# The Global Soil Moisture Data Bank

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## ABSTRACT

Soil moisture is an important variable in the climate system. Understanding and predicting variations of surface temperature, drought, and flood depend critically on knowledge of soil moisture variations, as do impacts of climate change and weather forecasting. An observational dataset of actual in situ measurements is crucial for climatological analysis, for model development and evaluation, and as ground truth for remote sensing. To that end, the Global Soil Moisture Data Bank, a Web site (http://climate.envsci.rutgers.edu/soil_moisture) dedicated to collection, dissemination, and analysis of soil moisture data from around the globe, is described. The data bank currently has soil moisture observations for over 600 stations from a large variety of global climates, including the former Soviet Union, China, Mongolia, India, and the United States. Most of the data are in situ gravimetric observations of soil moisture; all extend for at least 6 years and most for more than 15 years. Most of the stations have grass vegetation, and some are agricultural. The observations have been used to examine the temporal and spatial scales of soil moisture variations, to evaluate Atmospheric Model Intercomparison Project, Project for Intercomparison of Land-Surface Parameterization Schemes, and Global Soil Wetness Project simulations of soil moisture, for remote sensing of soil moisture, for designing new soil moisture observational networks, and to examine soil moisture trends. For the top 1-m soil layers, the temporal scale of soil moisture variation at all midlatitude sites is 1.5 to 2 months and the spatial scale is about 500 km. Land surface models, in general, do not capture the observed soil moisture variations when forced with either model-generated or observed meteorology. In contrast to predictions of summer desiccation with increasing temperatures, for the stations with the longest records summer soil moisture in the top 1 m has increased while temperatures have risen. The increasing trend in precipitation more than compensated for the enhanced evaporation.

## 1. Introduction

Regular gravimetric observation of soil moisture was started in the 1930s in the former Soviet Union (FSU) at a network of agrometeorological stations. Several neighboring countries adopted the Russian method of soil moisture observation, among them Mongolia, China, India, and a few eastern European countries. In the United States, regular soil moisture observation was organized in the 1980s by the Illinois State Water Survey (Hollinger and Isard 1994). Very recently, an observational soil moisture network of more than 100 stations has been set up as part of the Oklahoma Moistnet, but the data are just now becoming available. There are many research stations around the world that conduct soil moisture observation pro-

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grams for specific projects. The lack of standardization in these data makes them of limited use for scientific study without a large amount of processing.

From the regular measurement programs, however, there are more than 600 stations with records longer than 6 years that can be used for climatological studies. We have assembled these data, conducted quality control, and made them available on a World Wide Web site we call the Global Soil Moisture Data Bank (http://climate.envsci.rutgers.edu/soil_moisture). We have already used these data for climate model evaluation (Vinnikov and Yeserkepova 1991; Robock et al. 1995, 1998; Schlosser et al. 1997, 2000; Yang et al. 1997; Entin et al. 1999), remote sensing of soil moisture (Vinnikov et al. 1999b), studying the spatial and temporal scales of soil moisture variations (Vinnikov et al. 1996; Entin et al. 2000), and for designing new networks of soil moisture observations (Vinnikov et al. 1999a). Here we describe the datasets and how they were observed, display examples of the data, and for the first time present the trends of summer soil moisture from the stations with the longest records. We continue to collect soil moisture data and seek out and encourage contributions of more datasets.

Much of the data in our data bank have never been used for scientific research or have only been used in a very limited way. We choose to release them now so that the community can make the maximum use of them. Our philosophy is that the more people use the data, the more valuable they become to us. The more people use the data, the more chances there are to correct errors in the datasets and make them more useful. Thanks to our past and current support from the National Oceanic and Atmospheric Administration (NOAA), the National Aeronautics and Space Administration (NASA), and the New Jersey Agricultural Experiment Station, we make the data available over the Web at no cost. We do this as a demonstration of the way all data should be distributed, in support of our common interest in scientific progress.

Sometimes the word "data" is used to describe output from theoretical model calculations, or values derived from theoretical analysis of radiances from remote sensing. We prefer to reserve this word for actual physical observations. All the data in our data bank are actual in situ observations. This distinction is particularly important, as sometimes a model-generated or remotely sensed soil moisture "datasets" are interpreted and used as genuine observations. Indeed, it is crucial to first validate these datasets with actual observations before they can be productively used. This is the main motivation for collection and dissemination of soil moisture data through our data bank. As long in situ observational records of soil moisture are limited to certain areas of the globe, global datasets will have to be produced by some combination of in situ, remotely sensed, and modeled products. If they can be validated in regions where we have actual observations, then they can be trusted for other regions and times.

In this paper we first define soil moisture and explain why it is important. We briefly explain how soil moisture is measured. We then present our set of observations and show examples of seasonal and interannual variations. In particular, we show that everywhere in Asia we look, we find large upward trends of soil moisture for several decades. Next we briefly describe current attempts to create soil moisture datasets with remote sensing and modeling that may have the potential in the future, when validated with actual observations, to be used to produce global soil moisture datasets.

## 2. What is soil moisture, and why is it important?

A major component of soil hydrology is soil moisture. In the past, many land surface modelers did not consider the soil moisture portion of their models to be physically based and thought of the soil moisture representation as more of an index used for evapotranspiration and runoff calculations rather than representative of the actual mass of moisture in the soil. But the latest generation of weather forecast models have as one of their aims to accurately predict soil moisture. Wei (1995) points out that:

> Soil moisture serves a critical role in shaping the ecosystem response to the physical environment. Near-surface soil moisture controls the partitioning of available energy at the ground surface into sensible and latent heat exchanges with the atmosphere, thus linking the water and energy balances through the moisture and temperature states of the soil. Adequate knowledge of the distribution and linkage of soil moisture to evaporation and transpiration is essential to predicting the reciprocal influence of land surface processes to weather and climate. Despite this importance, global measurement and analysis of soil moisture and temperature remains an outstanding

scientific problem with far-reaching significance to humankind.

We therefore present here our soil moisture data collection as a partial step toward addressing this problem.

Soil moisture is the main source of natural water resources for agriculture and natural vegetation. It affects not only the vertical fluxes of energy and moisture, but also the horizontal fluxes of moisture, namely, runoff. Soil moisture, along with snow cover, is also the most important component of meteorological memory for the climate system over the land (Delworth and Manabe 1988, 1993).

Soil moisture can be expressed in different units. The most common are as plant-available volumetric ($W$) or as total volumetric soil moisture ($W_T$), expressed as the depth of a column of water contained in a given depth of soil, or as the volumetric percent of water in a given soil depth. A fraction, typically less than half, of soil consists of pores that can be filled with air or water. This fraction is called the *porosity* ($P$). If this fraction were completely filled with water, the soil would contain its *total water holding capacity* ($W_O$), and the water table would be at the surface. For any layer of depth (thickness) $D$, $W_O = PD$. If the soil were saturated, so that $W_T = W_O$, and then gravitational drainage were allowed to occur until it was negligible, the amount of water left in the soil is called the *field capacity* ($W_f$). If vegetation then extracted as much water as possible until it wilted, the remaining soil moisture is called the *wilting level* ($W^*$), and this amount of water is unavailable to plants. The plant-available soil moisture is $W = W_T - W^*$. In a bucket model (Budyko 1956; Manabe 1969), $W^*$ is ignored and only $W$ is considered. Our observations are presented as $W$ or $W_T$, in cm for a given soil layer depth.

## 3. Measurement of soil moisture

There are many different techniques to measure soil moisture. The choice of a particular method depends on the application and the resources available. Here, we briefly describe the principal techniques used to observe our data. All our current datasets are measured with the gravimetric method, except that the Illinois and part of the Iowa data are measured with neutron probes, calibrated with gravimetric observations. The Oklahoma MOISTNET data are measured with heat dissipation sensors. Baker (1990) and Cuenca and Noilhan (1991) provide more detailed descriptions of these methods.

