the *local* values of both amplitude and phase of each of the two variables continuously through time. These local values at different times can help reveal temporally varying relationships of the phase and coherency of the two variations. These local and temporally varying features of the variations are over-

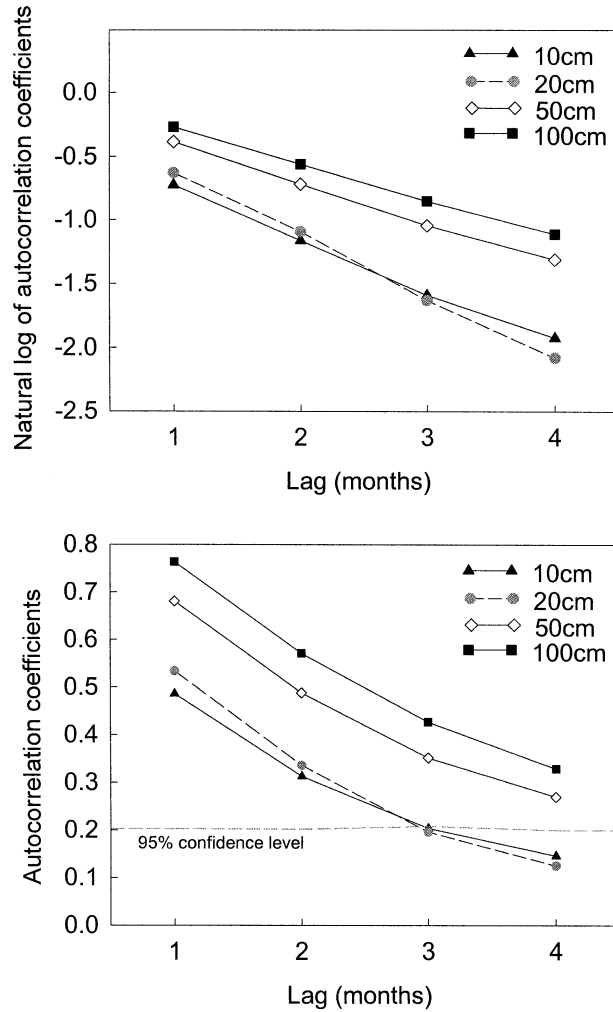


FIG. 2. Relationship of (a) $\ln|r(\delta t)|$ and (b) $r(\delta t)$ vs the time lag, δt , for various thicknesses of soil layers. The dashed line in (b) shows the threshold of significance at a 95% confidence level (based on a two-tailed Monte Carlo test).

looked, however, by other statistical methods, for example, correlation and lagged correlation analysis, which describes an “average” relationship of two variables over a specified time period. Specifically, in the cross-wavelet analysis, the wavelet transforms of the two variations $X(t)$ and $Y(t)$, $W_n^X(s)$ and $W_n^Y(s)$ are used to construct a cross-wavelet spectrum $W_n^{XY}(s) = W_n^X(s)W_n^{Y*}(s)$, where $W_n^{Y*}(s)$ is the complex conjugate of $W_n^Y(s)$, s is the scale, and n is the time index of the transform. As illustrated in Torrence and Webster (1999), the wavelet coherency, R_n , and phase difference of two variations at any given frequency, s , can be determined from $W_n^{XY}(s)$ as, respectively,

$$R_n^2(s) = \frac{|\langle s^{-1} W_n^{XY}(s) \rangle|^2}{\langle s^{-1} |W_n^X(s)|^2 \rangle \langle s^{-1} |W_n^Y(s)|^2 \rangle} \quad \text{and} \quad (3)$$

$$\phi_n(s) = a \tan \left(\frac{\text{Im}\{\langle s^{-1} W_n^{XY}(s) \rangle\}}{\text{Re}\{\langle s^{-1} W_n^{XY}(s) \rangle\}} \right). \quad (4)$$

TABLE 1. Persistence of the soil enthalpy anomaly (second column) in soil columns of different thicknesses. Properties of soil temperature data used in calculations of the persistence are given in columns 3 and 4.

