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ABSTRACT

Although affected by atmospheric circulations, variations in soil temperature result primarily from the radiation and sensible and latent heat exchanges at the surface and heat transfer in the soils of different thermal properties. Thus, soil temperature and its variation at various depths are unique parameters that are useful in understanding both the surface energy processes and regional environmental and climatic conditions. Yet, despite the importance, long-term quality data of soil temperatures are not available for the United States. The goal of this study is to fill this data gap and to develop a soil temperature dataset from the historical data of U.S. cooperative stations. Cooperative station soil temperatures at various depths from 1967 to 2002 are collected and examined by a set of quality checks, and erroneous data of extended periods are estimated using methods constructed in this study. After the quality control, the data are used to describe the climatic soil temperature as well as soil temperature change in the contiguous United States. The 35-yr climatological dataset shows that the annual soil temperature at 10-cm depth, at which most stations have soil temperature measurements, decreases gradually from 297 K in the coastal areas along the Gulf of Mexico to below 281 K on the United States–Canada border. In seasonal variation, the largest change occurs from spring to summer, during which time soil temperatures are adjusted from the cold season to the warm season, particularly in snow-cover regions. Mild changes are observed from autumn to winter, during which time the soil heat storage still dominates the soil temperature variations. An analysis of the soil temperature variation reveals a warming trend of soil temperatures in most of the stations in the northern and northwestern United States and a large cooling trend in some stations in the southeastern United States. Significant warming is found in the winter and spring season. Potential effects of these trends on regional agriculture are discussed.

1. Introduction

Among the processes that affect regional weather and climate in land areas are exchanges of energy and water between the atmosphere and the earth's surface. The rates of these exchanges are dependent on several factors, including soil temperature and moisture. Variations in soil temperature and moisture alter the partitioning of sensible and latent heat from the surface and affect atmospheric boundary layer processes and regional circulation (Pan and Mahrt 1987; Peters-Lidard et al. 1998). Although influenced by atmospheric circulation anomalies, variations in soil temperature result primarily from the radiation and sensible and latent heat exchanges at the surface and heat transfer in soils of different thermal properties in the vertical direction. Thus, soil temperatures at various depths are unique parameters that are useful to describe both the surface energy processes and regional environmental and climate conditions.

Soil temperature affects the surface heat flux at various timescales. Because heat conduction in soils is a very slow process (Hillel 1980), soil heat anomalies of daily or weekly timescales in shallow layers near the surface are released to the atmosphere before being distributed to the deeper layers. Only persistent long-term (such as interannual and decadal-scale) anomalies in surface heat budget can propagate to deep soil layers and affect temperature variations in those layers (Lachenbruch and Marshall 1986; Beltrami and Harris 2001; Beltrami 2002). This is shown by the relationship $z_m = c\tau^{1/2}$, which is obtained by solving the heat transfer equation in soils for the depth z_m at which a specific timescale variation in the surface heat process (e.g., annual solar cycle τ) has the largest amplitude in the soil temperature variation (Tang 1989). The parameter c is a constant and is proportional to the soil thermal conductivity. As this relationship indicates, soil temperature at different depths records surface temperature variations of different timescales, and effects of longer-timescale temperature and heat variations at the surface and

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atmosphere are eventually shown in temperature records of deeper soil layers. Because heat conduction in soil is always downgradient, a positive heat anomaly in deep soil layers after a persistent warm period, for example, would gradually release the extra heat to shallow layers, where the heat anomaly would produce anomalies in surface heat, as well as moisture fluxes, through effects on land cover and vegetation conditions. By affecting the surface heat and moisture fluxes at interannual and decadal timescales, deep soil temperature anomalies could be one of the sources affecting regional climate (Tang et al. 1982; Tang and Reiter 1986; Retnakumari et al. 2000). Thus, the potential use of soil temperatures is attractive for prediction of regional circulation and climate, if interactions of soil temperature and atmospheric variations are understood.

In additional to affecting the atmospheric circulation, soil temperature anomalies at various depths also directly affect growth and yield of agricultural crops. For example, cool spring-season soil temperature in shallow layers delays corn development, and, on the other hand, warm spring-season soil temperature contributes to an increase in corn yield (Bollero et al. 1996; Hu and Buyanovsky 2003). Warm soil temperature encourages leaf growth of corn, which further affects the evapotranspiration and soil water budget during corn growth (Bollero et al. 1996). Similar effects also were found for winter wheat (Wraith and Ferguson 1994). Warm soil temperature in early spring also allows planting at earlier dates, and an extended growing season would open the possibility to grow high-yield varieties that usually take a longer time to mature. Furthermore, soil temperatures anomalies affect root growth of a variety of crops, including corn, beans, and oats; cool soil temperatures limit root expansion and significantly affect the root system and, hence, yield (Kaspar and Bland 1992; McMichael and Burke 1998). Because of these effects of soil temperature on agricultural crops, it is important to understand soil temperature variations so that both farming technology and management strategies can be improved to reduce climatic risks and to sustain grain production and agriculture in the changing environment.

To understand these roles of soil temperature in land surface processes that affect weather and climate and in agricultural production, a reliable dataset of soil temperatures is required. Existing pieces of short-term soil temperature data series are in different archives with various formats. Because of their variable quality, they are difficult to use in research and application. This situation imposes a strong need for developing a quality dataset of soil temperatures from the existing sources. A part of this effort was recently completed and resulted in a high-quality dataset of hourly soil temperatures at multiple depths, using measurements from 21 automated stations in the U.S. Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) soil moisture–soil temperature (SM–ST) network (Hu et al. 2002). As a continuation of that previous work, this study extends the quality assurance analysis to the U.S. National Weather Service (NWS) cooperative station daily soil temperature data and produces a quality dataset for the contiguous United States from 1967 to early 2002. This quality dataset can be used, as demonstrated in some of the previously cited studies, in analysis and understanding of soil temperature variations, their interactions with regional circulation, and their impacts on agriculture productions.

In the next section, various data sources for soil temperatures from the cooperative stations in the contiguous United States are discussed. Major error sources in individual station's soil temperature data series are discussed in section 2, along with methods to detect the erroneous data and to calculate their estimates. Because the data were measured at various time schedules—for example, some stations measured daily maximum and minimum at midnight; some measured soil temperatures 2 times each day, one at either 0700 or 0800 local time and the other at either 1700 or 1800 local time; and still others measured once per day—a method is proposed in section 3 to calculate the daily average soil temperatures, which can be used for comparison and research purposes. In section 4, the new dataset of daily average soil temperatures at multiple depths from 1967 to early 2002 is used to describe the climatological characteristics of soil temperatures in the contiguous United States. Additional features, such as trends and major changes over the 36 yr of record for the soil temperatures at various depths, are examined and the potential impact of these changes on agriculture is discussed in section 5. Section 6 contains a summary of this study and remarks on the significance of major results.

2. Daily soil temperature data and quality control

a. Daily soil temperature data sources

Daily soil temperature data for the contiguous United States are from three major sources: (i) the TD-9639 soil temperature data archive for the period from January 1967 to December 1981, (ii) the TD-3200 daily data archive from January 1982 to December 1993, and (iii) station daily soil temperature data from January 1994 to March 2002 (which was available online at http://cdo.ncdc.noaa.gov/plclimprod/plsql/poemain.poe). All three datasets were produced at the National Climatic Data Center (NCDC) from reports of individual stations. Additional soil temperatures from cooperative stations that were not contained in these datasets, for example, some stations in Missouri, were found from archives at the Missouri state climate office and were included in this analysis. Soil temperatures in all of these archives were not previously subjected to quality control, although the air temperature and precipitation data in TD-3200 and the online archives were quality controlled