### a. Gravimetric

The gravimetric method, also called the thermostat–weight technique, has been in use for a long time. Soil samples are taken using coring devices or augers at required depths and locations (Fig. 1). Typically (in the Russian method) 10-cm long segments down to a depth of 1 or 1.5 m are extracted and a smaller sample is removed from each segment (Fig. 2). The sample is weighed, oven-dried, and weighed again. The difference in mass gives the total soil moisture in the sample, which is converted to volumetric units using the density of the soil. The wilting level, previously determined from laboratory experiments with an oat crop (Vinnikov and Yeserkepova 1991), is then subtracted, giving plant-available soil moisture, expressed as depth of liquid water.

Typically, samples are taken at four different locations at a station each 10 days. Figure 3 shows the

FIG. 1. Two types of augers used for gravimetric soil moisture observations, sitting on a neutron probe. The one on the left is pounded into the ground and used when the ground is frozen. The one on the right is twisted into the ground. Photograph by A. Robock.

FIG. 2. Sampling soil moisture on pasture land at Zuunmod, Mongolia, using the gravimetric technique. After the samples are collected in sample cans, they are weighed, oven dried, and weighed again. Photograph by A. Robock.

holes made from sampling at a station near Beijing, China. After 10 days, the cores are replaced in the holes and samples are taken from other holes. In this way, after some time the effects of sampling disappear and the same locations can be reused.

The gravimetric method is low-tech and simple, making it an excellent technique for long homogeneous climatological records. As it is labor-intensive, and somewhat destructive to its site, new electronic methods are being introduced, which are indirect and require calibration and theoretical assumptions. With suitable parallel measurements, the new methods can produce useful long records and are briefly described below.

*b. Neutron probe*

The neutron probe is relatively easy to use, accurate, and capable of measurements in real time. A probe with a fast neutron source is placed on the surface or lowered in an access tube (transparent to the neutrons), and the backscattered slow neutrons are measured. The backscattered flux of slow neutrons is proportional to the density of hydrogen atoms. Water is the major source of hydrogen atoms that changes with time, therefore the neutron probe provides a good measure of soil water content. Calibration of slow neutron counts with gravimetric samples of soil moisture content and bulk densities yields a relationship to estimate the volumetric soil moisture content. Since radioactive scattering occurs over a spherical domain, a neutron probe samples a volume of soil rather than a point. As this volume of influence depends on soil moisture content, there are differences in the soil volumes sampled in dry and wet soils. These differences are generally small as compared to the total volume sampled by the probe, but they influence the depth resolution of the probe. The probe's relatively large volume of influence makes observations at shallow depths prone to errors, as adjoining air is also sampled. Disadvantages of neutron probes include their requirement to be calibrated to soil types and zones over a period of time with different soil moisture, that they are also labor-intensive, the need for precautions associated with handling radioactive material, and the relatively high costs.

*c. Heat dissipation sensors*

These sensors make point measurement of soil moisture tension by measuring temperature changes in response to a heat pulse. A small ceramic block with an embedded sensor is briefly heated. The rate of heating is affected by the ability of the surrounding soil to dissipate the heat, which is related to the soil moisture content. The measured heating rate must be calibrated, and soil moisture tension related to volumetric water content, by gravimetric observations for each location. These sensors are relatively inexpensive and can produce measurements every 30 minutes.

*d. Other sensors*

Other soil moisture measurement techniques include the tensiometer (a bulb of porous ceramic material is placed inside the soil and connected to a water-filled tube, which is used to measure soil moisture tension after allowing the system to equilibrate), the gypsum block (small cylindrical gypsum blocks embedded with electrodes are buried at required depths in the soil and measure the electrical resistance, which is related to the water content), time domain reflectometry (TDR; based on monitoring changes in the dielectric properties of the soil at microwave frequencies), frequency domain reflectometry (FDR; similar to TDR, except that it derives soil moisture content based on changes in the frequency of signals due to the dielectric properties of the soil), and gamma densitometry (based on the relatively greater gamma radiation attenuation factor of water compared to other soil components). Each technique has limitations and advantages, and all must be calibrated with gravimetric observations.

## 4. Current data collection

The Global Soil Moisture Data Bank currently contains data from many hundreds of stations for many years. A map of these stations is presented in Fig. 4 and they are summarized in Table 1. For most of these datasets we have files with soil constants for wilting level, field capacity, and porosity. Here we describe each dataset with its name.

*a. RUSWET-130STA*

This dataset contains, for 1978–85, soil moisture gravimetric measurements from 130 meteorological stations of the FSU. The dataset contains plant available soil moisture for the upper 10-cm and 1-m soil layers at flat observational plots with natural grass-type vegetation about 0.1 ha in area. Since these are flat plots and not catchments, and chosen so as to minimize horizontal subsurface transport, runoff measurements are not available. Observations are made with temporal resolution of about 10 days during the warm season, and once a month during winter. Four points in each plot are used for each measurement and the results averaged. The data for 1978–85 are a small part of the data that were published in annual reference books (for governmental use only) and contain data for Russia, Ukraine, Byelorussia, Moldova, Lithuania, Latvia, Estonia, and Kazakhstan. Due to the lag between observations and publication of the data in reference books, and the collapse of the Soviet Union, the observations taken after 1985 were never published, and many of these stations have been closed. Therefore, we do not expect to be able to update this dataset.

*b. RUSWET-50STA*

This is a subset of RUSWET-130STA of stations with longer time series of top 1-m data. The entire dataset covers the years 1952–85, but the spatial extent of these data is poor until about 1975. This is the dataset used by Vinnikov and Yeserkepova (1991), which contains a detailed description of the data.

*c. RUSWET-6STA*

Robock et al. (1995) used six heat balance stations (Yershov, Tulun, Uralsk, Kostroma, Khabarovsk, and Ogurtsovo) from the RUSWET-50STA archive (also in the 130-station archive) to demonstrate that land surface models [the bucket (Budyko 1956; Manabe 1969) and SSiB (Xue et al. 1991)], when forced with actual meteorological and actinometric data, can be evaluated by comparison with actual soil moisture, snow depth, albedo, and net radiation observations. The heat balance stations are specially selected meteorological stations that make an additional suite of measurements of snow and energy balance. These data have been used by a number of land surface groups to exercise their models, and we encourage further use of these data by others. Douville et al. (1995) used these data to develop the Météo-France land surface model. Yang et al. (1997) subsequently used the same

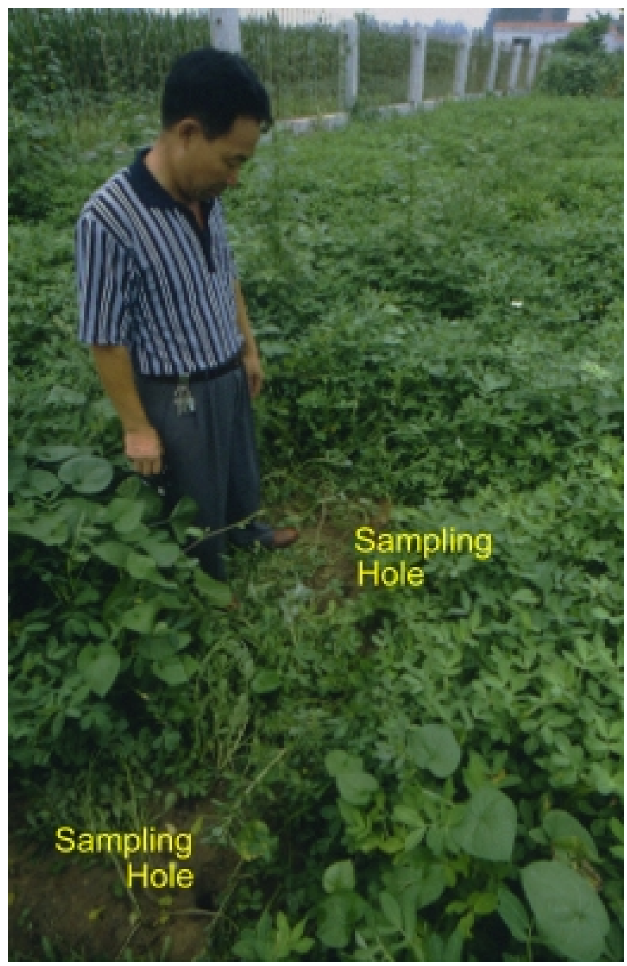


FIG. 3. Holes produced by gravimetric sampling at the Miyun station near Beijing, China, with Dr. Zhang, director of the station. The observations are taken in a peanut crop. The plants were pushed to the side for photographic purposes only. Observations are made every 10 days. When the next observation is taken, the cores that were removed from these holes are replaced and samples are taken from other locations in the field. Photograph by A. Robock.