Soil column thickness (cm)	Persistence (month)	No. of stations used in calculation	Average record length of the stations (month)
10	2.1	50	206
20	2.1	46	201
50	3.0	33	194
100	3.5	29	188

In (3) and (4), $\langle \cdot \rangle$ denotes smoothing in both time and frequency, and $\text{Re}\{\langle \cdot \rangle\}$ and $\text{Im}\{\langle \cdot \rangle\}$ in (4) are the real and imaginary parts of $\langle \cdot \rangle$, respectively. Because the phase difference in the variations of the soil enthalpy and the surface temperature is expected in the order of a few days, (3) and (4) are calculated using daily soil and surface temperature data. Additionally, because the wavelet calculations require continuous daily data, only 16 soil temperature stations satisfy this requirement. Among the 16 stations, the 3 in the western United States are circled in Fig. 1.

3. Results

a. Persistence of the soil enthalpy anomaly

Using (2), we calculate the lagged autocorrelations of the monthly soil enthalpy anomalies in soil columns of different thickness between 5 and 100 cm at the 292 stations shown in Fig. 1. The natural log of the station-averaged autocorrelation, $\ln|r(\delta t)|$, for different δt is shown in Fig. 2a. For each soil column of different thickness, a nearly straight line is shown, proving that the soil enthalpy variation is a reasonable first-order Markov process. When we define a residual to be the sum of squares of the shortest distance from each dot to a straight line representing each case in Fig. 2a, the residual is near 0. This accuracy is superior compared to that for soil moisture reported in previous studies and asserts that the soil enthalpy is more relevantly depicted by the Markov process than soil moisture is. Another important feature in Fig. 2a is that the superior accuracy is maintained for time lags longer than that for soil moisture (see figures in Entin et al. 2000). (Individual station autocorrelation was also examined, and it showed similar features as the average in Fig. 2a.)

The persistence of soil enthalpy anomalies is determined by the negative inverse of the slope of the straight line for each case in Fig. 2a. The slope of these lines varies, indicating a different persistence time of the soil enthalpy anomaly in different layers of thickness. These persistence values are given in Table 1. Also in Table 1 is the total number of soil temperature stations used in the analysis and their record lengths, complementing information necessary to support the results. Table 1

shows that the persistence is longer than 2 months for soil enthalpy anomalies in the 20-cm column and increases to longer than 3 months for soil enthalpy in the 50-cm column below the surface. The persistence of the enthalpy anomaly in the 100-cm column is over 3.5 months, much longer than the 1.8-month persistence for the soil moisture anomaly in a soil column of the same thickness (Entin et al. 2000). The increase of the persistence with increase of the soil column thickness suggests an extended effect of soil enthalpy in deeper soils on land surface processes.

A more intuitive way of showing these persistence results is to plot the autocorrelation coefficients of the enthalpy anomaly in different soil columns, albeit these coefficients cannot show whether the variation of the soil enthalpy anomaly follows the first-order Markov process. Nonetheless, we plot these coefficients in Fig. 2b. They indicate that the soil enthalpy anomalies at the 10–20-cm column have statistically significant autocorrelations at a lag over 2 months, and the anomalies in the thicker layers, 50 and 100 cm, have significant autocorrelations of longer time lags. These results are consistent with those derived from Fig. 2a.

By showing that the soil enthalpy anomaly has considerably long persistence, these results indicate that the soil enthalpy could play an important role in the land memory. A speculated process is the following: The persistent soil enthalpy anomaly during spring and early summer can maintain a soil heat flow anomaly. A negative soil enthalpy anomaly, for example, will serve as a heat sink to the surface and create a tendency for the surface and lower-troposphere temperatures to cool. During the persistence of the soil enthalpy anomaly, this cooling can result in a negative anomaly of the surface and lower-troposphere temperatures. Depending on the magnitude and persistence of the enthalpy anomaly, its effect on the surface temperature could initiate a unique atmospheric temperature and pressure condition to influence the subsequent summer circulation and rainfall in the adjacent regions. This hypothesized process is examined in the next two sections. Because of the lack of high-resolution data to calculate soil heat flows and their interaction with other components in the surface energy budget, we will be limited to empirical analyses of the relations between variations of the soil enthalpy and the surface temperature and lower-troposphere mass field.