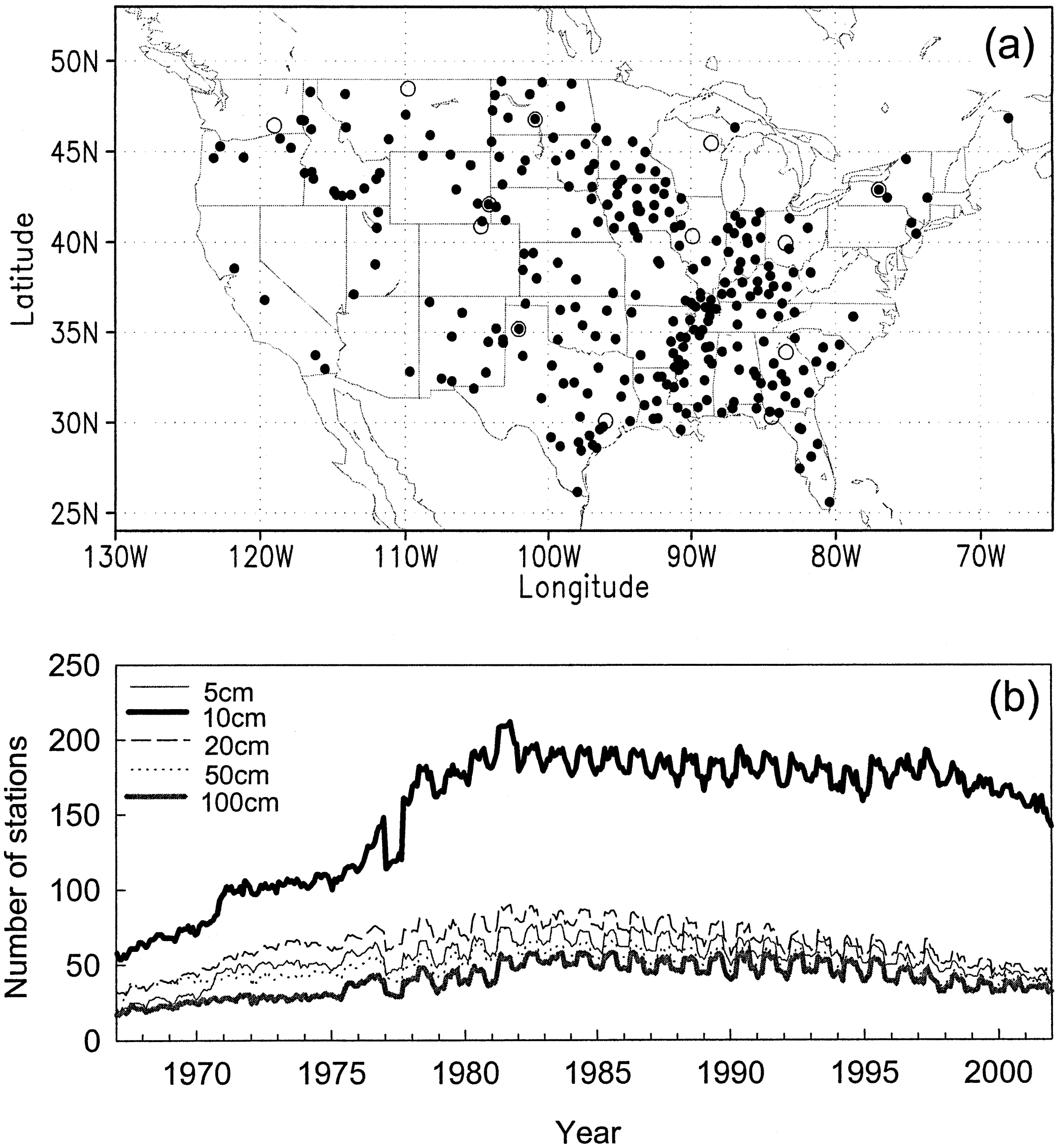

FIG. 1. (a) Distribution of the 292 U.S. cooperative stations (dots) and USDA SM–ST network soil temperature stations (open circles) whose data are used in this study. (b) Variation of the number of cooperative stations that measured soil temperatures.

using the method developed at NCDC (Reek et al. 1992).

According to these data sources, there were 337 stations in the contiguous United States with soil temperature measurements between 1967 and 2002. Of these 337, only 292 stations continued their measurements for longer than 5 years for at least one depth. The spatial distribution of these 292 stations is shown in Fig. 1a. The spatial distribution of the stations is irregular: more stations were in the Ohio and Mississippi River valleys and in Iowa and the Dakotas, there were only a few in the southwestern and northeastern United States, and there were none in Nevada and Wisconsin. Among these stations, the number of stations in service also changed over the years. As shown in Fig. 1b, more stations were installed after 1978, after a dry period in the central United States; the number of stations peaked in the early 1980s but has since been decreasing. Figure 1b also shows that most of the stations measured soil temperature at 10-cm depth, and only about 50 stations measured temperature at 100-cm depth. The number of stations in service also shows an ''annual cycle'' in Fig. 1b because some stations, particularly in the northern states, only measured soil temperature in the warm season or during the growing season for agricultural crops from mid-April to late September.

At these individual stations, soil temperatures were often measured under different ground covers. A total of seven different covers were found in the records: bare ground, fallow, grass, brome grass, sod, straw muck, grass muck, and bare muck. Except for some stations that did not specify their cover types, most stations have measurements under bare ground, and these measurements often have the longest record length. The measurements under other cover types at a station were sometimes made for specific experimental purposes, such as soil temperature effect on vegetation health and crop growth, and continued only for certain seasons or for short time periods. So, in developing the dataset, we used the soil temperatures measured under bare ground cover, and, for stations without measurements under bare ground cover, we used the soil temperatures under the ground cover that had the longest measurement record.

At most stations, soil temperatures were measured at multiple depths, and for various reasons both English and metric units were used to define the depths at the stations. Stations that used the English units measured soil temperatures at depths of 2, 4, 8, 20, and 40 in. below the surface, and stations that used the metric units measured the temperature at depths of 5, 10, 20, 50, and 100 cm below the surface (only a few stations had measurements at 80 in. or 200 cm). Although each pair of these English and metric units (e.g., 2 in. vs 5 cm, 4 in. vs 10 cm) is not identical, they are very close to one another. The differences range from 0.08 cm between 2 in. and 5 cm to 1.6 cm between 40 in. and 100 cm. Temperature differences between the pairs of comparable depths are very small because depth differences are small in shallow depths, and the slightly bigger differences at deeper depths will have little effect on temperature because of the small temperature gradient across them [see Fig. 4 in Hu et al. (2002)]. Therefore, we accepted the temperatures at depths in English units as comparable to temperatures at the corresponding depths in metric units, and we obtained soil temperatures at five metric depths (5, 10, 20, 50, and 100 cm) at each station (the same notion also is accepted at the NCDC).

Soil temperatures at different stations were measured at three different ''times-of-observations.'' Some stations measured the maximum and minimum soil temperatures at various depths at midnight; some stations measured soil temperatures at two times per day, one in the early morning hours at either 0700 or 0800 local time and the other in the late afternoon hours at either 1700 or 1800 local time; and the remaining stations measured soil temperature only once per day, fixed at one of these local hours: 0700, 0800, 1200, 1700, or 1800. Table 1 summarizes the stations and their different observation schedules.

These considerable irregularities among station data in terms of observation period, ground cover, depths at which data were measured, and time of observations; in addition to those differences in intrinsic properties among stations, such as elevation, soil type, and station environment; make it difficult to develop a soil temperature dataset with a consistent format for all of the stations. A practical approach is to apply quality control methods to *individual* stations and their various time series of soil temperatures at specific times of observation, depths, and ground cover and to obtain a dataset of station soil temperatures that is a mosaic yet is useful. A quality-control method to obtain such a dataset is described in section 2b.

TABLE 1. Number of stations with different measurement schedules. (Note: because a station that was once in service is counted regardless of how long it stayed in service, the number of stations measuring at any depth with any schedule can be greater than the maximum number of stations in any particular year shown in Fig. 1b.)

Depth (cm)	Daily max and min	Twice daily	Once daily
5	78	42	0
10	255	44	0
20	86	43	0
50	16	19	97
100	12	18	77

b. Data quality control

Although many methods have been developed to identify erroneous air temperatures (Menne and Duchon 2001; Peterson et al. 1998; Vincent et al. 2002), little attention has been given to quality control of soil temperature data. Hu et al. (2002) developed a quality-control method to examine the soil temperature data from the USDA NRCS SM–ST network. In that approach, a soil temperature model was established to calculate annual and diurnal reference soil temperatures at various depths for each station. These reference temperatures are used in evaluation of observed soil temperatures to identify erroneous data and to provide their estimates. In developing quality-control methods for the cooperative stations, we use some of the tools developed in Hu et al. (2002) and also expand their method to include additional evaluation tools. Several evaluation methods introduced in quality control for air temperatures also are used. Details of each of these evaluation tools and their application procedures to the soil temperatures are presented below.

1) INTERNAL CONSISTENCY CHECK

Reek et al. (1992) outlined eight rules to identify erroneous data of all meteorological variables resulting from data reporting and digitizing, typos, unit differences, and use of different based values in data reporting (see their Table 1). We used three of their eight rules for temperatures to check the soil temperatures for (a) *internal inconsistency*, which includes cases with a daily maximum temperature T_{max} smaller than the daily minimum T_{min} and unrealistically large or small temperature values; (b) *excessive diurnal range,* which includes cases with extraordinarily large daily temperature range

(T_{max} − T_{min}) even though T_{max} and T_{min} may be within their reasonable ranges; and (c) *spikes in temperature series*, which are defined ''as the smallest absolute result from the comparison of singular differences of three consecutive days, centered on the day in question'' (Reek et al. 1992). Spikes greater than 28°C are flagged for deletion, and spikes smaller than 28°C but greater than 22°C are marked as suspect. Applications of these rules to individual station soil temperature series singled out the suspected data totaling 0.10% of the entire soil temperature data. These suspected data values were flagged.

2) VARIATION RANGE CHECK

The above internal consistency checks identified some obvious outliers in the data series, but they cannot detect erroneous data that have the following problems: data values that are much larger than neighboring values but not larger than the threshold for being detected by the consistency check in section 2b1, data that create substantially large changes in soil temperature from the previous day or days, and data that show absence of any change over some extended period. To identify these erroneous data, we used two methods based on the two rules proposed and used by O'Brien and Keefer (1985) in their identification and elimination of erroneous data in real-time hydrological data. These methods define (a) high/low bounds for soil temperature at given depths (LIM) and (b) the limit for the rate of change of soil temperature at given depths (ROC). By defining the high/low bounds, the LIM method can help to identify the data outside the variation range of soil temperatures at each depth. In a similar way, defining the bounds for the rate of change of soil temperatures, the ROC detects data inconsistent with temporal variation in soil temperatures. Similar methods derived from these rules also were used in quality control of daily air temperatures in Meek and Hatfield (1994, 2001).