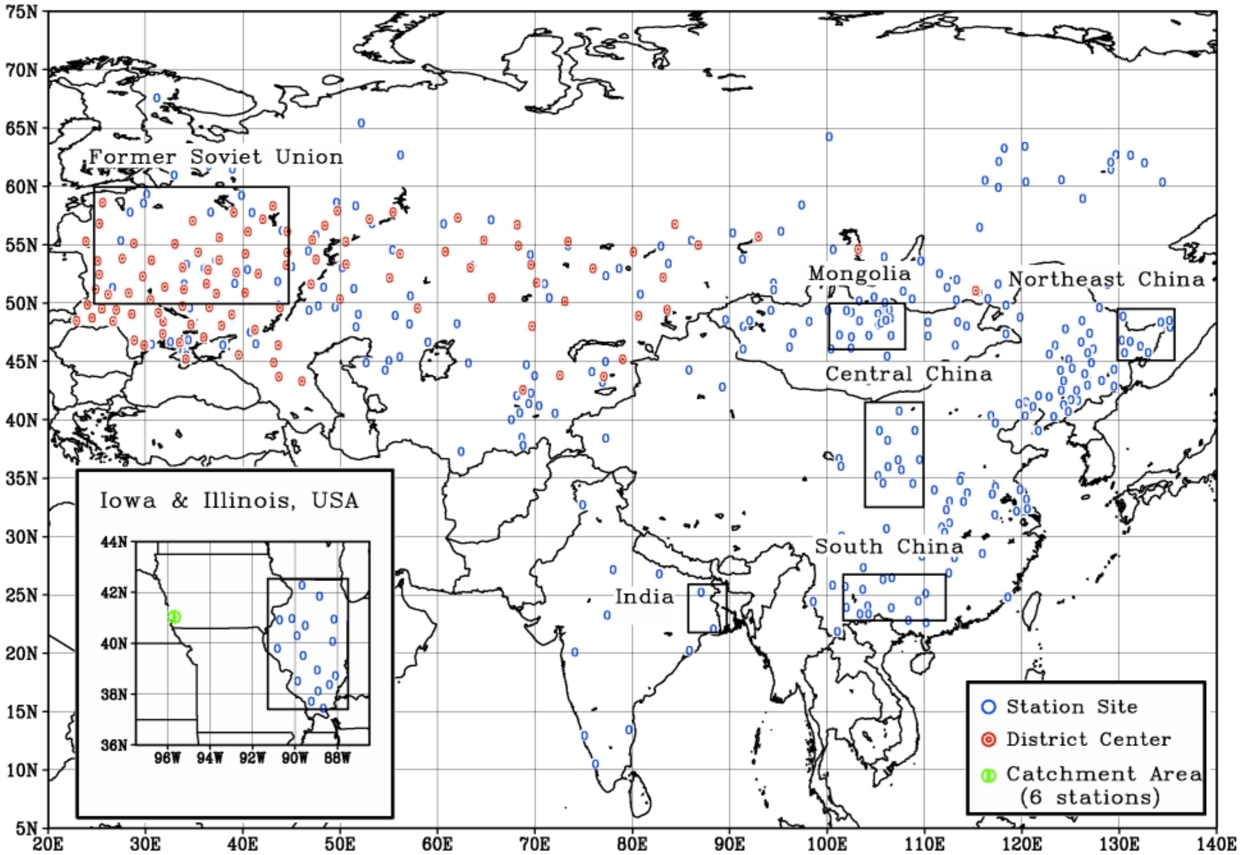


FIG. 4. Global Soil Moisture Data Bank. Map of the distribution of the stations in our current collection and location of the regions used for sample seasonal cycle plots (Fig. 5). Part of the Russian data represent averages for administrative districts, rather than individual stations, from the RUSWET-AGRO and RUSWET-AGROCLIM datasets, and are indicated as circled dots.

data with the BATS model (Dickinson et al. 1986) to evaluate and improve the snow cover parameterization, and Slater et al. (1998a,b) have used the data to evaluate snow parameterization and subsurface winter hydrology with their BASE model (Desborough 1997). Data on the Web site for these stations include forcing (meteorological and actinometric observations) and validation data, including soil moisture for four different layers (0–10, 0–20, 0–50, and 0–100 cm), net radiation at the surface (longwave and shortwave), surface albedo, snow cover thickness, snow covered area, evaporation from snow, total evaporation, freezing depths, ground temperature and heat balance at different depths, and depth and temperature of water table.

*d. RUSWET-16STA*

We have data from 16 other energy-balance stations like the 6 above that we have not used for modeling. We also have meteorological observations for four of these stations.

*e. RUSWET-AGRO*

This dataset has been prepared by V. Zabelin (Rosgidrometcenter, Moscow, Russia). It contains district-average, plant-available soil moisture for the upper 20-cm and 1-m layers at agricultural fields with winter and spring cereal crops (given separately) for 102 administrative districts of the FSU. The measurements of an average of about six stations were used for each district with equal weights. The average area of each district is about 30 000 km$^2$ (ranging from 10 000 to more than 100 000 km$^2$). The data have temporal resolution of 10 days (three measurements per month) during the growing period, from 8 April to 28 October. Soil moisture for winter cereal crops is a good analog of natural vegetation. This is not true for spring cereals, but for many regions in southern Siberia and northern Kazakhstan spring cereal crops occupy up to 90% of the total territories. These data are the product of a system for soil moisture monitoring at agricultural fields of the FSU. This information was not secret but was used only for agricultural predictions and until

Table 1. Current status of the use of the soil moisture datasets.

| Dataset | No. of stations | Years | Frequency | Soil properties | Forcing data |
|---|---|---|---|---|---|
| RUSWET-130STA Grass | 130 | 1978–85 | 3/month | Yes | 28 stations |
| RUSWET-50STA Grass | 50 | 1952–85 | 3/month | Yes | 28 stations |
| RUSWET-6STA Grass | 6 | 1978–85 | 3/month | Yes | 6 stations |
| RUSWET-16STA Grass | 16 | 1978–85 | 3/month | Yes | 4 stations |
| RUSWET-AGRO Winter and spring cereals | 102 | 1958–now | 3/month* | | |
| RUSWET-AGROCLIM Winter and spring cereals | 144 | 1927–82 | 3/month* | | |
| Valdai Water balance station | 1 (3 catchments) | 1961–91 | 3/month | Yes | Yes |
| Podmoskovnaya Water balance station | 1 | 1955–88 | 3/month | Yes | Yes |
| Kammennaya Steppe Water balance station | 1 (6 catchments) | 1956–90 | 3/month | Yes | Yes |
| China Grass and agriculture | 102 | 1981–91 | 3/month | Yes | 46 stations |
| Mongolia Pasture and wheat | 40 | 1973–95 | 3/month* | Yes | |
| India Grass | 11 | 1987–95 | 1/week | Yes | |
| Illinois Grass | 19 | 1982–present | 2 or 3/month | Yes | 5 stations |
| Iowa Corn | 6 | 1972–94 | 2/month* | Yes | Yes |

*Growing season only, Apr–Oct.

now has been absolutely unavailable for the international scientific community. It has never been described or even mentioned in scientific publications until Entin et al. (1999).