b. Coherency and phase relationship between variations of the soil enthalpy and the surface temperature anomalies

One way to examine the effect of the soil enthalpy on the surface temperature is to evaluate the coherency and phase relationship between their variations. Specifically, a leading phase of the soil enthalpy anomaly to the surface temperature would suggest an effect of the soil enthalpy on the surface temperature variation.

In the western United States, this effect of the soil enthalpy is expected to be prominent shortly after snowmelt in mid- and high latitudes or after the end of the winter rainy season in coastal and low-elevation regions of the same latitudes, when interactions become active between the soil enthalpy anomaly and the surface temperature variation. The soil enthalpy effect will continue during the persistence of the enthalpy anomaly.

Figure 3a shows the composite variations of the phase relationship (isolines) and the coherency (shading) of variations of the surface temperature and soil enthalpy (5–20-cm column) anomalies in the wavelet space. The data are from the Pullman 2 Northwest (NW) station (45.75°N, 117.18°W) in Pullman, Washington. The ordinate in Fig. 3a is the frequency/period of the variation components. Because the soil enthalpy anomaly in the 20-cm soil column can persist up to 2 months, the ordinate ranges from 8 to 64 days. The abscissa in Fig. 3a is time, from March through July, in days relative to 1 April (“0” in the figure), which coincides with the ending date for snowmelt or the ending date of the cold season rainy period at the Pullman station (see Fig. 4a). For stations in low-elevation regions in the northwest, winter snow cover is temporary. However, frequent and abundant winter precipitation keeps the soil moisture high in the upper layers in the winter months (Fig. 4a). Wet soils in the upper layers retard the heat exchange between the soil and the atmosphere. After March, when the winter rainy season ends, precipitation decreases, soil starts drying, and the heat exchange becomes active.

The results in Fig. 3a show that before April, the phase difference between the variations of the soil enthalpy and surface temperature anomalies of 8–20-day periods is small and their coherency is weak. Starting in April, the phase relation changes and the soil enthalpy variation begins to lead the surface temperature variation. The coherency of the variations also improves dramatically. The coherency change appears at all the frequencies. The strong coherency along with the leading phase relation continues through the first half of May. The average lead in phase during April and May for waves of 8–20-day periods is between 1 and 2 days. After May, the lead phase by the soil enthalpy anomaly gradually fades, while the coherency of the variations remains high for the 8–20-day waves.

Another case showing similar variations is presented in Fig. 3b using data from the N. Willamette Experiment Station (45.28°N, 122.75°W) close to a forested area near Molalla, Oregon (also see the station’s precipitation variation in Fig. 4b). In this case, the coherency of variations in the soil enthalpy and the surface temperature anomalies is very low in March and most of April. The phase relationship in this period also shows randomness, indicating a lack of any “organized” variations between the two variations. After April, the variations become highly coherent and, concurrently, the soil enthalpy anomalies take a lead over the variations of the surface temperature. This particular and coherent relationship