To derive the high/low bounds in LIM for a given soil temperature data series, for example, the daily maximum soil temperature measured at an early morning hour at a depth, we first identified both the highest and the lowest values of soil temperatures on each calendar day of a year in the data history of up to 36 yr. After getting these pairs of ''extreme'' values for each day, we used functions of form $T(z, t) = T_o(z) + A(z)\sin(\omega t)$ to describe the envelope of annual variation of these extreme temperatures. In this function, t is the day of year, ω is the frequency ($=2\pi/365$), z is depth, and $T_o(z)$ and $A(z)$ are the annual mean of these extreme soil temperatures and their amplitude of variations, respectively. Because of the potential for some of these extreme values to be erroneous, this envelope was determined by visual inspection and embraced 98% of those daily extreme values.

After the envelope functions are derived at each station and for each observation time series, they were denoted as the upper and lower bounds of soil temperature variations, T_U and T_L, respectively, for those series and were applied to compare with the individual data values. Data satisfying $T_L(z, t) \le T(z, t) \le T_U(z, t)$ passed the LIM test, and data that failed it were flagged as suspicious. A typical result is shown in Fig. 2a for minimum soil temperature at 20 cm from 1994 to 1997 at Auburn, Alabama. The two thin lines are T_U and T_L, and the thick line is the soil temperature. The open circles indicate erroneous data identified by this LIM test.

To check the daily rate of soil temperature change, we used a method in Meek and Hatfield (1994, 2001) to determine the bound of the changes, similar to finding the bounds in LIM. At each station and for each time series, the soil temperature change between two consecutive days was calculated from $\Delta T(z, t) = |T(z, t) - T(z, t-1)|$ and then the maximum daily ROC was identified among all the values for the same day from the data of up to 36 yr. Again, a fitting function was constructed to describe the annual variation in those extreme values of the rate of daily soil temperature change. However, because the daily rate of change for soil temperatures is very small in winter, particularly when a station has snow cover (Beltrami 2001), and is large during spring, it was difficult to describe the variation of the extreme values except for a step function. For simplicity, we took a different approach and used a constant value as the ROC bound (no bound for minimum change). In deriving this bound, we first calculated the standard deviation (std dev) of the daily soil temperature change for a data series and denoted the values larger than 8 std dev as suspect. The time series of soil temperature change without the suspect values was examined and was used to recalculate the std dev, and the new 8 std dev value was used as the ROC bound. In this method, the first std dev analysis was necessary because a few large outliers in data series can make the std dev of the series large enough to cause acceptance of some erroneous data. Such erroneous data can be detected by the ROC criterion determined in the second std dev analysis on the new data series, which has the large outliers removed.

An example of the ROC test is shown in Fig. 2b for the minimum soil temperature at 20 cm from 1994 to 1997 at Auburn. The dashed line is the ROC bound. Many of the erroneous data identified by the ROC also were found to be erroneous by LIM.

Both the ROC and LIM checks were applied to the entire soil temperature dataset and raised flags on 0.17% of the data (see Table 2).

3) CHECK DRIFT IN SOIL TEMPERATURES

After these consistency and variation range checks, the remaining possible errors in a soil temperature data series would be those embedded in the variations of the series, including changes in the ''average'' and variance

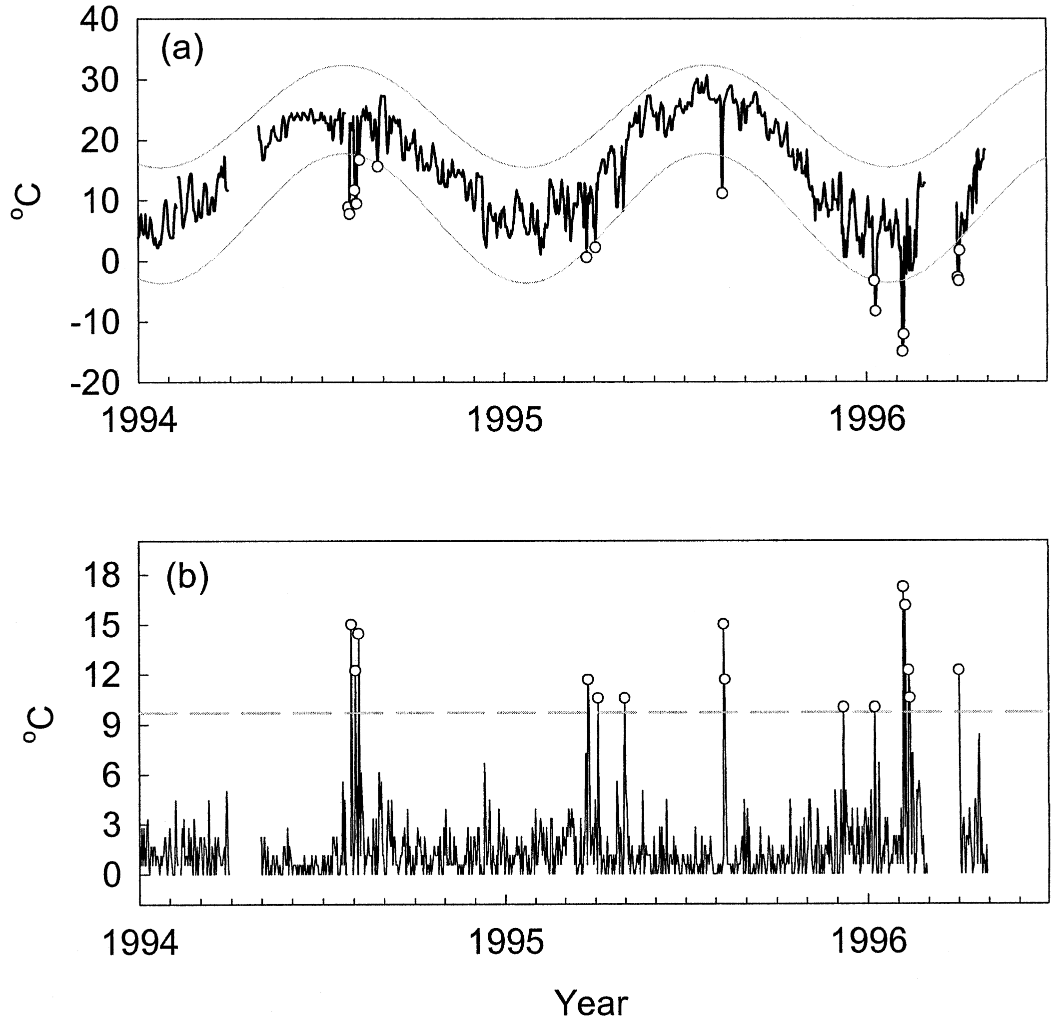

FIG. 2. (a) Minimum daily soil temperature variation at 20 cm (solid line) and its T_U and T_L derived from the LIM method (gray thin lines), and (b) daily rate of change of the daily minimum temperature (solid line) and the ROC bound (dashed line). The open circles in (a) and (b) are the suspect data points. The data are from Auburn Agronomy Farm station (32.6°N, 85.5°W) in Auburn, AL.

(amplitude) of soil temperatures in a period of a few months or years. In this section, we use ''drift'' to refer to such changes in short-term average soil temperatures. Sources causing such drifts are unclear because of lack of documentation. In this section and in section 2b(4), we describe the methods that identify these two kinds of errors in the data and also provide estimates of soil temperatures in those erroneous periods.

To identify the drift in a soil temperature series, we displayed each station's data and compared the variation of the target time series with time series at different depths. When there was no observation at other depths at the same station, the comparison was made between observations at the station and two–three neighboring stations within a 200-km radius. From this comparison, we identified the segment in the data series with sudden changes of the trend. A similar inspection method also was used in examining soil moisture data (Robock et al. 2000) and was used in automated-weather-station data quality control (Ashcroft et al. 1990). A result of this inspection is shown in Fig. 3a for the data at the station in Brawley, California. From 1989 to 1992, a drift of the station's soil temperature at 20 cm is clearly shown. No similar decrease was observed at the other depths of the station. Another example is shown in Fig. 3b for Estherville, Iowa. In this case, an unknown source caused the station's soil temperature at 100 cm to de-

TABLE 2. Percentages of erroneous data by categories.

Inconsistency data (%)	0.10
Violating LIM rule (%)	0.15
Violating ROC rule (%)	0.02
Drift in avg soil temperature (%)	1.48
Drift in soil temperature variance (%)	0.54
Total (%)	2.29

