

NOTES AND CORRESPONDENCE

Operational Soil Moisture Estimation for the Midwestern United States

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2 January 1990 and 5 June 1990

ABSTRACT

An operational soil moisture monitoring capability for the midwestern United States is developed using a multilayer soil water balance model which incorporates daily weather data to calculate precipitation, soil evaporation, plant transpiration, runoff, and drainage through the soil profile. The effects of vegetation on soil evaporation and plant transpiration are incorporated through the use of a model for the growth and development of corn. Data requirements include daily observations of maximum temperature, minimum temperature, and precipitation and hourly observations of cloud cover, humidity, and wind speed; these data are collected in real time and aggregated on a climate division scale. The average characteristics of the dominant soils in each climate division are used as representative of that climate division. Using these weather and soils data, the model makes estimates of the current soil moisture status on a climate division basis updated daily. Historical soil moisture estimates using this same model were generated for the period 1949–89 to provide an historical perspective on current soil moisture estimates. This information is accessible to the public through a dial-up computer information system.

1. Introduction

Analysis of the climate informational needs of midwestern U.S. agribusinesses (Lamb 1985; Wendland and Vogel 1986) revealed a widespread interest in regularly updated information on soil moisture on a region-wide basis, particularly during the growing season. Soil moisture can be more directly related to crop status and crop potential than "pure" climatological variables such as precipitation and temperature. Unfortunately, routine measurements of soil moisture are not widely available and are generally not done with sufficient frequency to monitor rapidly changing conditions. For example, soil moisture measurements made twice a month by the Illinois State Water Survey at 23 sites around Illinois have been used routinely by many public and private agricultural concerns. However, the manual nature of these measurements causes a delay in dissemination, with the result that the information is occasionally out-of-date before it is available. Even this situation is far superior to what is available in most of the other midwestern states. These limitations suggest that regional soil moisture estimates using models may provide useful information to the agricultural sector.

The Midwestern Climate Center (MCC) has recently developed a climate information system called the

Midwestern Climate Information System (MICIS) which is accessible to the general public. The system is described in detail in Kunkel et al. (1990). One purpose of this system is to provide a capability for monitoring current climate conditions in a timely manner and over the large (nine state) area served by the MCC. To this end, temperature and precipitation data are collected daily from an average of 500 stations across the midwestern United States. These data are used to generate a wide variety of climate informational products. One of their uses is to drive a model of the soil water balance in order to make regional estimates of the soil moisture content in a manner relevant to agricultural applications. These soil moisture estimates are updated daily and made available on a computer system, which is accessible to public users. The approach used to generate these estimates is described in this paper.

The region of interest includes the nine states; Illinois, Indiana, Iowa, Kentucky, Michigan, Minnesota, Missouri, Ohio, and Wisconsin. This area produces about 70% of the nation's corn and soybeans. The estimates are made on a climate division scale; there are 75 climate divisions in this region. Derivation of real-time estimates for smaller areas is not practical at this time, given the density of climate data available on a real-time basis.

2. Model characteristics

There are several considerations that must be addressed in order to provide accurate regional soil mois-

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ture estimates. These are the inherent accuracy and sophistication of the soil water balance routine, the accounting for regional variations in soils characteristics, and the representativeness and completeness of the climate data. These are addressed below.

a. Soil water balance model

An accurate soil water balance model must account for the components of the water balance given below

$$\frac{\partial S(d)}{\partial t} = P - R - E_S - E_T - D \quad (1)$$

where

$S(d)$	surface soil water content in a layer of depth d appropriate for agriculture
P	precipitation rate
R	runoff rate
E_S	evaporation rate from the bare soil surface
E_T	rate of transpiration by plants
D	rate of drainage into the sub-surface soil layer.

There are several candidate soil moisture models for such an application (e.g., Baier and Robertson 1966; Dyer et al. 1988; Dale and Shaw 1965). For a variety of reasons, the CERES-Maize¹ corn development and simulation model (Jones and Kiniry 1986) was chosen. This model contains a routine for calculating the daily changes in soil water content due to the above components of the soil water balance. The details of this routine are given in Ritchie (1985) and Jones and Kiniry (1986), and briefly described in appendix A. An important reason for choosing this model is that it was also required for an operational corn yield estimation program (Kunkel and Hollinger 1990). Therefore, the implementation effort was minimized. Other contributing reasons are as follows.