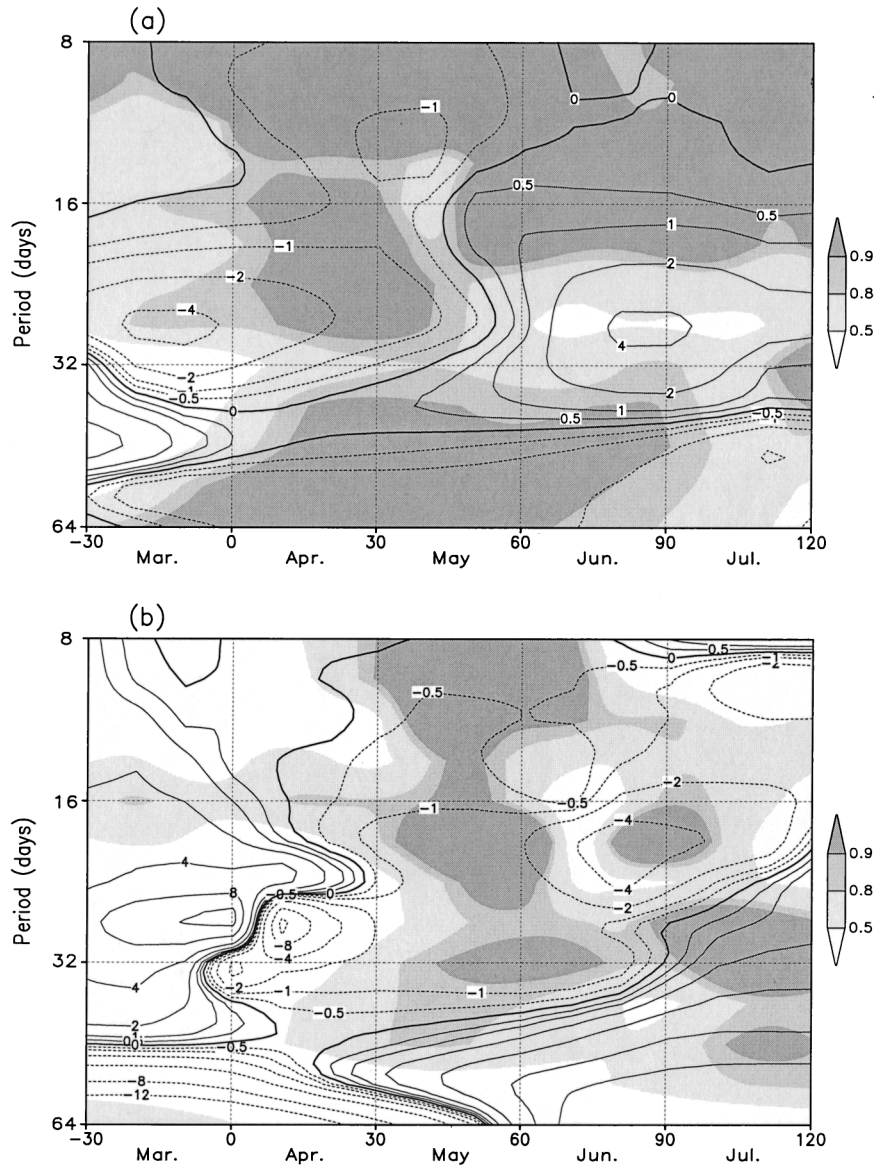


FIG. 3. Coherency (shading with scale on the side) and phase relationship (contour lines) of variations in soil enthalpy and the surface temperature. Negative (positive) contour lines indicate that the soil enthalpy variation leads (lags) the variation of the surface temperature (contour line interval: 0, ± 0.5 , ± 1.0 , ± 2.0 , ± 4.0 , ± 8.0 , and ± 12.0 ; unit: day).

of the variations persists from May through mid-June. In this period, the average lead time for the waves of 8–20-day periods is also 1–2 days.

Compared to Fig. 3a, a difference in this result is that the lead phase relation sustained through the month of July, although the poor coherency after late June suggests little significance of the phase relationship in the variations of the two variables. The disintegrated variations between the anomalies of the soil enthalpy and the surface temperature after June are speculated to result from the wet condition in the area. In wet areas, because of surface vegetation effect, the relationship of

the soil enthalpy and surface temperature variations could become complicated.