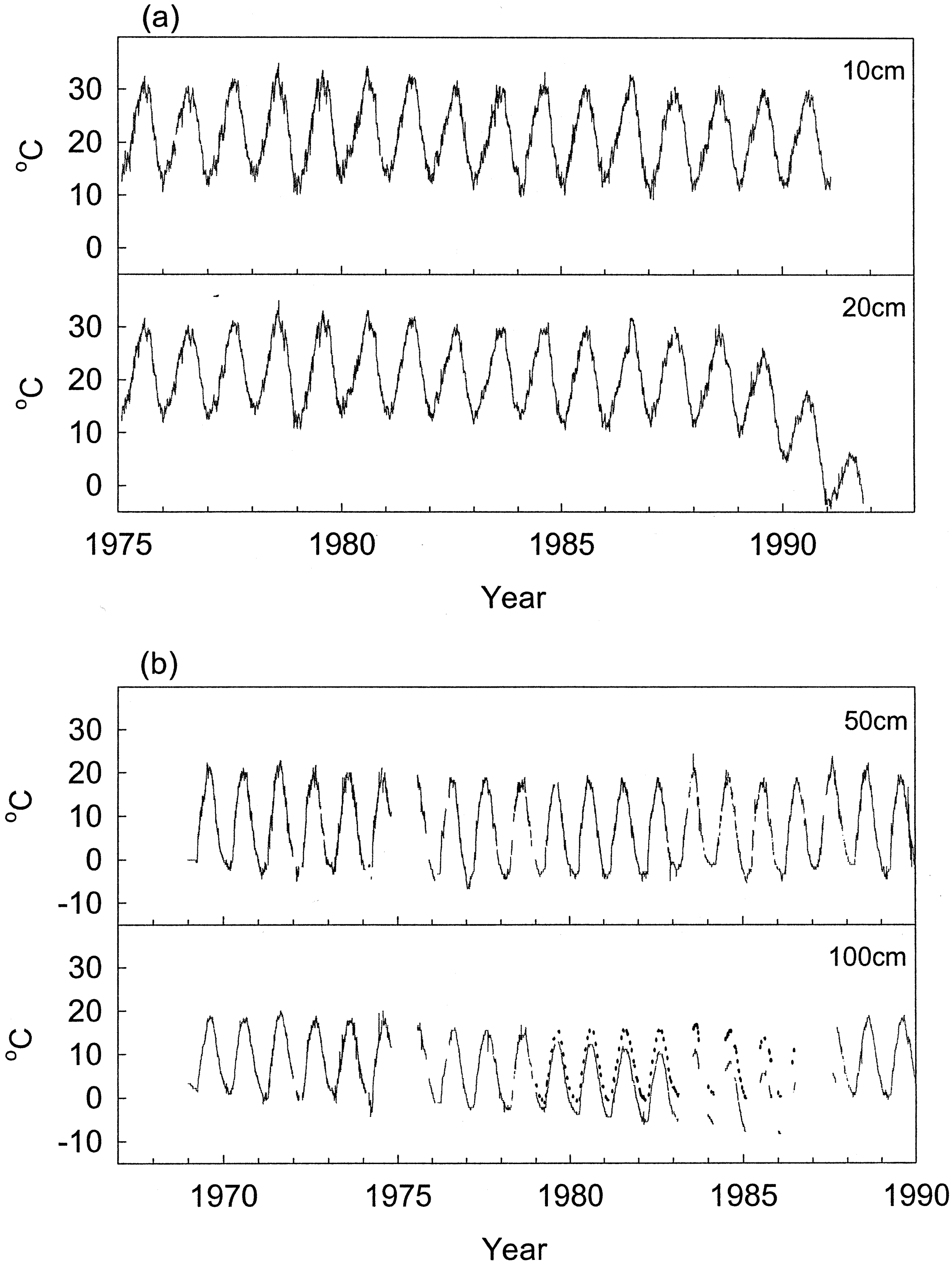

FIG. 3. (a) Soil temperatures at 10- and 20-cm depths at the station (33.0°N, 115.5°W) in Brawley, CA. In comparison with the temperature at 10 cm, the temperature at 20 cm shows a drift from 1989 to 1992. (b) Soil temperatures at 50- and 100-cm depths at the station (43.5°N, 94.8°W) in Estherville, IA. A drift of soil temperature is shown in the 100-cm data from 1979 to 1987. The estimated values of soil temperature for the drift period are shown by the dashed line.

crease continuously from 1979 to 1986. This drift of the soil temperature was inconsistent with temperature variations at other depths for this station (see the upper panel of Fig. 3b). These and similar erroneous data identified using this method were flagged to indicate their error type. This procedure flagged 1.48% of the data with this drift error.

Because data with the drift usually continued for a period of a few months or years, as in the previous two examples, it is desirable to provide estimates of soil temperatures for some of those drift periods. Such an effort is justifiable for those periods in which only the average of soil temperatures was incorrect but the temperature variance was similar to that of the neighboring periods, such as in the case at Estherville from 1979 to 1986 (Fig. 3b). For periods of drift resulting from sensor problems when both drift and error in variance occurred, such as in the case at Brawley from 1989 to 1992 (Fig. 3a), no estimate was attempted.

There are several ways to correct the drift. For example, we could use soil temperatures at the same depth for the period excluding the drift segment to get a mean temperature and use it as an estimate of the average temperature in the drift segment. This method may miss fluctuations in the mean temperatures in the segment, however, especially if the segment contains several years. Another way is to use the average from soil temperatures at different depths observed at the same time. As showed in Hu et al. (2002; see their Fig. 3), the trend in soil temperatures is consistent between the shallow layers. In addition, Zhang et al. (2001) used 100-yr soil temperature records from a station in Irkutsk, Russia, and showed that the long-term soil temperature trends at 40 and 80 cm are nearly identical. These results suggest that the soil temperatures of different depths at the same station vary with the same trend. Thus, the trend at one depth can be used as a good reference to estimate the soil temperatures in a drift segment at a different depth. Based on these results, we constructed the following equation to estimate the soil temperatures in drift segments:

$$T_e = T_c - (a_c + b_c t) + (a_r + b_r t) - \Delta T_{\rm rc}. \quad (1)$$

In the above, T_e and T_c are the estimated and candidate soil temperatures in the drift segment, respectively; t is time in day; and $a_c + b_c t$ and $a_r + b_r t$ are linear regressions of the candidate and reference average soil temperature for the drift segment, with a_c, b_c, a_r; and b_r as the regression coefficients. The reference temperatures are from a different depth. The difference of average soil temperatures between candidate and reference series excluding the drift segment, $\Delta T_{\rm rc}$, is included in (1) to account for soil temperature variation with depth.

This method was used at 16 stations at which drift of soil temperatures at some depths was identified. As an example, the estimated soil temperatures for the station at Estherville are shown in Fig. 3b. The estimated values at 100 cm from 1979 to 1986 describe a consistent variation with the observed values in the other depths at the station.

4) Check changes in soil temperature variance

A problem parallel to the drift is the change or drift of variance or amplitude of the soil temperatures. In detecting this kind of error, we used the method of ''scale cumulative sum'' (SCS) proposed by Peterson et al. (1998) to measure changes in amplitude (variance) of a soil temperature time series. An example of this error and SCS test result is shown in Fig. 4 for the station in Salt Lake City, Utah. In this case, the SCS revealed significant changes in variance of the soil temperatures at 10- and 20-cm depths after December of 1995. Applying the SCS to the entire dataset, we found about 0.54% of the data with such errors.

Again, because such errors often continued for a period of a few months or years (Fig. 4), it is useful to provide estimated soil temperatures for those erroneous data periods. To estimate the soil temperatures with the variance error, we took an approach similar to that in section 2b(3) and used the soil temperatures at different depths of the same station as the reference temperatures. The candidate soil temperature series at one depth was compared with the soil temperature series at other depths, or from neighboring stations if data at only one depth were observed at the target station, for their variance in the periods *excluding* the erroneous segment to select the soil temperature series that yielded the least difference in both the variance and average with the candidate station series. After identifying the reference time series, the following was used to calculate the estimate of soil temperatures in the erroneous segment:

$$T_e = [(T_c - \overline{T}_c)/\sigma_c](\sigma_r \sigma_{c1}/\sigma_{r1}) + \overline{T}_c - \Delta T_{\rm rc}, \quad (2)$$

where T_c and T_e are candidate (erroneous) soil temperature and its estimate, respectively; $\overline{T}_c$ is the average candidate soil temperature; σ_c and σ_r are standard deviations of the candidate and reference temperature series, respectively, for the erroneous data segment; and σ_{c1} and σ_{r1} are standard deviations of candidate and reference temperature series for the data period excluding the erroneous data segment(s). The difference of the average soil temperatures between candidate and reference series excluding the erroneous data segment, $\Delta T_{\rm rc}$, is included in (2) to account for soil temperature variation with depth. The estimate temperatures from (2) will have a consistent variance with the rest of the data series, as shown in Fig. 4 by the result from applying this method to the data at the station in Salt Lake City.

5) Procedure of the quality control

These previously described individual procedures are used in the following sequence to perform the quality

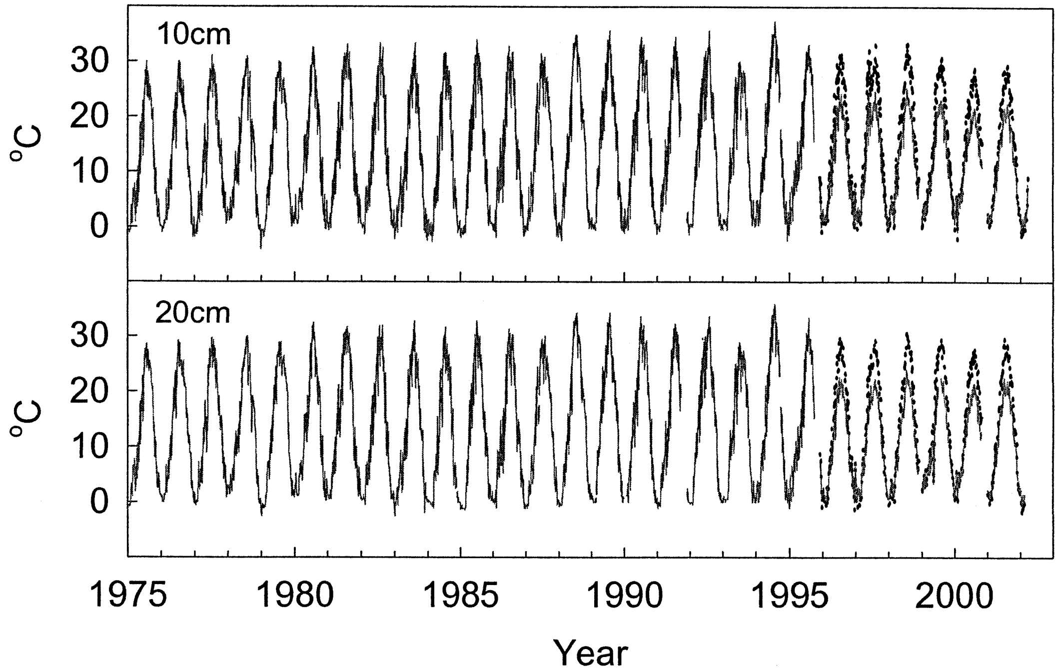

FIG. 4. Soil temperatures at 10 and 20 cm from a station (40.8°N, 112.0°W) in Salt Lake City, UT, showing a change in variance or amplitude of the soil temperatures after 1995. The estimated values of soil temperature for the drift period are shown by the dashed line.