- 1) The model has been relatively well tested (Ritchie 1972; Ritchie and Otter 1985; Ritchie 1985).
- 2) This is a multiple layer model which allows calculation not only of the total soil water content but also of the vertical distribution of the water.
- 3) The soil evaporation and plant transpiration (Ritchie 1972) are simple but realistic functions of the potential evaporation and leaf area index. The seasonal changes in the leaf area index are realistic since the soil moisture model is integrated with a crop development model. The accurate modeling of plant transpiration is important in the early part of the growing season when evaporation will occur at less than the potential rate when the soil surface is dry even if there is abundant subsurface moisture.

¹ CERES is an acronym for Crop Estimation through Resource and Environmental Synthesis.

4) Corn is one of two dominant crops in this region. The other is soybeans. Seasonal changes in leaf area index and water use are quite similar between these two crops. Therefore, the soil moisture estimates should be representative of a large percentage of the regional crop acreage. However, it would not be as applicable to crops such as alfalfa and wheat, which have a different seasonal water use distribution.

5) The computer code is easy to obtain and well documented (Jones and Kiniry 1986).

b. Regional soils' characteristics

Each climate division was assigned a set of soils' characteristics by performing a weighted average of the characteristics of the major soils. County acreages for 73 major soil series in the region were obtained from a computerized soil database (SOILS).² In total, these 73 soils represent a cropped area of about 2.3×10^5 km² in these nine states or about 28% of the total cropped area of 8.0×10^5 km². The county acreages were combined to yield climate division acreages for each soil series. The CERES-Maize model requires the following soils characteristics: albedo, soil water conductivity, a soil surface evaporation rate coefficient (Ritchie 1972), Soil Conservation Service (SCS) runoff curve number [U.S. Department of Agriculture (USDA) 1972], and the soil water content for the following conditions: lower limit of plant available water (S_L), drained upper limit (S_U), and saturation (S_S). A computerized database of soil characteristics assembled by the USDA (Dyke et al. 1985) provided the albedo, the runoff curve number, and a layer-by-layer description of the bulk density and the percentage of sand, silt, and clay. Relationships developed by Ritchie et al. (1987) were used to calculate the soil water conductivity and soil water contents at S_L , S_U , and S_S from the bulk density and sand, silt, and clay contents. The climate division values of these variables were generated by an acreage-weighted averaging of those soil series (out of the set of 73 soils) which are present in that climate division.

A soil depth of 2 m was used. This was divided into nine layers with the following thicknesses beginning at the surface: 10 cm, 15 cm, 25 cm, 25 cm, 25 cm, 25 cm, 25 cm, 25 cm and 25 cm. Figure 1 lists the total potential plant available water (S_P) between S_L and S_U for the 2 m soil water profile by climate division. In most cases, S_P is between 20 and 30 cm. The few cases

² The SOILS data provided were compiled as a cooperative effort between the Environmental Technical Information System (ETIS) of the University of Illinois, Department of Urban and Regional Planning; and the U.S. Army Corps of Engineers, Construction Engineering Research Laboratory (CERL), Champaign, IL. The source of original SOILS data is the USDA Soil Conservation Service (SCS).

where S_p is less than 20 cm occur where sandy soils are widespread.

c. Climate data

The CERES-Maize model requires daily values of precipitation, maximum and minimum temperature, incoming solar radiation, and potential evaporation. The choice of data sources is influenced by two factors. First, the soil moisture in the top 2 m is an integrative quantity and can reflect the climatic history of a lengthy time period of several months or more. Second, it is desirable to use as many stations as are available to provide the most representative value of soil moisture for a climate division. With regard to temperature and precipitation, data are collected by the National Weather Service for two rather different purposes: 1) forecasting and nowcasting applications, and 2) climate applications, which affect their availability and density. Both of these types are incorporated into the calculations and are explained below.

The most complete source of temperature and precipitation climate data is the National Weather Service's (NWS) cooperative observer network. This network provides daily data from an average of about 20 stations in each climate division. The cooperative observers record their observations on a paper form and send the form to the National Climate Data Center (NCDC) at the end of each month, where the data are digitized. Through a special arrangement with NCDC these data are obtained in digital form about five weeks after the end of a month. Despite this delay, the integrative nature of soil moisture makes it advantageous to incorporate these data into the calculations when they are received in order to provide a more accurate estimate of current soil moisture.