The locations of these stations are shown in Fig. 4 using circled dots. They are in the grain belt of the FSU (Russia, Ukraine, Byelorussia, Moldova, Lithuania, Latvia, Estonia, and Kazakhstan). The dataset for two years, 1987–88, has been used in the International Satellite Land Surface Climatology Project (ISLSCP) Global Soil Wetness Project (GSWP; Dirmeyer et al. 1999). The entire dataset from 1958 through the present for Russia and the Ukraine, and during 1958–91 for other parts of the FSU is now available. We have arranged to continue to receive these data in real time from Russia. Soil moisture data for the upper 20-cm layer were lost for 1958–75, but are available starting in 1976. Only the data from Russia and the Ukraine are available after 1991 due to the disintegration of the FSU.

*f. RUSWET-AGROCLIM*

This dataset consists of multiyear averages of plant available water content in the soil layers 0–100, 0–50, and 0–20 cm of the RUSWET-AGRO data, from agricultural fields with winter cereal crops and spring cereal crops (given separately) for 144 administrative districts of the FSU. The measurements of six stations (on the average) were used for each district with equal weights. The period of observations is 1946–80 for the western part and 1927–82 for the eastern part of the FSU. The data were retrieved and digitized from Kelchevskaya (1989) and Zhukov (1986). This dataset provides a comprehensive climatology of agricultural soil moisture and serves as a basis for climate variation studies using the recent data. It has been subjected to rigorous quality control.

*g. Valdai*

The water balance station Valdai (57.6°N, 33.1°E) in the forest zone of Russia, is operated by the State Hydrological Institute in St. Petersburg, Russia (Fedorov 1977; Vinnikov et al. 1996). This station is a scientific center where the methods of water balance measurements were tested and then used for the creation of a network of 24 water balance stations in different climatic zones of the FSU. Observations from these stations have been published in annual reference books that have never before been available to the international scientific community. These data, for 1960–90, are from three small experimental catchments with different vegetation: Usadievskiy (grassland), Tayozhniy (old forest), and Sinaya Gnilka (growing forest). They include observations of all the components of the land surface water balance: soil moisture, runoff, water table, snow cover, and evaporation; some components of the land surface energy balance, including soil temperature and depth of the frozen layer; and regular meteorological observations. Vinnikov et al. (1996) used these data to study temporal scales of soil moisture variations.

Schlosser et al. (1997) showed that Valdai data can be used for validation of land surface models. The Usadievskiy dataset for 1966–83 was chosen as the basis for the Project for Intercomparison of Land-surface Parameterization Schemes (PILPS; Henderson-Sellers et al. 1993) Phase 2(d) study. Validation data include soil moisture, water table, and daily runoff and soil temperature at different depths. So far, 21 scientific groups have run their models using identical model parameters and the same forcing. The first results (Schlosser et al. 2000) showed large differences between different land surface schemes and helped the modelers to improve their treatments of snow cover, infiltration, and runoff. Similar studies using the old forest and growing forest are planned.

*h. Podmoskovnaya*

The water balance station Podmoskovnaya (55.7°N, 37.2°E) is 30 km from Moscow. Our dataset is similar to that of Valdai and contains observations for 1955–88 at nine small experimental catchments of all the main components of the water and energy balance, and special meteorological observations. Routine meteorological measurements are also available.

*i. Kamennaya Steppe*

The water balance station Kamennaya Steppe (51.1°N, 40.7°E) was organized as a special station for studying the influence of forest strips on the meteorological and hydrological regime of the very dry steppe. Our dataset contains observations for the period 1956–90 at six small experimental catchments. It is mostly the same information as for station Podmoskovnaya, except that water table data are unavailable. (These data have never appeared in the reference books for this station. This is probably because ground water in the dry steppe is usually very deep and does not influence the water regime of the upper soil layer.)

*j. China*

This dataset currently contains gravimetric observations at 102 Chinese stations for the 11-year period 1981–91. Most of the observations are made at agricultural fields. The temporal resolution is the same as for the Russian data, with three measurements per month. Each measurement is at 11 vertical levels: 0–5, 5–10, 10–20 cm, and each 10-cm layer down to 1 m. The vegetation types include winter wheat, maize, rice, sorghum, and beans. Soil moisture measurements are made at permanent sites with an area of from 0.5 to 20 ha yearround (e.g., Fig. 3). Gravimetric measurements are made on the 8th, 18th, and 28th day of each month, using the same schedule and technique as in the FSU (Vinnikov and Yeserkepova 1991), except that for some stations, no measurements were taken in the cold season due to the frozen surface.

### *k. Mongolia*

This dataset contains soil data of 42 stations with records starting in 1973–84 and ending in 1993–97. Soil moisture observations were started in Mongolia more than 20 years ago (Erdenentsetseg 1996). Using the same standard techniques introduced by the Russians, gravimetric observations are taken at 10-cm layers in the top 1 m every 10 days, on the 7th, 17th, and 27th of each month. As with the RUSWET datasets above, the total soil moisture observations are converted to volumetric plant-available soil moisture by considering soil density and subtracting the wilting level. Approximately half of the stations are pasture (Fig. 2) and half are summer wheat. The variety of wheat grown in Mongolia does not get very tall, and we can detect no difference in the soil moisture variations as a function of vegetation.

### *l. India*

The Indian dataset contains soil moisture data of 11 stations for 1987–95. They were taken in regions with grass vegetation once per week at several depths, and are total soil moisture. We converted from gravimetric percent by mass to volumetric soil moisture by multiplying by the ratio of soil density to water density.

### *m. Illinois*

This dataset contains soil moisture measurements at 19 stations (18 grass-covered and 1 bare soil sites from 1981 to the present; Hollinger and Isard 1994). The neutron probe method was used and was calibrated using gravimetric measurements. The time resolution of measurements is about two weeks during the growing season and once per month the rest of the year. Vertical resolution is 0–10-, 10–30-, and 20-cm layers down to 2 m.

### *n. Iowa*

This dataset is from two catchments in southwestern Iowa (41.2°N, 95.6°W). Each catchment has three different observation areas. Corn was planted in each catchment, although two different techniques were used to prepare the plots for the planting of the vegetation. The data were observed for 13 consecutive layers; the top four were 7.8 cm thick, the next four were 15.2 cm thick, and the next five were 30.5 cm thick. For the first catchment, the data from the top four layers were taken using gravimetric measurements and the deeper measurements were made using neutron probes. For the second catchment, gravimetric techniques were used for the upper five layers and neutron probes were used for the deeper layers. For the most part, soil moisture was observed between April and October, on average twice a month. Although the observations were not taken at a standard time throughout the year, if observations were taken, they were performed on the same day at all six sites.

## 5. Scales of temporal and spatial variations

It is well known that the complex topography of natural landscapes, with spatially variable vegetation and soil types, and gravitational drainage and infiltration of water after heavy rains, is responsible for very small-scale spatial (tens of meters) and temporal (up to few days) variability in the soil moisture field (Vachaud et al. 1985; Rodriguez-Iturbe et al. 1995). In addition to this small-scale component of soil moisture variability, analysis of spatial fields and time series of soil moisture observations also finds a long-term (about 1–4 months) and large-scale (about 400–800 km) signal related to atmospheric forcing. The meteorological component of soil moisture field variability has been found in observations (Meshcherskaya et al. 1982) and later received theoretical explanation (Delworth and Manabe 1988, 1993; Vinnikov and Yeserkepova 1991; Vinnikov et al. 1996; Entin et al. 2000). This soil moisture component, driven by atmospheric forcing, may be successfully modeled using routine meteorological observations at regular meteorological stations (Robock et al. 1995; Yang et al. 1997; Schlosser et al. 1997). Small-scale variability of the soil moisture field is unpredictable and appears as a stochastic process in this context. The spatial structure of actual soil moisture obviously depends on the distribution of topography, soils, and vegetation on all scales, but the scale of soil moisture variations can be related to the scale of atmospheric forcing. Therefore we focus on the climatic time and space scales in our datasets. Some of our Russian data consist of spatial averages of all measurements of stations inside specific administrative districts (Meshcherskaya et al. 1982; Kelchevskaya 1989; Zhukov 1986), essentially prefiltered at the appropriate scales. Since the spatial scale of soil moisture variation is approximately 500 km in the Northern Hemisphere midlatitudes (Entin 1998; Entin et al. 2000) for all the regions we investigated, including the FSU, China, and Mongolia, the soil moisture station network (Fig. 4) is perfectly adequate to investigate hemispheric-scale soil moisture anomalies. Table 2 gives the temporal and spatial scales from the different datasets.