Both of these cases, as well as the case from the station in western Montana (not shown), depict an evolution of the soil enthalpy in the 5–20-cm column and the surface temperature from a disorganized relationship in the cold and rainy season to a highly coherent relationship in the early warm season. This evolution indicates interactions of the variations in soil enthalpy and the surface temperature, and the lead phase relation of the former over the latter suggests an influence of the soil enthalpy on the surface tem-

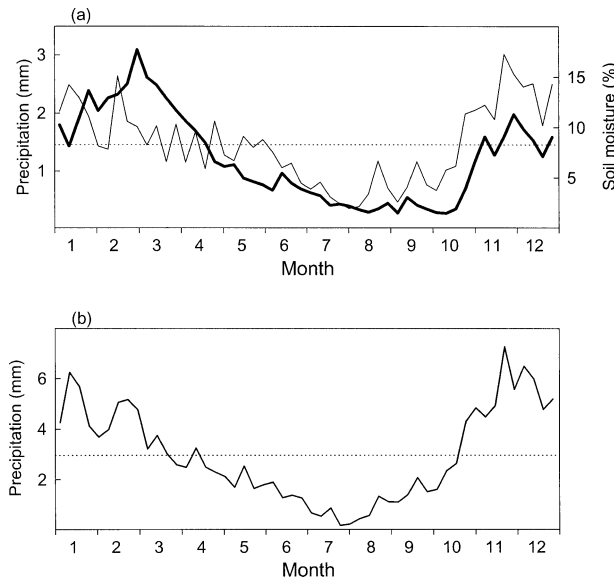


FIG. 4. Variations of the pentad (5 day) precipitation averaged in 1961–90 (thin solid line) for (a) Pullman 2 NW station (45.75°N, 117.18°W) in Pullman, WA, and (b) N. Willamette Experiment Station (45.28°N, 122.75°W) near Molalla, OR. The dotted line in (a) and (b) shows the annual average of the pentad precipitation. The thick solid line in (a) shows the variation of pentad soil moisture at 10 cm averaged in 1994–2000 for Lind, WA.

perature variation. This influence persisted for a period of 2 months during April–June, in agreement with the results in Table 1.

c. A potential role of the soil enthalpy in summer monsoon rainfall and the land memory

These previous results indicate that soil enthalpy anomalies could have affected the surface temperature variation. The effect is particularly active after the winter rainy season, or when snowmelt is completed in high-elevation regions in the northwest. Moreover, the lead phase of the soil enthalpy variation at the end of the cold season indicates that the enthalpy anomaly would have existed at the time when the active interactions began between the soil enthalpy and the surface temperature. Thus, the soil enthalpy anomalies have to result from the preceding winter season anomalies of precipitation and temperature. With the persistence of soil enthalpy anomalies, those winter anomalies could

extend their effects onto the land surface and atmospheric processes in late spring and early summer and influence the summer monsoon rainfall.

Before examining the detailed processes that may have connected the soil enthalpy anomaly with the summer monsoon rainfall, we summarize in Table 2 the correlations between anomalies of the soil enthalpy and the summer monsoon rainfall. In the table, the second and third columns show the correlations of May–June average soil enthalpy anomalies in the northwest versus the monsoon rainfall anomaly in the Southwest. [April data were excluded in this average because, based on our analysis of snow data, May is usually the end time of the snowmelt in high-elevation regions and also the end time of the cold rainy season in some low-elevation regions (see the results of the Oregon station in Figs. 3b and 4b).] These results indicate significant negative correlations especially at the interannual scales.

The role of the soil enthalpy in variations of the southwestern summer monsoon rainfall is further shown by the change in the sign of the correlation coefficients in the fourth and the fifth columns from that in the second and third columns in Table 2. Those coefficients are from correlations of the anomalies during the monsoon season. The significant positive correlation (at a 95% confidence level) indicates that the negative correlation of the summer monsoon rainfall versus the soil enthalpy anomalies in May–June is unique and, hence, demonstrates a unique role of the late spring and early summer soil enthalpy anomaly in the summer monsoon rainfall variation.