control of a station's soil temperature data. The internal consistency check [section 2b(1)] was used to flag inconsistent data. Then, the variation range check [section 2b(2)] is used to identify data outliers. Last, errors from drift and inconsistent variance are examined [sections 2b(3) and 2b(4)] in sequence to assure consistent variations in soil temperatures at a depth and observation time. This procedure has been applied to the soil temperature dataset from the NWS cooperative stations in the contiguous United States. Erroneous data are flagged, and their estimates also are calculated. The total percentage of erroneous data detected is 2.29%, and the percentages for individual error categories are listed in Table 2. In Table 2, the percentage for ROC error was small because the ROC check was applied after the LIM check, which flagged many erroneous data.

3. A daily mean soil temperature dataset

a. Why use a daily mean soil temperature?

In this ''quality controlled'' dataset of soil temperatures, nearly all of the station data are for bare ground cover and at a depth from 5 to 100 cm under the surface. The stations still have different times of observations (i.e., daily maximum and minimum, observations at morning and afternoon hours, and observation at a single hour on a day), however. For the reasons we stated before, it is necessary for each station to keep its quality-controlled data series. For research purposes, however, these various stations' data series are least desirable because they offer little common ground for comparison and analysis of soil temperature variation between stations and regions. On the other hand, although the station data were measured in different formats, for example, daily maximum vs observation at a specific time, and at different times in a day, it may still be possible to derive one measure of ''daily soil temperature.'' From analysis of the stations' data series, it was apparent that a ''daily mean soil temperature'' at each depth is a reasonable way to ''synchronize'' the data. We accordingly defined a daily mean soil temperature at each depth and developed a method to calculate this mean temperature using stations' data series.

b. Calculate daily mean soil temperatures

In this method, for stations measuring the daily maximum and minimum soil temperatures, the daily mean soil temperature is obtained as an arithmetic average of the maximum and minimum temperatures. Similar calculation also has been used to obtain daily mean air temperatures at the NCDC (Karl et al. 1995). For stations that measure temperatures two times per day, one in an early morning hour and the other in an afternoon hour, the daily mean is defined as the arithmetic average of the two temperatures. For stations that measure temperatures only once per day, no similar mean can be defined. However, because soil temperatures at depths below 50 cm have very small amplitudes in daily variation (see Fig. 4 in Hu et al. 2002), these single daily

TABLE 3. Total number of daily mean soil temperatures at five depths and percentages of the daily mean soil temperatures (local time) calculated using T_{mm}, T_{ap}, and T_{sm}.

Depth (cm)	No. of obs (daily mean × stations)	T_{mm} (%)	T_{ap} (0700+1700) (%)	T_{ap} (0700+1800) (%)	T_{ap} (0800+1700) (%)	T_{ap} (0800+1800) (%)	T_{sm} (0700) (%)	T_{sm} (0800) (%)	T_{sm} (1200) (%)	T_{sm} (1700) (%)	T_{sm} (1800) (%)
5	692 074	66.16	2.86	4.48	22.59	4.92	—	—	—	—	—
10	1 991 490	87.73	1.04	1.89	7.64	1.71	—	—	—	—	—
20	824 914	71.15	2.40	4.21	18.10	4.14	—	—	—	—	—
50	634 032	2.16	1.06	0.81	2.94	0.06	4.59	34.57	0.01	33.51	14.19
100	515 452	1.69	1.30	0.99	3.60	0.07	5.65	37.97	0.00	31.86	11.86

measurements at some particular hours can be reasonable representations of daily mean temperatures at those depths. In the following, we present the analysis results that verify the use of the three definitions for mean soil temperature and their consistency.

We examined the differences between the daily mean calculated from the arithmetic average of daily maximum and minimum temperatures (T_{mm}) and the averages calculated from the second and third definitions. The data used in the evaluation were quality-controlled hourly soil temperatures from 1994 to 2002 at 21 automated soil temperature stations in the USDA NRCS SM–ST network (Hu et al. 2002). At each station, the data are at depths from 5 to 100 cm under the surface. After calculating T_{mm} and the average from the two observations in the morning and afternoon hours (T_{ap}) at each depth, we examined the average difference between T_{ap} and T_{mm}, $\overline{T} = [1/(mN)]\ \Sigma_{n=1}^{N}\ \Sigma_{t=1}^{m}\ [T_{ap}(t,\ n) - T_{mm}(t,\ n)]$, and the average root-mean-square error (rmse) of the difference, $E_r = (1/N)\ \Sigma_{n=1}^{N}\ \{(1/m)\ \Sigma_{t=1}^{m}\ [T_{ap}(t,\ n) - T_{mm}(t,\ n)]^2\}^{1/2}$, where m is the number of observations at a depth and N is the total number of stations. Our results show that the largest average rmse between T_{ap} and T_{mm} is less than 0.25°C. At depths below 50 cm, the difference reduces to a few tenths of a degree Celsius. These small differences indicate that the T_{ap} calculated from temperatures at those specific morning and afternoon hours is a reasonably accurate measure of T_{mm} in both the shallow and deep depths.

Comparisons of T_{mm} and the single measurement of soil temperature at various hours (T_{sm}) show that at 5, 10, and 20 cm, the differences of T_{sm} and T_{mm} are large, and the largest average rmse at 5 cm is about 1.3°C. These large differences clearly indicate that T_{sm} cannot be used to represent T_{mm} at those shallow depths. However, at deep depths of 50 cm and below, because the daily temperature cycle has very small amplitudes (Hu et al. 2002), T_{sm}, particularly at the two morning hours, can represent T_{mm}. For example, at 50-cm depth, the largest average difference between T_{mm} and T_{sm} is 0.12°C, and the difference further reduces to a few tenths of a degree Celsius at 100 cm.

These results indicate that T_{ap} calculated from the pair of morning- and afternoon-hour observations at the stations consistently describe T_{mm} at all depths, with the maximum average error of 0.25°C at 5 cm. A single daily measurement T_{sm} can only represent T_{mm} at depths below 50 cm, with an error smaller than 0.12°C. An explanation for T_{ap} and deep-depth T_{sm} being able to describe T_{mm} is the soil's thermal damping on temperature variations so that the amplitude of diurnal cycle of soil temperature is small, particularly in deep soil layers. In addition, the phase shift of diurnal cycle with depth also results in shift of the daily maximum and minimum temperatures and helps to reduce the difference between T_{ap} and T_{mm}. These calculations of daily mean temperatures were applied to the soil temperatures at all of the stations, and a summary of the applications is in Table 3.

We then further compare the daily mean values produced from the three calculations with the daily mean soil temperature calculated from averaging the 24 hourly measurements at stations in the USDA NRCS SM–ST network. This comparison serves to verify the accuracy of these three calculations and their values in describing the daily mean soil temperatures, and we shall consider the average of 24 hourly values in a day as an adequate measure of daily mean temperature. The comparison results are shown in Figs. 5 and 6. The two pairs in Fig. 5 show the differences between the daily mean temperatures (and their rmse) calculated from the hourly values and those calculated from twice-daily measurements at different hours and also those obtained from averaging the daily maximum and minimum temperatures. The results in Fig. 5 show that the average daily mean calculated from the two measurements in a day remains within 0.15°C of the daily mean calculated from the 24 hourly data. At 50-cm depth, this difference, as well as the rmse, is within a fraction of one-tenth of a degree Celsius (Figs. 5c,d). Thus, the daily mean values calculated from the arithmetic average of the two measurements in a day and from daily maximum and minimum temperatures are within a reasonable accuracy to represent the daily mean temperature.

Similar accuracy was confirmed for using the single measurements to represent the daily mean soil temperatures at the 50-cm depth (Figs. 6c,d). However, this test also showed that the one time measurement in a day at shallow depth cannot represent the daily mean temperature because of large differences, up to 2.0°C, from the daily mean calculated using the 24 hourly data (Figs. 6a,b). Because we use single measurements to

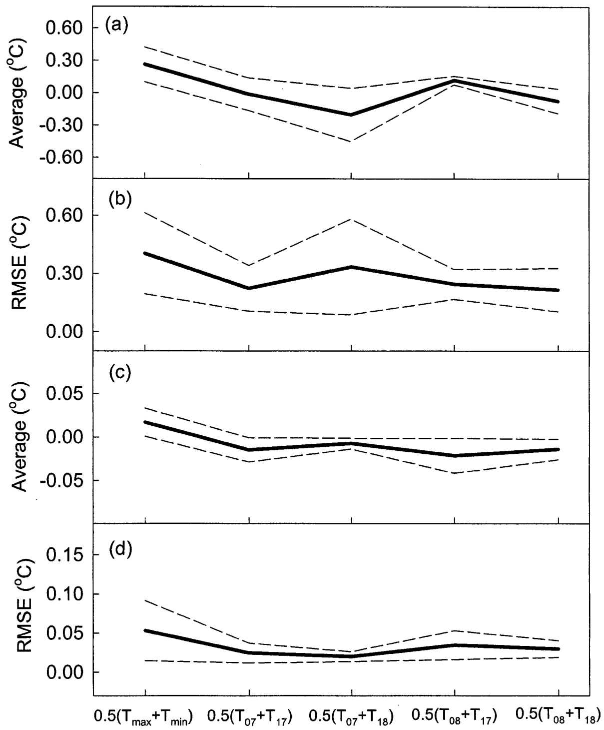

FIG. 5. (a) Station average difference between 5-cm T_{mm} or T_{ap}, which is calculated as arithmetic average from observations at the two local hours indicated in the legend of the abscissa, and the daily mean temperature calculated using hourly data from stations in the USDA NRCS SM–ST network. The two dashed lines show one std dev from the average. (b) The same as in (a), but for average rmse (see text for details). (c), (d) The same as (a) and (b), respectively, but for soil temperatures at 50-cm depth.