## 6. Climatology examples

Figure 5 shows the mean seasonal cycle from eight different regions (Fig. 4). As we are interested in the climate of each region, we use optimal averaging (Kagan 1979) to produce one value at each time representative of the area. Optimal averaging takes into account the spatial scale of soil moisture (Table 2) and gives less weight to repeated information and more weight to independent information. This is particularly important when there is missing information at particular times producing a changing distribution of stations. It also produces an estimate of the error of the estimated average, which is also shown on the figure.

The seasonal cycle for western Russia, Illinois, and Iowa shows a typical midlatitude seasonal cycle in a climate with precipitation distributed uniformly throughout the year. Soil moisture is high in the winter and when the snow melts in the spring, some of the water infiltrates into the soil producing the peak soil moisture for the year. During the summer, when evapotranspiration exceeds precipitation, soil moisture falls with the minimum value at the end of the summer. In the autumn, evapotranspiration falls and soil moisture increases until the winter. When the ground is covered by snow, there is less, but not zero, change in soil moisture. Vapor exchange is still important in frozen soils.

The seasonal cycle in eastern Asia, on the other hand, shows a different character, as there is a large summer precipitation maximum associated with the summer monsoon. In Mongolia, during the half-year for which we have data, soil moisture stays almost constant. The increased evapotranspiration is almost exactly matched by the increased precipitation. In India, where evapotranspiration is much larger, soil moisture falls from the end of the rainy season and reaches a minimum just before the onset of the summer monsoon precipitation.

## 7. Trends

To investigate the suggestion that summer drying would accompany global warming, we examined the trends of summer (June, July, August) soil moisture from the longest time series available in our data bank (Figs. 6, 7). Although all the stations or regions show an upward trend in temperature during the period shown, all but Iowa show an upward trend in soil moisture. The Iowa and Illinois time series, however, are quite short; we would like to have longer trends for analysis of climate change. All the locations also have an upward trend in precipitation that one might think would compensate for the implied upward evapotranspiration trend. However, as much of global warming so far has been at night (Karl et al. 1991, 1993; Folland et al. 1992; Stenchikov and Robock 1995), daytime evapotranspiration has probably not changed much. To truly study the complete water budget, detailed datasets of water in the entire soil column, including water table depth, would be desirable, but we know of no such observations.

For the entire length of record, Iowa shows a decreasing trend, but neighboring Illinois shows an upward trend (Fig. 7). When the overlapping period of 1981–94 is examined, however, they both have similar upward trends. The similarity shows that we are justified in using our station distribution and validates the spatial scale of soil moisture variations we have observed (Table 2).

TABLE 2. Scales of temporal ($T_a$) and spatial ($L_a$) correlation for the atmospheric portion of the variance for the top 10-cm and top 1-m soil layers for different regions (Vinnikov et al. 1996; Entin 2000).

| | 0–10-cm soil layer | | 0–100-cm soil layer | |
|---|---|---|---|---|
| | $T_a$ (Month) | $L_a$ (km) | $T_a$ (Month) | $L_a$ (km) |
| China | 1.1–2.4 | 500–550 | 1.6–2.4 | 475–575 |
| Illinois | 1.5–1.8 | 380–490 | 1.8–2.1 | 510–670 |
| Iowa | 1.1–1.5 | | 1.3–1.8 | |
| Mongolia | 1.5–1.7 | 200–400 | 1.6–1.8 | 200–400 |
| Russia (VALDAI) | | | 2.6–2.9 | |
| Russia (RUSWET-50) | | | | 500–750 |

We have examined the summer soil moisture trends simulated by the Geophysical Fluid Dynamics Laboratory general circulation model (GCM) forced by transient $CO_2$ and tropospheric sulfate aerosols for the periods and regions of the observations (Haywood et al. 1997; Wetherald and Manabe 1999). Although this model predicts summer desiccation in the next century, it does not in general reproduce the observed upward trends in soil moisture very well. This may be because the model does not have a diurnal cycle and thus cannot simulate the observed diurnal asymmetry of warming, but the model also does not simulate the observed upward trend in precipitation in most locations. This is a general problem with current GCMs, and we expect the long time series in our data bank to help evaluate and improve simulations of the recent past so we may have more confidence in predictions for the next century.

## 8. Interannual variations

The data can also be used to investigate interannual variability. For example, for the average soil moisture in the top 1 m in Illinois, there is a pronounced seasonal cycle (Figs. 8, 9) and also large changes from one year to the next. Figure 8 shows the effects of the Midwest drought in 1988 and the Midwest floods in 1993. While the soil moisture stations were not flooded, their data reflect the general wet climate of the region. Figure 9 also illustrates the temporal scale of soil moisture variations, with anomalous periods lasting several months, especially in the summer.

## 9. Other datasets

In addition to the above datasets, which we maintain and distribute in our data bank, we maintain links to several other shorter soil moisture datasets described here.

### *a. Australia*

A set of detailed TDR measurements at 500–2000 locations in one 10.5-ha field on 13 separate days at Tarrawarra in southeast Australia (Western and Grayson 1998) illustrates the hydrological scale of soil moisture variations.

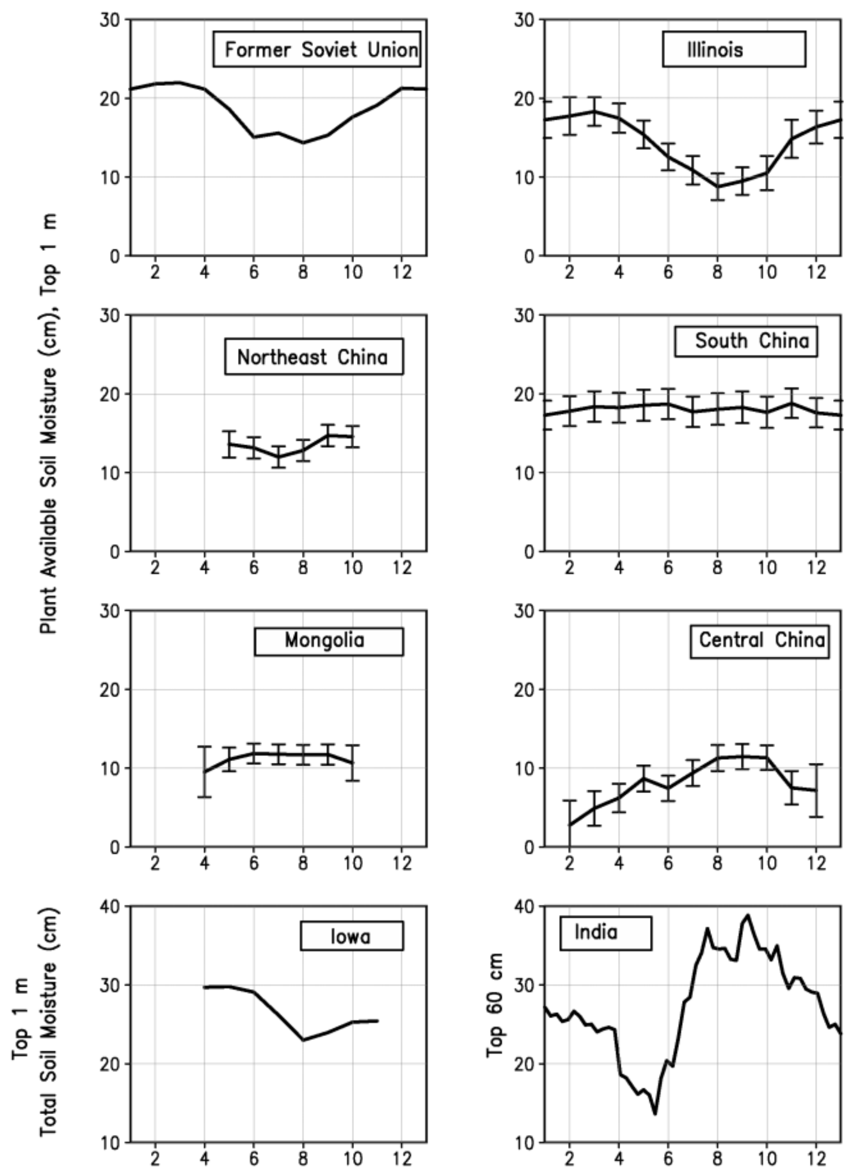


FIG. 5. Average seasonal cycles of soil moisture, averaged for the entire length of each dataset (Fig. 4). Units are cm of water in the top 1 m, except the top 60 cm for India. Months are indicated with numbers on the abscissa. For those regions where optimal averaging (Kagan 1979) was used, whiskers indicate the estimated one standard deviation error range associated with the spatial distribution of the stations.