What processes may have connected these cross-season variations depicted by the correlations in Table 2? To answer this question, we examine the relationship of the surface temperature and the lower-troposphere geopotential height (proportional to the layer's average temperature), and how geopotential height anomalies may influence the summer monsoon rainfall. Recall that soil enthalpy anomalies affect the surface temperature variations (Fig. 3). If the surface temperature affects the geopotential height and temperature in the lower troposphere, the persistent soil enthalpy anomalies resulting from the antecedent winter anomalies would influence the lower-troposphere geopotential and temperatures in subsequent seasons. Figure 5a shows the correlations of April–June variations of the surface temperature in the northwest and the 850-hPa geopo-

TABLE 2. Correlations between southwestern summer monsoon rainfall and soil enthalpy anomalies in the northwest (ID, OR, and WA; 1967–90).

Soil column	May–Jun		Jul–Sep	
	All scales	Interannual	All scales	Interannual
5–10 cm	–0.21	–0.41*	0.33	0.50*
5–20 cm	–0.53*	–0.56*	0.48*	0.53*
10–20 cm	–0.39	–0.51*	0.48*	0.53*

* Significant at 95% confidence levels based on the two-tailed *t* test.

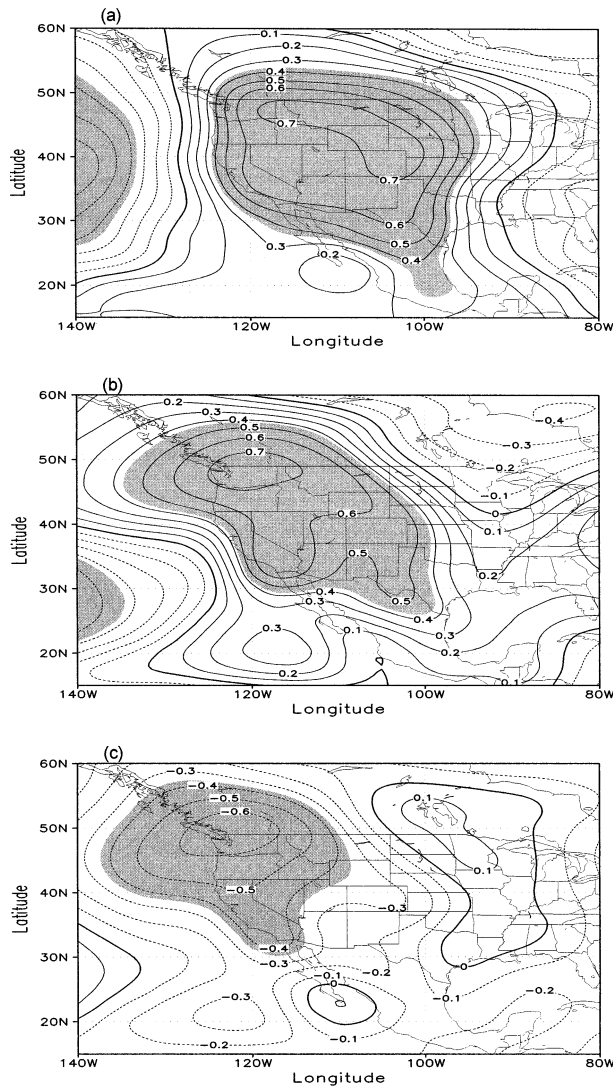


FIG. 5. Correlation of Apr–Jun (a) surface temperature anomalies and (b) soil enthalpy anomalies in the northwest vs the 850-hPa geopotential height. (c) Correlation of Apr–Jun 850-hPa geopotential height vs the southwestern summer monsoon rainfall. Shading indicates statistically significant correlation at a 95% confidence level (based on a two-tailed t test).

tential height in the same season. (We notice that at a few small areas in Colorado and Wyoming, the 850-hPa height is under the surface. This fact will not affect our discussion, however, which focuses on the northwest). In calculating the correlations, we removed variations of periods longer than 9 yr in the data using the binomial method, focusing on the interannual scales that explain most of the correlations (see Table 2). The correlations are positive in the northwest and significant at a 95% confidence level (based on a two-tailed t test). They indicate that a warmer surface temperature would correspond to a warmer mean temperature in the lower troposphere of the northwest and a higher elevation of the 850-hPa geopotential. Because warmer surface tem-

peratures in April–June are led by positive soil enthalpy anomalies, they would thus lead to positive geopotential height and temperature anomalies in the lower troposphere from April to June.