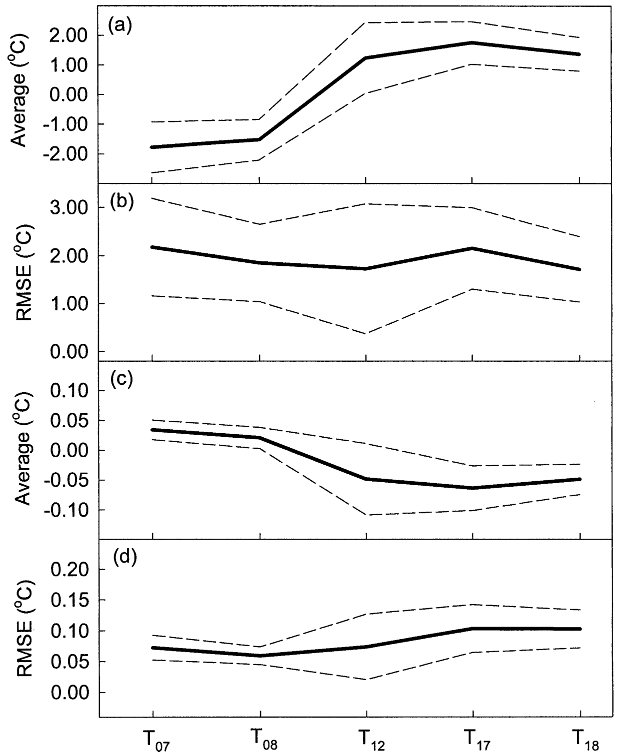

FIG. 6. Same as in corresponding panels in Fig. 5, but for difference between T_{sm} measured at different local times, indicated in the legend of the abscissa, and the daily mean temperature calculated using hourly observations from stations in the USDA NRCS SM–ST network.

represent daily mean soil temperatures at only depths at and below 50 cm (see Table 3), it is safe to say that all three calculations provide consistently accurate measures of daily mean soil temperatures, although the error ranges shown in Figs. 5 and 6 (except for Figs. 6a,b) should be borne in mind in evaluating the results of the next two sections.

4. Soil temperature climatology

From the calculated daily mean soil temperatures, we derived the stations' annual and seasonal soil temperatures at various depths averaged over the period of 1980–2002, because of more stations in service after 1980 (see Fig. 1b), and analyzed seasonal variations of soil temperatures in the contiguous United States. The mean and standard deviation of annual soil temperatures at five depths (5, 10, 20, 50, and 100 cm) are shown in Fig. 7 at individual stations and are shown also by contour lines, which were added to assist evaluation of spatial soil temperature variations because of the low density and highly irregular distribution of the stations. (Low density of stations, particularly in the mountainous and plateau regions, was a major factor preventing us from elaborating elevation effects on soil temperature variations.) The number of stations is highest at 10 cm and is reduced considerably at the other depths (also see Fig. 1b).

Figure 7 shows that the annual average soil temperature decreases northward as the climate changes from subtropical humid or dry in the southern United States to a temperate continental climate in the northern regions. At 5 and 10 cm below the surface, the average soil temperature and temperature distribution are similar; the mean temperature ranges from 24°C in the coastal areas along the Gulf of Mexico to below 8°C on the United States–Canada border. At 20 cm, the annual soil temperature is the coolest among temperatures at all five depths.

Interannual variations in the soil temperature are shown by the standard deviation in Fig. 7. Primarily because of soil's thermal damping property, the interannual fluctuations are smaller than 4°C at all five depths, with relatively large fluctuations in the central and north-central United States.

Seasonal means and standard deviations of soil temperature are shown in Fig. 8, and they describe seasonal changes in the soil temperatures. At 5 and 10 cm, freezing occurs in December–January in the northern plains north of the 40°N parallel from western Montana to west of the Great Lakes and also in the northeastern United

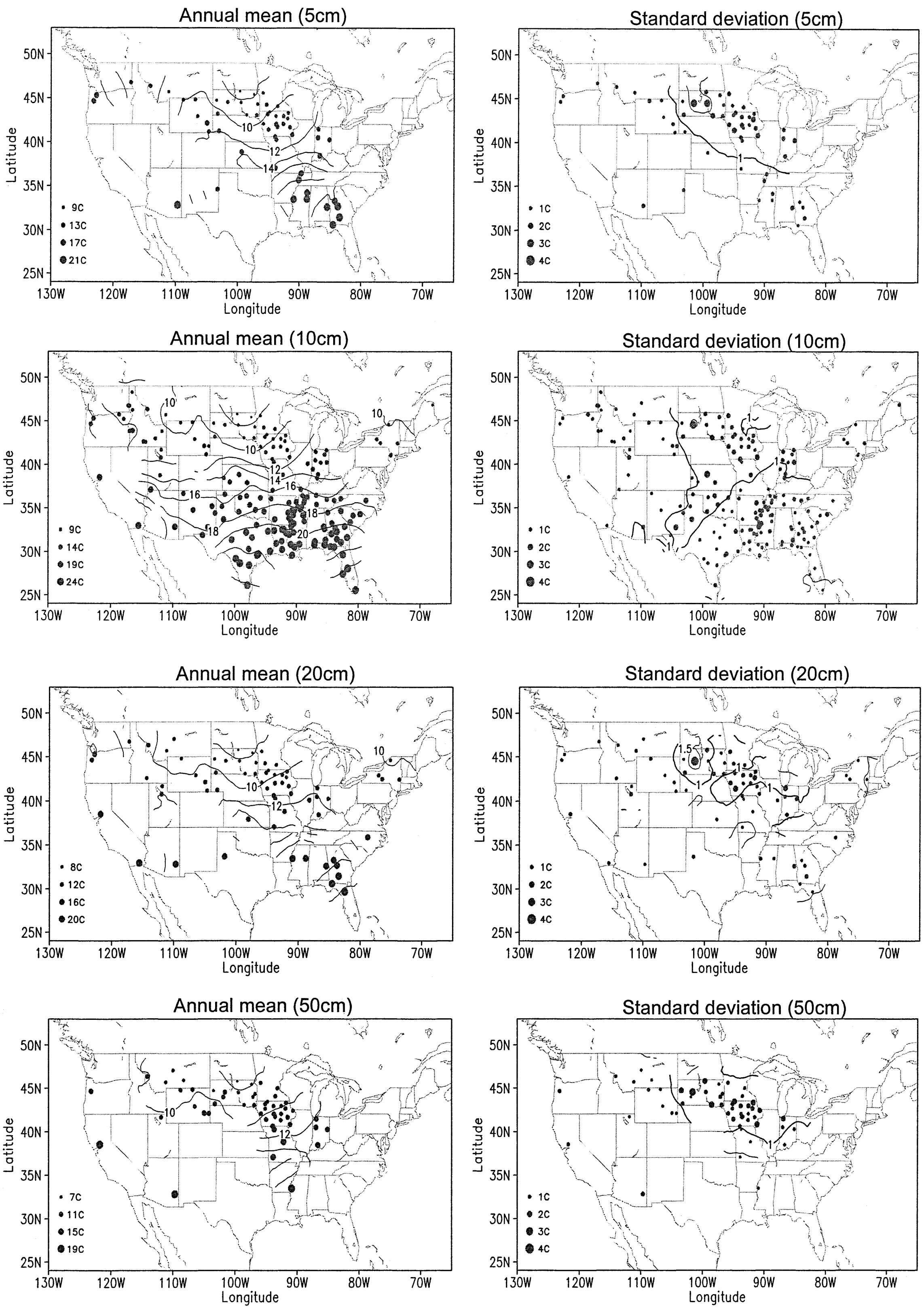

FIG. 7. Annual mean and std dev of soil temperatures at five depths at individual station (scales are marked in the lower-left corner of each panel). Contours are to assist evaluation of the stations' values and are not drawn in regions without stations. Contour interval is 2°C for annual mean temperature and 0.5°C for std dev.