In order to monitor soil moisture changes on a daily basis, more current data are obviously needed to supplement the NCDC data. This need is largely provided by a variety of NWS networks related to aviation, agricultural, and hydrologic applications. Most of these stations are also part of the cooperative observer network but have the additional responsibility of reporting

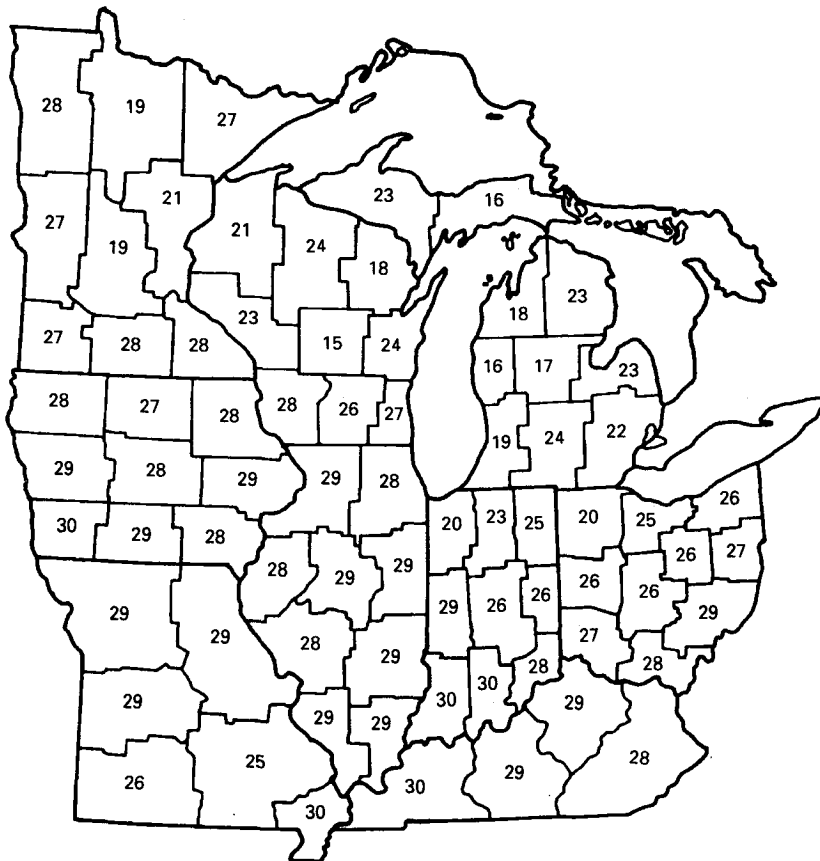


FIG. 1. Total potential plant available water in a 2 m soil profile between the lower limit of plant available water and the drained upper limit. Values are in cm.

their observations to their local NWS office on a daily basis. These data are obtained from Zephyr Weather Information Services Inc. (their Domestic Data Plus service) by satellite transmission.

The major problem in using these current data is that data from any particular station are often incomplete. Many stations are criterion reporters; that is, they report to their local NWS office only when some criterion is met (e.g., when precipitation occurs or when precipitation exceeds some threshold value). In addition, many reporters are volunteers and may not report for other reasons, such as absence due to illness or vacation. Therefore, a missing value can be equivalent to little or no precipitation but this is not always the case. When significant rain occurs in a climate division there are generally 5–15 reports available. When no precipitation occurs, most climate division will have at least 1 report, but there may be a few climate divisions which have no reporting stations and therefore no data to drive the model. To address this problem, we conducted a four-month comparison of current precipitation data received via Zephyr and NCDC data received 1–2 months later. This identified about 200 stations which are reliable in the following sense: when no data are received, a precipitation value of 0 can be assumed with a high degree of confidence. This means that, for any particular day, the daily precipitation for a climate division is the mean of all stations which report on that day plus those stations on the list of reliable stations which do not report (for which a zero value is assumed). In the case of temperature, the daily value is the mean of all stations that report. If there are no temperature reports, temperatures are calculated by linear interpolation among the nearest grid points in a gridded temperature dataset produced from the observations using the objective analysis method of Achtemeier (1989).