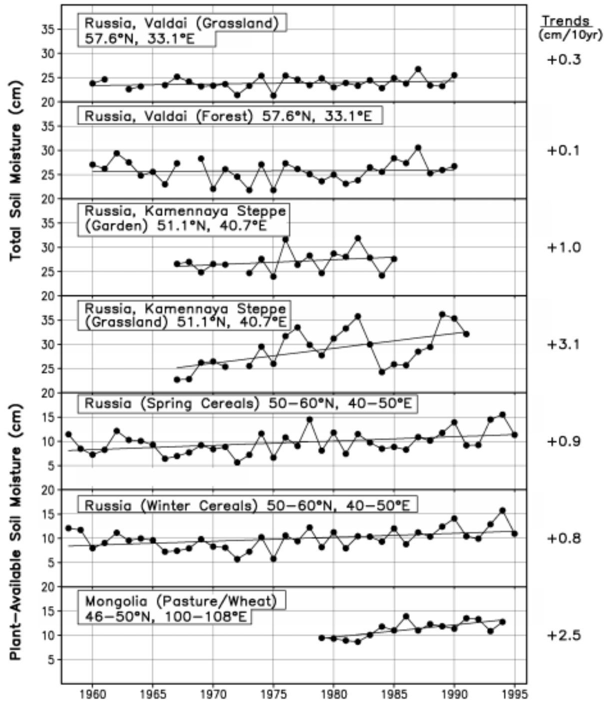


FIG. 6. Trends of summer soil moisture from stations or regions with the longest records.

*b. Brazil*

Data have been observed in Manaus, Brazil, using neutron probes for 3 years in a tropical forest at three pasture and three forest sites (Hodnett et al. 1995). The current Large-scale Biosphere Atmosphere (LBA) experiment in Amazonia is producing soil moisture datasets in the Brazilian tropical region.

*c. Sweden*

The Northern Hemisphere Climate-Processes Land-Surface Experiment (NOPEX) produces soil

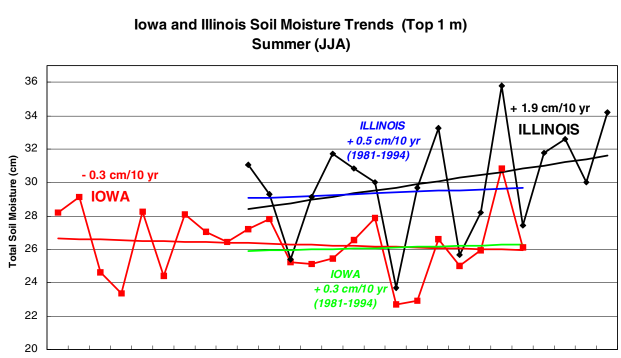


FIG. 7. Summer soil moisture trends for Iowa and Illinois (optimally averaged). The overall trend for Iowa is negative and for Illinois is positive, but for the overlapping period of 1981–94, they are very similar and upward.

moisture measurements in a boreal forest, starting in 1994.

*d. Russia, Ukraine*

Our RUSWET-AGRO dataset presents measurements from administrative regions in the Russian and Ukrainian grain belt. Each region has on the average six stations. For calibration of active microwave remote sensing, W. Wagner and P. Groisman collected observations from each of these individual stations for a limited period (1992–96) and they are available from the National Climatic Data Center.

*e. AmeriFlux*

Long-term $CO_2$ flux measurement stations have begun in the past few years, and 10 of them measure soil moisture with various instruments and at different depths.

*f. New Mexico*

At the Jornada, New Mexico, Long-Term Ecological Reserve, monthly soil moisture data at 10 access tubes at each of 15 different sites have been collected with neutron probes since 1989. A transect of 89 tubes has also been used from 1982 to the present.

*g. Alaska*

The Bonanza Creek, Alaska, Long-Term Ecological Reserve has collected daily soil moisture for one 2-year period and weekly soil moisture from 1992 to the present in the summer using TDR probes.

*h. Tennessee*

The Throughfall Displacement Experiment (Hanson et al. 1995) in Oak Ridge, Tennessee, has measured detailed soil moisture patterns in a forest from 1993 to the present, studying the effects of different throughfall in a forest at three locations.

*i. United States*

The Natural Resources Conservation Service has set up a U.S. national network of 26 stations reporting real-time soil moisture observations hourly using FDR probes at four different depths. The longest time series is six years long but most are shorter and some were just started.

*j. MOISTNET*

A network of heat dissipation sensors has just been established in Oklahoma and part of Kansas using 132 stations taking observations every 30 minutes. This is a joint project of the Oklahoma Climate Survey, the Agricultural Research Service, and the Atmospheric Radiation Measurement program.

*k. Other measurements*

We know that the Russian system of soil moisture measurement was introduced into eastern Europe, and that data probably exist for Poland, East Germany, Hungary, Czech Republic, Slovakia, Romania, Yugoslavia, and Bulgaria. We have no direct knowledge of soil moisture in North Korea, but guess that the Russian system of soil moisture measurement was introduced there, also.

In the collection above, we have focused on all the large, homogeneous datasets we are aware of. We know that there are other soil moisture datasets in the world, but they are shorter in time and smaller in number of stations, and many lack meteorological and ancillary data. We welcome contributions of other datasets, which we will be happy to distribute, or provide links to.

## 10. Model simulations of soil moisture

For many purposes, including accurate climate modeling, seasonal prediction, and water resource management, it is crucial to have accurate land surface models. Land surface models, whether driven by general circulation models (GCMs) (Pitman et al. 1993, 1999; Robock et al. 1998) or by observations (Robock et al. 1995; Chen et al. 1997; Schlosser et al. 1997, Schlosser 2000; Entin et al. 1999), currently do an imperfect job of simulating the mean seasonal cycle and interannual variation of soil moisture, when compared to observations. Nevertheless, models are now