Another result showing this relation is presented in Fig. 5b where we plot the direct correlation coefficients of the April–June soil enthalpy anomaly in the northwest versus the 850-hPa geopotential height anomalies. The correlations are also for interannual scales. The correlation pattern in Fig. 5b is similar to that in Fig. 5a, showing significant positive correlations in the western United States. These results support that persistence of soil enthalpy anomalies resulting from winter anomalies could affect both the surface temperature and geopotential height in the lower troposphere from April to June. If the lower-tropospheric mass field anomalies in those months could have initiated anomalies leading to the southwestern summer monsoon rainfall variations, the soil enthalpy anomalies would have extended their effect on the monsoon rainfall and hence played an important role in the monsoon and in the land memory. This relationship between the lower-tropospheric geopotential height and the summer monsoon rainfall is confirmed by the results in Fig. 5c. While showing strong negative correlations of the April–June 850-hPa geopotential height versus the southwestern summer monsoon rainfall, Fig. 5c also reveals a rather intriguing feature in the correlations. Significant correlations only appear in the northwest United States, southwest Canada, and their adjacent oceanic regions. Because the geopotential height anomalies in that region are significantly influenced by the soil enthalpy as well as surface temperature anomalies in the same region (Figs. 5a–b), this feature helps emphasize the important role of the soil enthalpy and the land surface processes in the northwest in the variations of the southwestern summer monsoon rainfall.

The results in Figs. 5 and 3 and Table 2 call for the following proposition on the role of the soil enthalpy in the monsoon rainfall and land memory. First, soil enthalpy anomalies appear in the late spring as a result of antecedent winter anomalies, as well as spring snowmelt and the ending time of the cold season rainy period in spring in the low-elevation regions in the northwest. Colder temperatures in winter and associated extended snowmelt or the rainy period in spring would cause negative anomalies in soil enthalpy. Otherwise, less snow and higher temperatures would result in positive soil enthalpy anomalies. Second, the soil enthalpy anomalies can persist for 2–3 months from the ending time of the cold rainy period into the early summer season. In those months, a negative anomaly of the soil enthalpy, for example, would influence and lead to a negative anomaly in the surface temperature, which influences and contributes to a similar anomaly in the lower-troposphere geopotential height (and average temperature). Third, the negative anomaly of lower-troposphere geopotential in the northwest in late spring

and early summer leads to a positive anomaly of the summer monsoon rainfall in the Southwest, connecting a colder and snowy winter in the northwest to a more intense summer monsoon rainfall in the Southwest.

The change of lower-troposphere geopotential resulting from the surface temperature and soil enthalpy anomalies in the northwest is important in achieving this connection. Since negative anomalies of geopotential height in the lower troposphere correspond to more mass in the air column and higher atmospheric pressure in the lower to midtroposphere (Palmen and Newton 1969), negative soil enthalpy and surface temperature anomalies would help to establish and support a high pressure anomaly. Because the negative correlation between the soil enthalpy (surface temperature) and the geopotential height is most prominent in the northwest (Fig. 5), high pressure anomalies would develop in the lower and midtroposphere of the northwest from the late spring to the early summer in response to negative anomalies of the soil enthalpy in that region. This high pressure anomaly would likely establish a pressure ridge and "pull" the monsoon ridge, discussed in Carleton et al. (1990), northward of the Arizona–New Mexico area. When the monsoon ridge in the lower and midtroposphere takes such a northern position in June and July, it allows moisture-rich flows from the Gulf of California and the Gulf of Mexico to enter the Southwest, favoring intense summer monsoon rainfall development (Carleton et al. 1990; Douglas et al. 1993; Castro et al. 2001). In addition, depending on the intensity of the pressure anomaly and the processes during the high pressure buildup, the onset data of monsoon rainfall is affected. Early onset would bring more monsoon rainfall (Higgins et al. 1998). On the other hand, a reversed anomaly in the atmospheric pressure, resulting from a reversed soil enthalpy anomaly, would stall a low pressure system in the northwest, leaving the monsoon ridge to the Southwest and suppressing the summer monsoon rainfall development.