Solar radiation measurements are not widely available in the Midwest and it was therefore necessary to estimate this variable. The method of Meyers and Dale (1983) is used. In this method, solar radiation is estimated from hourly cloud cover, humidity, and air temperature observations. These estimates of solar radiation, along with the hourly observations of wind speed, humidity, and air temperature, are used to estimate the daily potential evaporation using the relationship given in the Appendix. Historical values were calculated using historical hourly surface observations obtained in digital form from NCDC. A daily dataset of solar radiation and potential evaporation was calculated for the period 1949 to present for 55 observing sites across the Midwest. A daily dataset for each climate division was generated using the objective analysis method of Achtemeier (1989). For each day from 1949 through the present, those stations available on that day were used to generate values on a $0.5^\circ \times 0.5^\circ$ latitude–longitude grid. The climate division value was

calculated by linear interpolation among the four nearest grid points. Daily updates of this dataset are made using the hourly airways data obtained through the Zephyr data service.

3. Calibration

The water balance model has been tested using wheat as the cover crop with generally good agreement with measurements (Ritchie and Otter 1984). Long-term measurements of soil moisture values under corn in the Midwest are scarce and only a limited test was possible. A set of field soil moisture measurements taken under corn at Lancaster, Wisconsin, ($42^\circ 50'N$, $90^\circ 47'W$) were used for this test. Gravimetric measurements were taken twice per year, in the spring before planting and in the fall after harvest, during 1969–88. The spring measurements are of relatively little value because both model estimates and measurements are near field capacity in almost every year. By contrast, the fall measurements exhibit high year-to-year variability. The model was run using Lancaster temperature and precipitation measurements. Figure 2 shows a year-to-year comparison of plant available water in a 150 cm soil profile between the fall measurements and the model estimates; the 1974 and 1987 data are not plotted because of missing precipitation data and missing soil moisture measurements, respectively, at Lancaster. The general agreement is very encouraging. The relative year-to-year changes are modeled rather accurately. The mean error between the measurements and the model is 1.2 cm, indicating a small systematic

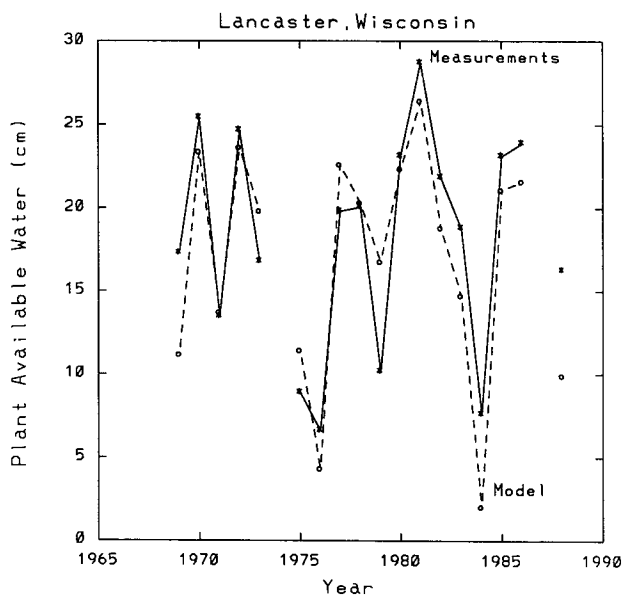


FIG. 2. Plant available water (cm) in the top 150 cm at Lancaster, Wisconsin, in the early part of autumn. Measurements are represented by the solid line while the dashed line represents model estimates.

bias on the low side. The root-mean-square error is 3.5 cm, which is about 20% of the measurement mean of 18.1 cm.

Since this comparison suggests the possibility of a slight systematic bias, MICIS users were encouraged to use relative soil moisture values such as the deviation from the long-term average rather than absolute measures such as the actual plant available water.

4. Sensitivity to soil characteristics

The sensitivity of the soil moisture estimates to the soil characteristics was tested using the following set of soil variable values as a control: runoff curve number (R_N) = 78; upper limit of stage 1 soil evaporation (U) = 9 mm; soil surface albedo (a_s) = 0.14; soil water conductivity (k_s) = 0.12 day⁻¹; and total potential plant available water (S_P) in a 2 m soil profile = 30 cm. Each of the above variables was adjusted across a range of values encountered in the 73 soil series, keeping all other variables at their control values. For each test, the model was run for the period 1949–89 using climate data from the east-central climate division of Illinois. The last week of July (a key period when corn pollination occurs) was chosen to compare the test values with the control values. Table 1 gives the difference in plant available water (test minus control) for the median value, the value which is exceeded in 10% of the years, and the value which is exceeded in 90% of the years. Variations in U and a_s have relatively little effect on the estimates. The effect of variations in R_N are somewhat larger, but probably insignificant in view of the other uncertainties. The effect of variations in k_s are larger still, but rather small when considered against the nearly 2 orders of magnitude range in k_s . By contrast, the effect of variations in S_P are much larger. Therefore, errors in the specification of this variable may be the largest potential source of error in the model estimates.