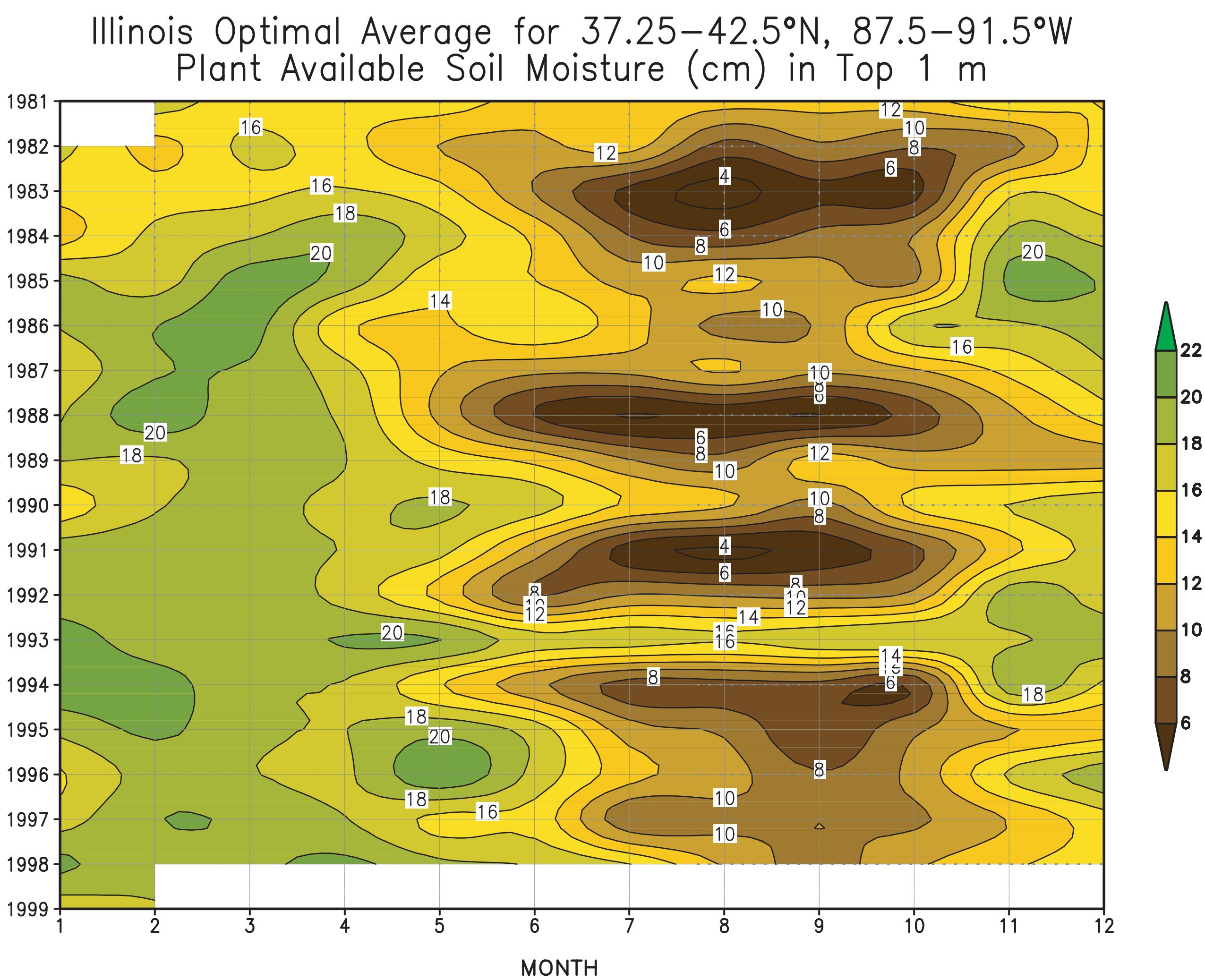


FIG. 8. Year/month plot of plant-available soil moisture variations in the top 1 m, optimally averaged for the state of Illinois.

being used to calculate the global distribution of soil moisture (Table 3) and they are described here.

There are several so-called datasets of soil moisture (Mintz and Serafini 1981, 1989, 1992; Schemm et al. 1992; Liston et al. 1993) that have been used for verification, initialization, and surface and subsurface boundary conditions for GCMs. All were run as offline stand-alone land surface parameterizations, forced by observations. They have the advantage over actual observations in that they are global, but they are actually model simulations, forced with monthly average or daily temperature and precipitation observations. Mintz and Serafini (1981, 1989, 1992) used a 15-cm bucket (Manabe 1969) with Thornthwaite (1948) evaporation and all precipitation treated as rain (no storage as snow and no snow melt), forced by monthly precipitation climatology (Jaeger 1976) and monthly temperature climatology (Spangler and Jenne 1984) on a global $4° \times 5°$ lat–long grid. Schemm et al. (1992) used the Mintz and Serafini method forced by monthly average observations from NCAR data for individual months for 1979–1992 on a global $2° \times 2.5°$ grid, so that they produced different "soil moisture" for different years. Liston et al. (1993) used a modified version of the Simplified Simple Biosphere (SSiB) model (Xue et al. 1991). For model initialization, these fields are valuable as they provide a climatology with the same properties as the model, but Robock et al. (1998) showed that they do not agree well with existing observations from the Global Soil Moisture Data Bank.

Archives of climate model–produced soil moisture, output from GCM runs, are also now becoming available. The soil moisture results from different types of simulations will be different, depending on

TABLE 3. Soil moisture model calculated "datasets."

| Model | Soil moisture scheme | Forcing | Nudging? |
|---|---|---|---|
| Mintz and Serafini (1992) | Bucket (Manabe 1969) | Climatology | No |
| Schemm et al. (1992) | Bucket (Manabe 1969) | NCAR data, 1979–92 | No |
| Liston et al. (1993) | SSiB (Xue et al. 1991) | NCAR data, 1979–88 | No |
| NCEP Reanalysis (CDAS) | Chen et al. (1996) | Model | Yes |
| Eta EDAS | Chen et al. (1996) | Model, but observed snow | No |
| Eta LDAS | Chen et al. (1996) | EDAS, but observed precip and downward SW | No |
| Mosaic LDAS | Koster and Suarez (1992) | EDAS, but observed precip and downward SW | No |
| VIC-3L LDAS | Liang et al. (1996), updated | EDAS, but observed precip and downward SW | No |
| ECMWF Reanalysis | Viterbo and Beljaars (1995) | Model | Yes |
| GEOS-1 Reanalysis | Specified, Schemm et al. (1992) | Not applicable | N/A |
| MAPS | Smirnova et al. (1997a,b) | Model | No |
| GEM | Specified, Mintz and Serafini (1992) | Not applicable | N/A |
| AMIP II | Various | Model (indirectly from SST observations) | No |
| GSWP II | Various | Observations | No |

the way the calculation was done. The Global Soil Moisture Data Bank contains actual in situ observations of soil moisture, literally "ground truth," that has proven and will prove to be very useful for evaluation of model calculations of soil moisture. But it is important to not confuse actual observations with model calculations.

Weather forecast models now incorporate land surface schemes (LSSs) to predict latent and sensible heat fluxes from the earth's surface, as well as the radiative balance. In the process, soil moisture and other hydrological quantities, such as runoff, are calculated. These models are used both for real time forecasting and for reanalysis of past weather changes (Kalnay et al. 1996; Gibson et al. 1997). The Global Soil Wetness Project was conducted for 2 years, 1987–88, but GSWP II will be for at least a 10-year period beginning in 1987, with the goal of using LSSs to produce global soil moisture datasets (Dirmeyer et al. 1999).

If a soil moisture dataset is to be used to initialize an LSS, then the dataset must be calculated with the same LSS, even if the LSS is known to produce a bias in soil moisture. Otherwise, there will be spinup problems with the model trying to adjust from the initial values to its own climatology. A more satisfying solution is to use an LSS that accurately reproduces observations, and then use actual observations as initial conditions. This will probably require some combination of in situ observations, remote sensing, and land data assimilation schemes. Even if an LSS does not reproduce the actual soil moisture observations, the observations can be translated into relative wetness and then introduced into the LSS to give the same rela-