Following the onset of the monsoon, the correlation between the soil enthalpy and the monsoon rainfall anomalies reversed (columns 4–5 versus 2–3 in Table 2). This reversal indicates a response of the soil enthalpy and the lower-troposphere pressure and temperature in the northwest to the monsoon in the Southwest. When the surface temperature rises and the atmospheric pressure decreases in the northwest, the pressure ridge weakens there (not shown). Because weakening the monsoon ridge leads to weak monsoon circulation and rainfall (Carleton et al. 1990; Higgins et al. 1998), the southwestern summer monsoon creates a negative feedback that eventually weakens and likely interrupts the monsoon. This feedback, its development, and its progress deserve further studies that could yield results improving our understanding of monsoon breaks and resets during the monsoon season.

4. Summary and concluding remarks

Several features of soil enthalpy discovered in this study along with those identified in previous studies shed light on a potentially important role of soil enthalpy in land memory. First, the soil enthalpy develops anomalies from winter anomalies in both temperature and precipitation. This feature allows the soil enthalpy to record the atmospheric and surface anomaly in both warm and cold seasons. [This feature is not possessed by soil moisture in the cold season, as shown in Robock et al. (2003).] Second, variations of the soil enthalpy in soil columns of different thickness have magnitudes comparable to the atmospheric enthalpy variations at different time scales from monthly to seasonal to annual. Third, anomalies of the soil enthalpy in the top 1 m can persist for 2–3 months. This persistence is longer than that of the soil moisture anomalies of about 1.8 months. Fourth, because of the longer persistence, soil enthalpy anomalies can affect the surface temperature via soil heat flows for up to 3 months after the surface snow melts or the cold season rainy period ends in April or May in the northwest United States. We found that during the persistence period of the soil enthalpy anomaly, the enthalpy variations in the time scales from 8–20 days lead the surface temperature variations at the same frequencies by 1–2 days. Near the end of the persistence period, the lead in phase relationship fades and the variations of the soil enthalpy and the surface temperature become synchronized in dry areas. In wet areas, because of rainfall and surface vegetation effects the variations are complicated.

With these characteristics, the soil enthalpy appears to play a significant role in extending the effects of the winter temperature and precipitation anomalies in the northwest onto the variation of the summer monsoon rainfall in the southwest United States. This notion is further supported by the following results: First, both the soil enthalpy and surface temperature variations in the northwest have a significant positive correlation with the anomalies of the lower-troposphere geopotential height and average temperature during April–June. Owing to this connection, the effect of the soil enthalpy anomalies resulting from the winter anomalies is extended, by the persistence of the anomalies, to influence the lower-troposphere geopotential height and temperature in the northwest. Second, because colder temperature in the lower troposphere leads to a higher atmospheric pressure in the same layer, a negative anomaly of the soil enthalpy would help to develop a high pressure anomaly in the lower to midtroposphere of the northwest. Third, such a high pressure anomaly would favor a northward shift of the monsoon ridge in the lower troposphere. As described in Carleton et al. (1990) and in Castro et al. (2001), this northward position of the monsoon ridge in June can help establish a monsoon circulation that enhances convergence of southerly flows to the Southwest. Convergence of these moisture flows

could cause both early onset of monsoon and intense rain events during the subsequent monsoon months.

These processes and their relation with the soil enthalpy anomalies articulate a role of the soil enthalpy in “recording” the winter season precipitation and temperature anomalies in the northwest and “releasing” their effects in late spring and summer to modulate the southwestern monsoon rainfall. Because this study has focused on the role of the soil enthalpy, other related processes and their interaction with the soil enthalpy are not explored. Among those processes, soil moisture and surface fluxes could have close interactions with the soil enthalpy anomalies and play important roles during the monsoon variation. Those roles need to be examined and can be better understood with the knowledge from this study when better observations of soil moisture and energy fluxes become available.

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