TABLE 1. Sensitivity of plant available water (cm) to changes in soil characteristics.

Tested variable	Test run minus control run		
	Median value	10% value	90% value
$R_N = 65$	0.3	0.0	0.6
$R_N = 89$	-2.1	-2.4	-1.8
$U = 6$ mm	0.3	0.6	0.0
$U = 12$ mm	0.0	-0.3	-0.3
$k_s = 0.89/\text{day}^{-1}$	-1.5	-2.1	-3.6
$k_s = 0.02/\text{day}^{-1}$	1.2	1.2	0.6
$a_s = 0.11$	-0.5	-0.5	-0.1
$a_s = 0.18$	0.7	0.7	0.3
$S_P = 20$ cm	-5.4	-1.4	-9.1
$S_P = 10$ cm	-14.1	-4.1	-19.0

5. Operation

a. Historical database

A “historical” soil moisture database was generated for each climate division by running the model continuously for the period 1949–89 using historical daily temperature and precipitation data from NCDC and the derived values of solar radiation and potential evaporation described in section 3. This was done in a two-pass process. First, soil moisture on 1 January 1949 was initialized as S_U . After running through the 41 years, an “average” soil moisture value for 1 January was calculated from the mean for the last week of the year for all years from 1951 to 1989. The model was then initialized with this average value and rerun through the 41 years. The results of this second run were used to create a historical file containing weekly average values for each of the nine layers; this file is used in an operational mode for comparisons with current estimates of soil moisture.

b. Real-time operations

To obtain current soil moisture values, the model is initialized with the model values from the last day of the previous calendar year (e.g., during 1990, the model was initialized with model estimates from 31 December 1989). Daily climate data are used from the aforementioned NCDC database for the period for which they are available. Each day’s climate division values are the means of data from all stations reporting on that day. “Current” data are used for the more recent time period for which NCDC data have not yet been received. Soil moisture values are automatically updated daily at about 0930 local time. Each day, the model is rerun from 1 January. This is convenient in that intermediate values of crop development status do not have to be stored in memory. This would be necessary if the model were run starting from a day during the growing season. In addition, the monthly NCDC data files are automatically incorporated as soon as they are received. (The computing resources are relatively small, a few seconds per climate division.)

Calculated values that can be accessed by a user include the current plant available water (S_A), last year’s S_A (at the same time of the year), the deviation of the current S_A from the long-term (1951–89) average for a particular calendar week, the current S_A as a percent of S_P , and the deviation of the current S_A as a percent of S_P from the long-term average. These can be obtained for a number of layers down to 2 m.

Table 2 gives an example of the tabular product for Illinois on 13 July 1989. At this time, soil moisture in the top 150 cm (5 ft) was well below the long-term average in northwestern, west-central, and central Illinois. In west-central Illinois, soil moisture was lower than for any other mid-July during the 1951–88 period.

TABLE 2. Sample soil moisture product available on the Midwestern Climate Information System. Deviations are from the records of 1951 to present. %ppam: percent of available moisture/potential plant available moisture.

Illinois Soil Moisture Summary 7/13/1989 Water (inches) in 60.0 inch soil profile (current year's value compared with historical record)								
Climate division	Current year	Last year	Deviation	Lowest value	Highest value	%ppam		
						Current year	Last year	Deviation
1	3.2	1.0	-4.4	1.0	11.9	35	11	-48
2	5.9	1.5	-1.2	1.5	10.5	66	17	-13
3	1.8	2.6	-5.7	2.6	12.0	20	29	-63
4	3.4	1.2	-3.1	1.2	10.6	38	14	-35
5	4.7	0.1	-2.3	0.1	10.7	53	2	-26
6	3.7	0.6	-2.5	0.2	11.9	41	6	-28
7	4.7	0.0	-0.2	0.0	9.2	58	0	-3
8	6.6	0.6	0.8	0.6	11.5	72	7	9
9	8.5	0.8	2.1	0.5	11.4	95	9	23