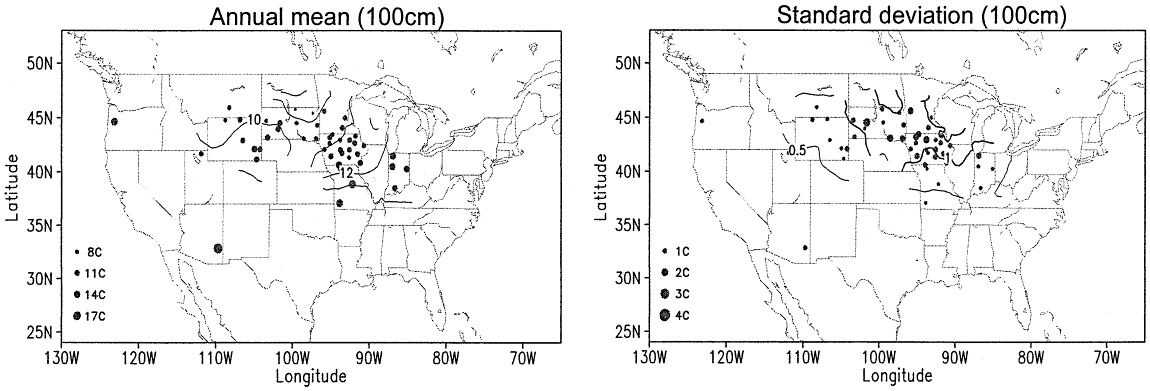

FIG. 7. (*Continued*)

States. Freezing is not observed at most stations in the central and southern United States at depths below 100 cm (figure not shown). The warmest soil temperature occurs in summer when the soil temperatures at 10 cm are as high as 34°C in the southern part of Texas. Seasonal changes in soil temperatures are the largest from spring to summer, when the 20°C contour line ''jumped'' over more than 20° of latitude from the southern United States to the United States–Canada border. In contrast, the soil temperature change in the transition from summer to autumn and from autumn to winter is mild.

The standard deviations of seasonal soil temperatures in Fig. 8 are the largest in spring and the smallest in autumn. In spring, the large standard deviations, indicating large variance of soil temperatures, have been related to fluctuations of winter snow amount in high-latitude regions of the north-central United States but are affected by alternations of contrasting weather regimes in the central United States. Our analyses showed that winters with more snow accumulation in the northern United States caused cooler soil temperatures in spring, because of spring melting, whereas considerably warmer soil temperatures were observed in springs that followed winters with less snow and snow accumulation. This snow effect on soil temperatures also contributed to the large winter-season soil temperature variations in the same region (Fig. 8). In the central United States, late snowstorms in April and early May during the warming course of temperatures caused large soil temperature variations and large soil temperature deviations in that region. In contrast, the lack of similar processes in autumn leaves small temperature fluctuations in that season.

5. Discussions

In addition to being useful in describing the average conditions and spatial and seasonal variations in the soil temperatures, the developed soil temperature dataset can be examined to reveal soil temperature changes and understand changes in land surface processes, as well as possible effects of these changes in agriculture and environment. Two of these features are discussed in this section.

a. Soil temperature trend

Although data length for most stations is only 35 yr (1967–2002), a trend analysis of the data could still provide insight into the soil temperature change and its relationship with changes in air temperature and precipitation. We show in Fig. 9a the linear trend of soil temperature at 10 cm for 38 stations that have more than 30 yr of data, and in Fig. 9b the temporal variation in the temperature averaged over the 38 stations in Fig. 9a is shown. Because the number of stations with 35-yr temperature records at 100-cm depth is much lower than that at 10 cm, we also plotted the stations' average 100-cm soil temperature variation and trend in Fig. 9c.

These results show that the soil temperature at 10-cm depth has been warming at most stations over the 35 yr, with an average rate of 0.31°C $(10\ \mathrm{yr})^{-1}$. This rate, though larger than the average of 0.10°C $(10\ \mathrm{yr})^{-1}$ for the air temperature, is comparable to the rate of change in air temperatures in recent decades (Karl et al. 1995). Among the stations with warming soil temperatures, those in the northern half of the United States have the largest rates. The warming trend at those stations is similar to the warming trend of their air temperature. On the other hand, among the few stations with cooling trends, those with the largest cooling rate are in the southeast, and the cooling of soil temperatures at those stations also was consistent with a decrease in the air temperatures at the stations (see Fig. 4 in Karl et al. 1996). At 100-cm depth, the few stations in the north-central United States showed a warming trend at an average rate of 0.30°C $(10\ \mathrm{yr})^{-1}$.

Superimposed on the trend of the soil temperatures in both the shallow and deep depths are interannual variations in the soil temperatures. The station-averaged variations of temperature deviation in Figs. 9b and 9c (solid lines) have similar phase and large amplitude from 5- to 100-cm depths over the years. These variations could result from various sources, including air tem-

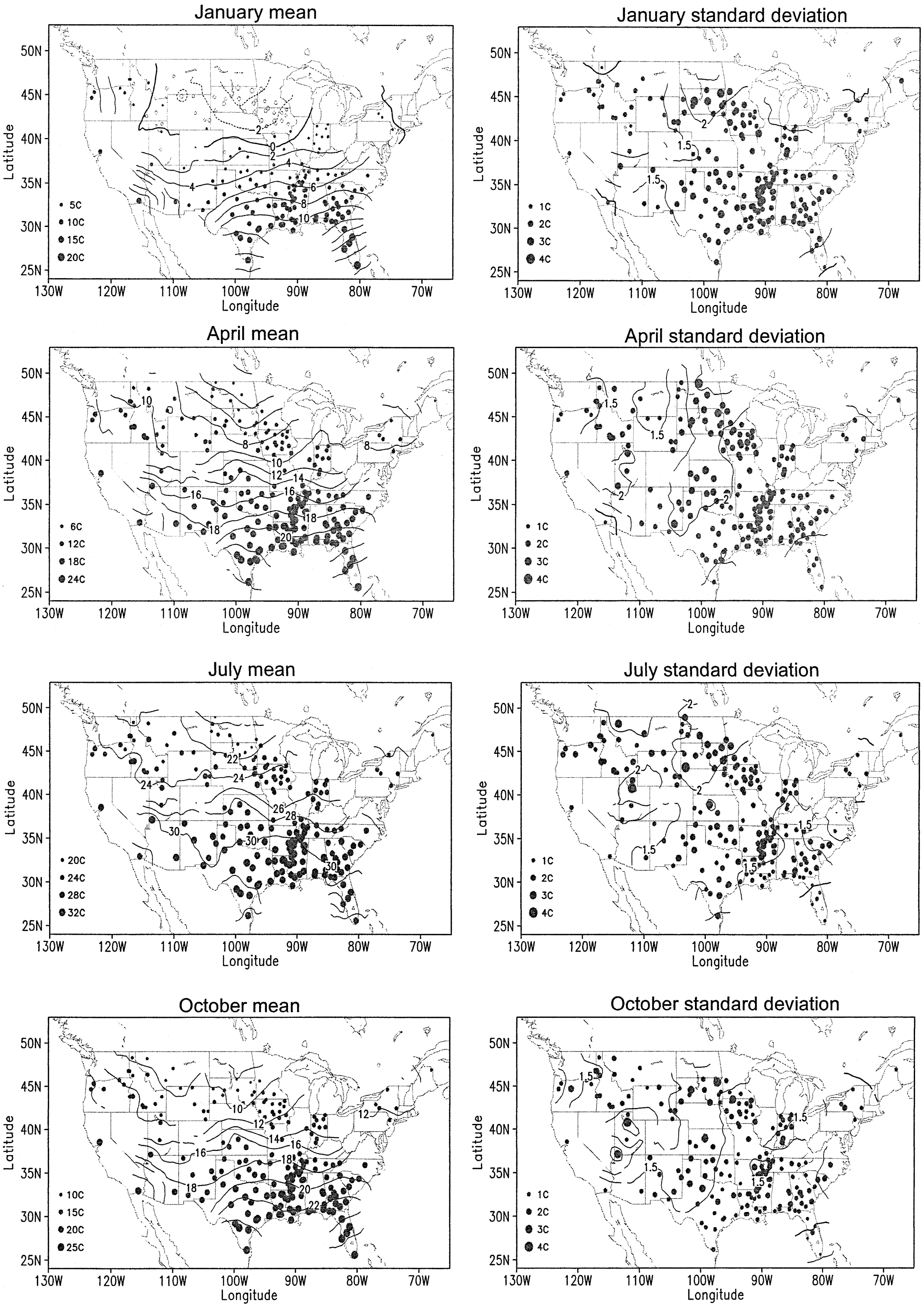

FIG. 8. Monthly mean and std dev of 10-cm soil temperature for Jan, Apr, Jul, and Oct. Individual station values are shown by the scales marked in the lower-left corner of each panel. Contours are to assist evaluation of the stations' values and are not drawn in regions without stations.