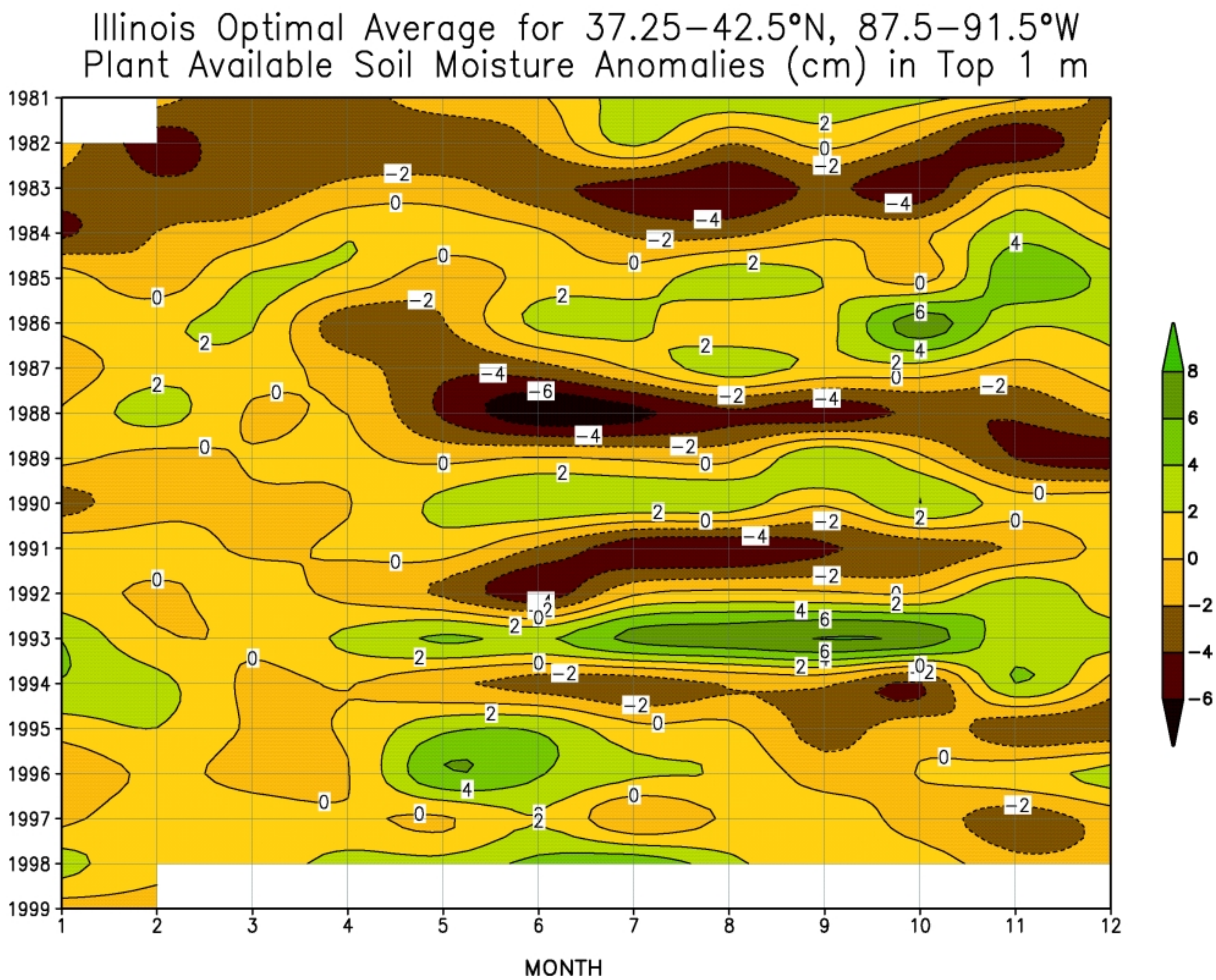


FIG. 9. Year/month plot of plant-available soil moisture anomalies in the top 1 m, optimally averaged for the state of Illinois, with anomalies calculated with respect to the average for each month for the period 1982–98.

tive wetness, in the same manner as Koster and Milly (1997) scaled relative soil moisture in LSSs.

Climate model simulations that produce soil moisture can be classified in the following ways.

*Climate models run with climatological boundary conditions.* LSS is forced with model-generated temperature, humidity, wind, radiation, precipitation, and snow. These models simulate day-to-day weather variations, but not the actual ones that occur on specific days. Therefore, it is appropriate to compare their soil moisture simulations with climatological soil moisture, but not with specific values from specific years.

*Climate models run with observed sea surface temperatures* (*SSTs*) but climatological greenhouse gas and aerosol concentrations and solar constant. This is the strategy of the Atmospheric Model Intercomparison Project (AMIP; Gates 1992). Each LSS is forced with model-generated radiation, precipitation, and snow, which may indirectly be affected by SSTs. In this case, the day-to-day weather variations would not match observations, but the monthly and seasonal anomalies might be expected to match observations if the envelope of the weather variations was controlled by remote boundary anomalies. Robock et al. (1998) did not find this to be the case for Russia for 1979–85 or for Illinois for 1981–88, but with strong El Niños like the recent 1997–98 one, we might expect an ENSO signal.

In these experiments and the ones in the category above, the LSSs are fully coupled with the GCM atmospheres, so that they are free to seek their own model climates. However, in the AMIP runs, the GCM precipitation (Lau et al. 1996; Sengupta and Boyle 1997) and clouds (Weare et al. 1995) were not very accurately simulated. For the AMIP experiment in which soil moisture simulations by 30 different GCMs were evaluated (Robock et al. 1998), the models did not do very well, and it was difficult to separate the effects of erroneous precipitation and radiation forcing (as simulated by the models) from problems with the LSSs.

*Weather forecast models run in reanalysis mode,* reinitialized daily or more often with standard observed meteorological elements. In this case, however, the LSS is still forced with model-generated radiation and precipitation. Snow may be taken from observations, but snowmelt is model generated. As these calculations attempt to reproduce the actual weather variations, model drift is not desirable. Hence, for the NASA/GEOS reanalysis, soil moisture is actually specified at the Schemm et al. (1992) values, and not allowed to change. For the European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis, soil moisture is nudged (flux corrected) to compensate for surface relative humidity drift. This, essentially, makes up for errors in model-generated precipitation, which in general was found to be too small (P. Viterbo 1998, personal communication). The National Centers for Environmental Prediction (NCEP) reanalysis was nudged toward the Mintz and Serafini (1992) specified values. For these calculations, it is appropriate to compare the soil moisture they generate with actual observations for specific days.

*Weather forecast models run in real-time forecast mode.* These models calculate soil moisture as part of a Land-surface Data Assimilation Scheme (LDAS), which can be driven either by model-generated or observed precipitation, radiation, and snow. The Global Environmental Multiscale (GEM) model of the Canadian Meteorological Centre (Mailhot et al. 1998) uses specified soil moisture and does not calculate it with an LDAS. The Mesoscale Analysis and Prediction System (MAPS) model, being run by NOAA's Forecast Systems Laboratory, uses an LDAS system based on the LSS of Smirnova et al. (1997a,b). This LSS has already been improved by forcing it with our PILPS 2(d) forcing from Valdai, Russia (T. Smirnova 1999, personal communication). At NCEP, there are three different versions of LDAS (K. Mitchell 1998, personal communication) run with the global and regional forecast models. For these calculations, it is also appropriate to compare the soil moisture they generate with actual observations for specific days.

*Stand-alone LSS's run with specified forcing* at specific locations (Project for Intercomparison of Land-surface Parameterization Schemes; Henderson-Sellers et al. 1993, Phase 2) or on a global grid (GSWP). In these offline tests the LSS will not be able to come to equilibrium with, and interact with, the model atmosphere. Theoretically, this interaction may compensate for some LSS biases, although we know of no such demonstration. Offline experiments gain an advantage as a testing tool because it is easier to compare models when all the models are forced with the same, more realistic, forcing. Thus, offline experiments have been the primary form of validation, in addition to the fact that offline experiments are generally easier and quicker to perform.

## 11. Remote sensing

There are no existing global soil moisture datasets measured from remote sensing. The data bank does provide links to experimental NOAA products (Basist et al. 1998) that use high-frequency passive microwave observations to produce a skin wetness product, which is valuable for monitoring flooding. The data in our data bank have been used in passive microwave (Vinnikov et al. 1999b) and active microwave (Wagner 1998) studies that demonstrate the potential for microwave remote sensing of soil moisture in regions without snow or tall vegetation. Visible and infrared radiation can also be used for indirect satellite soil moisture monitoring (Idso et al. 1975; Carlson et al. 1984; Nieuwenhus and Menenti 1986; Carlson 1986; Flores and Carlson 1987; Capehart and Carlson 1997), but cannot make measurements when cloudy. Microwave remote sensing (e.g., Van de Griend and Owe 1993; Vinnikov et al. 1999b; Wagner 1998) offers the most promise for future global datasets.

## 12. Discussion

The Global Soil Moisture Data Bank described here is a growing entity. We solicit users who will give us feedback on the data, and contributors who can enrich the collection. Through use of actual soil moisture observations, improved land surface models and remote sensing offer the promise of accurate prediction of future soil moisture anomalies.

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