Figures 3 and 4 show the weekly average and extreme values of soil moisture for a 2 m layer from the historical 1951-89 file for east-central Indiana and southwestern Minnesota, respectively. Average annual precipitation for these two regions are 970 mm and 650 mm, respectively. These figures illustrate the differences in growing season extraction and cool season recharge between the eastern and western portions of the midwestern region. As might be expected from the precipitation differences, recharge in southwestern Minnesota is less reliable than in east-central Indiana. An examination of these data for all climate divisions (not shown) indicate that the model median value of soil moisture is near 100% (indicating full recharge) on 1 May in all parts of the region except for northwestern Iowa (the value here is about 70%) and western Minnesota (the values here are in the range of 35%-60%).

6. Summary

An operational soil moisture model is being used to provide regional scale monitoring of conditions in a nine-state region of the midwestern United States. The model is run daily with results accessible to agribusinesses. This information differs from another commonly available measure of the soil moisture status, the NWS's Palmer Crop Moisture Index (CMI) (Palmer 1968) in the following way:

- 1) The use of a multi- (9) layer model allows a greater level of vertical detail. The depth of dry or wet layers can be identified.
- 2) Since the model is run continuously (through the winter), carryover of dryness from the previous growing season is allowed. By contrast, the CMI begins at zero (normal conditions) at the beginning of the growing season. This is important for the (drier) west-

ern part of the Corn Belt where carryover dryness occasionally affect crop production.

3) Crop water use is more accurately estimated in our procedure. Since the stage of vegetative development affects transpiration rates, the use of a crop development model allows realistic estimates of transpiration.

These soil moisture estimates are most appropriate for corn and other similar row crops (e.g., soybeans). Other

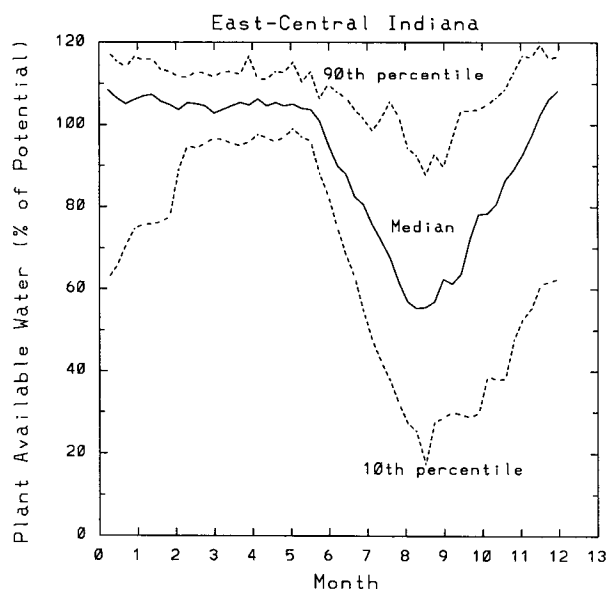


FIG. 3. Weekly values of the median, the 10 percentile, and 90 percentile soil moisture in a 2 m soil profile from the 1951-89 modeled values. Values are expressed as a percent of the total potential plant available water and are for east-central Indiana.

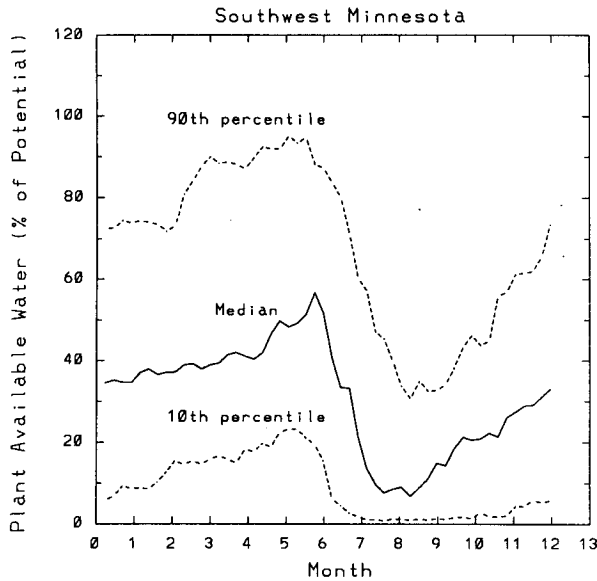


FIG. 4. As in Fig. 4 except for southwestern Minnesota.

crops, such as alfalfa and wheat, will have a different seasonal dependence of transpiration. These estimates would not be as applicable for those crops.