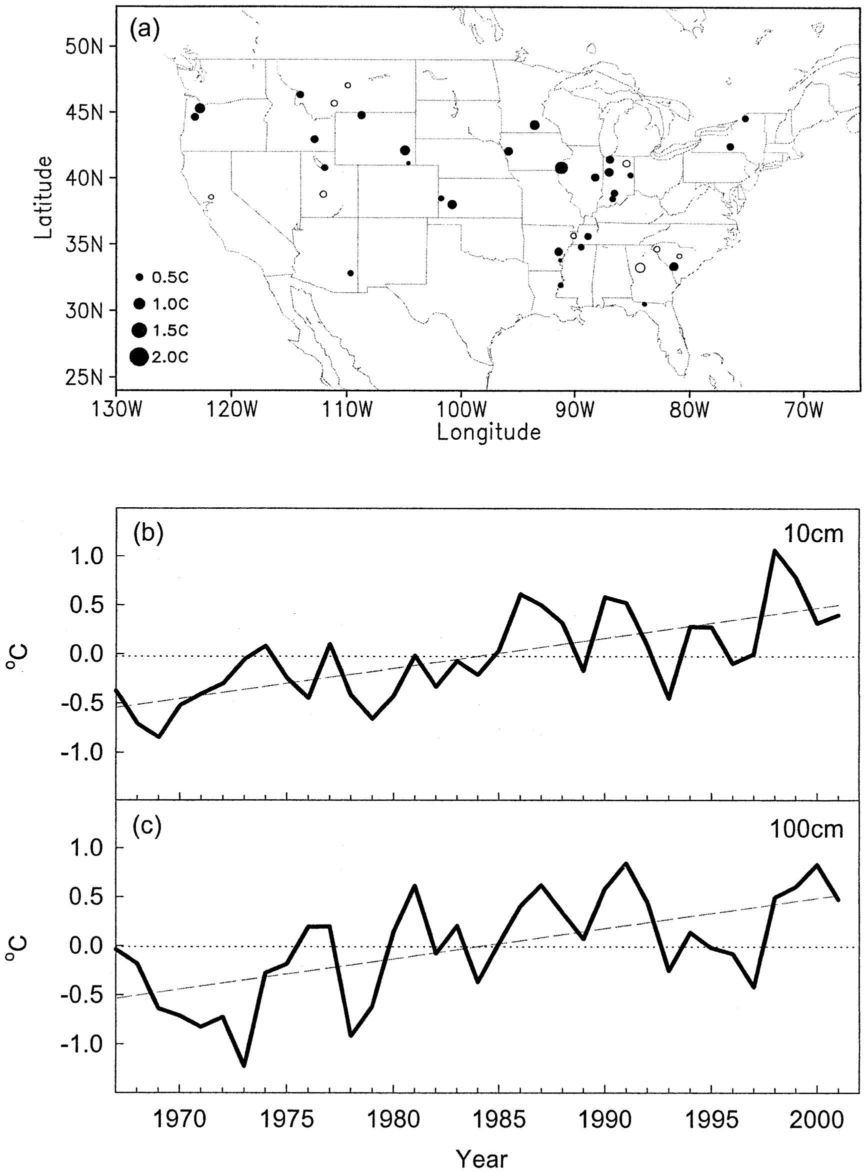

FIG. 9. (a) Trend in soil temperatures at 10-cm depth [°C (10 yr)$^{-1}$]. The scales are marked in the lower-left corner of the figure. (b) Temporal variations of 10-cm soil temperature averaged over the stations in (a). (c) Temporal variations of 100-cm soil temperature averaged over stations with record length longer than 30 yr. The dashed lines in (b) and (c) show the trend of the variation.

perature and precipitation variations, particularly from winter snow anomalies and snow melting in spring. Details of these effects on interannual soil temperature variations are currently examined in a separate study.

b. Soil temperature change and agriculture

Soil temperature under bare ground is often used as a measure of the thermal condition in cropland before planting and is one of the indicators for spring planting time, because warm soil temperature is essential to seed germination and early development (Bollero et al. 1996). As shown in Fig. 10, the averaged winter and spring soil temperatures at 10-cm depth both increased in the last 35 yr in the contiguous United States (significant above the 95% confidence level). Such a warming trend in spring soil temperature would favor planting in earlier dates, especially in the northern half of the United States (e.g., Meyer and Dutcher 1998), and would allow growth of high-yield varieties of certain crops (e.g., corn) that require a longer growing season to mature. Warmer soil temperature in the early spring season also would encourage both leaf and root growth and a higher yield of corn (Bollero et al. 1996; Mc-

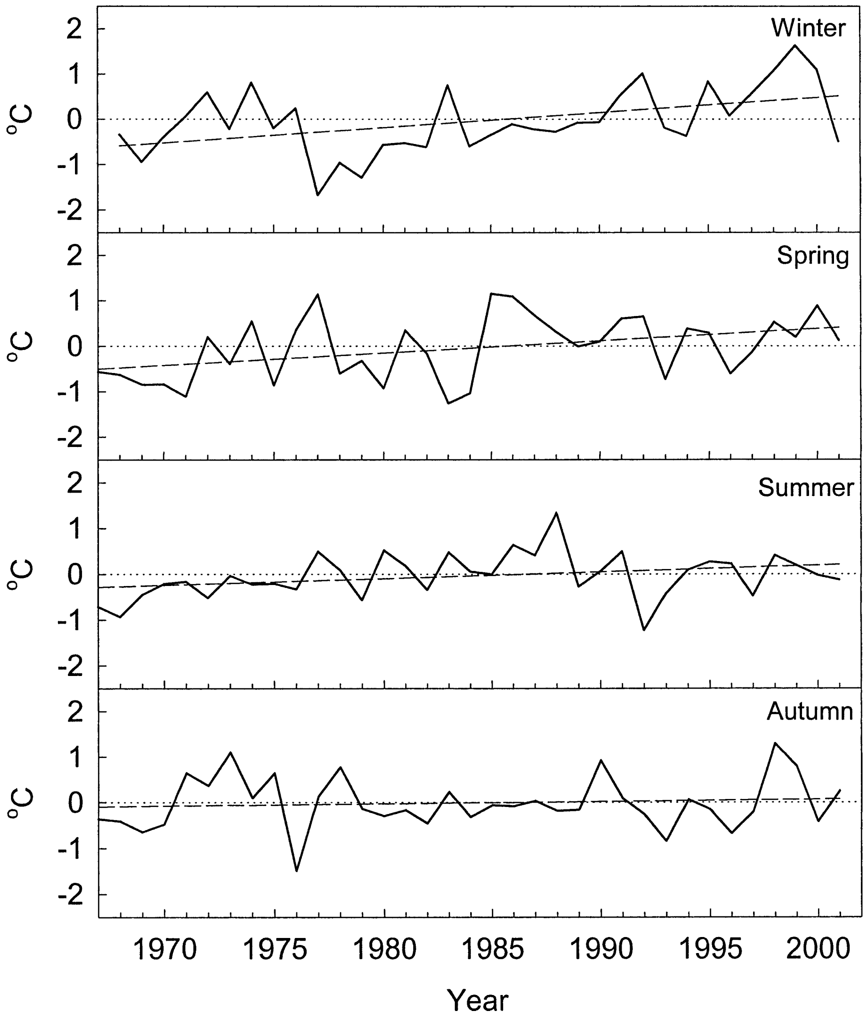

FIG. 10. Trend (dashed lines) of seasonal average 10-cm soil temperature variation (solid lines) for 1967–2002 (see text for details).

Michael and Burke 1998). The soil temperature dataset developed in this work can be used to quantify changes of average planting dates for various crops and additional statistical features of these new planting dates, for example, probability of temperature deviations from their mean. Moreover, analysis of the soil temperature data with local air temperature and precipitation could be used to evaluate the feasibility of growing a new variety of a crop or different crops.

Warming soil temperatures also can have negative impacts on agriculture. The rising winter soil temperatures would be favorable for insects to survive the winters and thus for large insect populations in the following growing season. In addition, warmer soil and air temperatures in winter and spring in the mid- and higher-latitude regions could assist in the fast melting of snow to reduce winter season snowpack and, hence, stream flows and water resources in the following growing season. The soil temperature dataset produced from this study can be used to analyze these various effects of soil temperature on agriculture and to assist in development of practical methods to maintain and improve agricultural production.

6. Summary

A dataset of soil temperatures is developed for the continuous United States. The soil temperature data were from the U.S. NWS cooperative stations. Each station has soil temperatures at up to five depths of 5, 10, 20, 50, and 100 cm below the surface for up to 35 yr from 1967 to 2002. These station data were examined for consistency in both temporal variations and variations at various depths. In addition, erroneous data that continue for extended periods were replaced with estimates using methods developed in this study. This dataset not only extends the climatic data array to include the soil temperatures but also opens opportunities for acquiring knowledge of soil temperature variations and their relationship with changes in air temperature and precipitation and knowledge of the effect of soil temperature change on regional agriculture.

Taking advantage of this opportunity, we explored soil temperature climatological behavior using daily mean soil temperatures derived from the quality-controlled dataset. The climatological data show both the soil temperatures at various depths averaged over each station's record history (up to 35 yr) and the dynamic aspects of the temperatures during transitions between seasons. The former describe a north–south gradient across the contiguous United States, and the latter reveal a large change of soil temperature from spring to summer. In the winter months, from December to January, soil temperature is below freezing in the north-central United States and the northern Great Plains in shallow layers above 100 cm. At 100-cm depth, the winter temperature is below freezing only at a few stations in high latitudes of the northern region. In the vertical direction across the soil column at each station, the annual average soil temperature is coolest at 20 cm below the surface. Soil temperatures at depths below 20 cm are as warm as, and at many stations warmer than, that above 20 cm—a result speculated to be due to soil heat storage capacity and slow heat release at the deeper layers.

Soil temperature at most stations has shown a trend of warming in the last 35 yr, a result similar to that observed in the air temperature changes. The average warming rate is 0.3°C $(10\ \mathrm{yr})^{-1}$ and is comparable to the warming rate of air temperatures. A few stations in the southeastern United States show a trend of cooling. These trends in soil temperatures are significant in both the shallow and deep layers. Potential impacts of the changing soil temperatures on agriculture are outlined, based on relationships of warming soil temperature in spring and earlier planting dates of various crops.

In addition to these applications, the developed soil temperature dataset can be used in studies that lead to improved understanding of, for example, the thermodynamic process in soils and the relationship of soil temperature and surface heat flux variations. This relationship could be used to examine the soil temperature variations described by regional circulation or climate models and to validate and improve the ability of models to describe the surface energy processes.

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