The primary users of the soil moisture information have been medium to large agribusinesses, for whom it provides an overall view of soil moisture conditions in the Midwest. Our interactions with these users indicate that this information is used mainly to estimate the potential impact of current climate conditions on regional crop yields as it may affect commodities prices.

Access to this information on MICIS can be arranged by contacting the Midwestern Climate Center. There is a fee for access.

Acknowledgments. I thank Prof. Joseph Ritchie for his assistance and advice on the use of CERES-Maize. I also thank Peter Lamb and Stanley Changnon for their helpful comments on the manuscript, and Steven Hollinger for his advice on crop modeling and soils. Doug Botner, Paul Dyke, and the University of Illinois Department of Urban and Regional Planning provided the soils data. Doug Clark and Birl Lowery provided the unpublished soil moisture measurements for Lancaster, Wisconsin. Finally, I thank Jean Dennison for her professional preparation of this manuscript. This work was supported under NOAA Grant NA87AA-DCP119.

APPENDIX
Model Equations

Runoff is calculated using the USDA-SCS procedure termed the curve number technique. Daily runoff R_d (mm) is given by

$$R_d = [P_d - 2(25.4)(100C^{-1} - 1)]^2 \times [P_d + 8(25.4)(100C^{-1} - 1)]^{-1}$$

where

P_d daily precipitation (mm)
 C factor related to the soil water content and the runoff curve number and calculated by

$$C = \begin{cases} R_N + (C_W - R_N)C_{PW} & \text{if } C_{PD} > 1 \\ C_D + (R_N - C_D)C_{PD} & \text{if } C_{PD} < 1 \end{cases}$$

where

$$C_{PD} = \sum_{i=1}^L W_i(S_i - S_L)/(S_U - S_L)$$

$$C_{PW} = \sum_{i=1}^L W_i(S_i - S_U)/(S_S - S_U)$$

R_N Runoff curve number specific for each soil series (maximum value is 100)

C_D curve number for dry soil
 $= R_N(0.3067 + 0.00618 R_N)$

C_W curve number for wet soil
 $[= R_N(2.4175 - 0.0276 R_N + 0.00014 R_N^2)]$

L total number of soil layers
 i index for soil layer with a value of 1 indicating the top layer

S_i, S_L, S_U, S_S fractional volumetric soil water content ($\text{cm}^3 \text{ water}/\text{cm}^3 \text{ soil}$)

W_i weighting factor calculated by

$$W_i = \begin{cases} 1.016(1 - e^{-4.16d_i/45}) & \text{for } i = 1 \\ 1.016 \{ e^{-4.16(\sum_{k=1}^{i-1} d_k)/45} - e^{-4.16(\sum_{k=i}^L d_k)/45} \} & \text{for } i > 1 \end{cases}$$

where d_i is the thickness (cm) of soil layer i .

The infiltration of precipitation into the soil layers is calculated in sequence beginning with the top layer. The maximum amount of water which layer i can absorb H_i (cm) is given by

$$H_i = (S_S - S_i)d_i$$

The potential infiltration into layer 1, T_1 (cm), is given by

$$T_1 = 0.1(P_d - R_d)$$

The potential infiltration for other layers is given by

$$T_i = \begin{cases} D_{i-1}, & H_{i-1} \geq T_{i-1} \\ D_{i-1} + (T_{i-1} - H_{i-1}), & H_{i-1} < T_{i-1} \end{cases}$$

where the daily drainage D_i (cm) from soil layer i to layer $(i + 1)$ is given by

$$D_i = \begin{cases} 0, & \text{if } S_i \leq S_U \\ k_s(S_i - S_U)d_i, & \text{if } S_S \leq S_i < S_U \end{cases}$$

where k_s = soil water conductivity (day^{-1}). Excess water in the lowest soil layer is allowed to drain into the subsurface soil layer. There is no provision in the model for perked water tables which would impede drainage of water into the subsurface soil layer. The new value of $S_i(t)$ is given by

$$S_i(t) = \begin{cases} S_i(t-1) + T_i/d_i - D_i/d_i, & T_i \leq H_i \\ S_i(t-1) + H_i/d_i - D_i/d_i, & T_i > H_i \end{cases}$$

where t is the time in days. The daily movement F_i (cm) of water due to unsaturated flow for $S_i < S_U$ between layer i and layer $(i + 1)$ is calculated by

$$F_i = \bar{D}(\theta_{i+1} - \theta_i)/[0.5(d_i + d_{i+1})]$$

where

$$\bar{D} = 0.88 e^{35.4[0.5(\theta_{i+1} + \theta_i)]}$$

$$\theta_i = S_i - S_L.$$

A negative value of F_i implies a flow of water from layer i to layer $(i + 1)$. The change in fractional water content is calculated by

$$S_i = S_i + F_i/d_i$$

$$S_{i+1} = S_{i+1} - F_i/d_{i+1}.$$

Total evaporation E is calculated as a sum of soil evaporation E_s and plant transpiration E_T according to the method of Ritchie (1972). The estimation of E_s is based on two stages of soil evaporation. Potential soil evaporation E_{SP} is calculated as

$$E_{SP} = \begin{cases} E_p(1 - 0.43 \text{ LAI}), & \text{for } \text{LAI} \leq 1 \\ E_p/(1.1) e^{-0.4 \text{ LAI}} & \text{for } \text{LAI} > 1 \end{cases}$$

where LAI is the leaf area index and E_p is the potential evaporation. E_p is calculated using the Penman-Monteith (Monteith 1965) formula with negligible surface resistance

$$LE_p = [\Delta(I_{\text{net}} - G) + \gamma f(u)(e_{\text{sat}} - e_a)]/(\Delta + \gamma)$$

where

- I_{net} net radiation
- G soil heat flux
- e_{sat} saturation water vapor pressure
- e_a actual water vapor pressure
- Δ de_{sat}/dT where T = temperature
- γ psychrometric constant
- $f(u)$ $(=[0.622\rho LU(z)k^2]/\{P[\ln(z/z_0)]^2\})$
- ρ air density
- L latent heat of evaporation
- $U(z)$ wind speed at height z

- k von Kármán constant
- P air pressure
- z_0 roughness height = 0.01 m.

During stage 1, E_s is equal to E_{SP} which continues until the upper limit of stage 1 evaporation (U) is reached. The quantity U is soil-dependent, generally falling in the range of 6–12 mm. During stage 2, E_s is a declining function of time since the beginning of stage 2. Two accumulated variables, SE_{S1} and SE_{S2} , are used to keep track of the accumulated soil evaporation during stages 1 and 2, respectively. When SE_{S1} is less than U , $E_s = E_{SP}$ and daily contribution to SE_{S1} is $(E_s - P_d + R_d)$ with the restriction that SE_{S1} cannot be negative. On the first day on which SE_{S1} exceeds U , E_s is given by

$$E_s = E_{SP} - 0.4(SE_{S1} - U)$$

and

$$SE_{S2} = 0.6(SE_{S1} - U)$$

The time after stage 2 has begun t_{S2} is calculated by

$$t_{S2} = (SE_{S2}/3.5)^2$$

where SE_{S2} has units of mm. On each subsequent day t_{S2} is increased by 1 with E_s being given by

$$E_s = 3.5t_{S2}^{1/2} - SE_{S2}$$

If precipitation occurs during stage 2, but $(P_d - R_d)$ is less than SE_{S2} , then E_s is the minimum of E_{SP} , $[0.8(P_d - R_d)]$, or $(E_s + P_d - R_d)$. If $(P_d - R_d)$ exceeds SE_{S2} , then t_{S2} is set back to zero and stage 1 evaporation occurs with $SE_{S1} = U + SE_{S2} - P_d + R_d$. Plant transpiration E_T is calculated by

$$E_T = \begin{cases} E_p(1 - e^{-\text{LAI}}), & \text{for } \text{LAI} < 3 \\ E_p, & \text{for } \text{LAI} \geq 3. \end{cases}$$

If $(E_T + E_s) > E_p$, then $E_T = E_p - E_s$. Soil moisture deficits in the root zone influence E_T through LAI. The plant development portions of CERES-Maize calculate changes in LAI through relationships which are a function of the soil moisture status.

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