jNSM 1.6.0 - Java Newhall Simulation Model

User Guide – Part II

United States Department of Agriculture
Natural Resources Conservation Service

Useful References for jNSM

Reproductions of the references listed below appear on the pages that follow.

Kellogg, C. E. 1969. United States Department of Agriculture, Soil Conservation Service Memo dated March 5, 1969 Re: ***Soil temperature and soil moisture measurements.***
(Two pages)

Newhall, F., and C.R. Berdanier. 1996. ***Calculation of soil moisture regimes from the climatic record.*** Soil Survey Investigations Report No. 46, National Soil Survey Center, Natural Resources Conservation Service, Lincoln, NE.
(Fifteen pages)

USDA Soil Conservation Service. 1964. ***Soil-Temperature Regimes -- their characteristics and predictability.*** SDS-TP-144 April 1964. 14 pages.
(Sixteen pages)

Van Wambeke, A. 1982. ***Calculated soil moisture and temperature regimes of Africa.*** Soil Management Support Services Technical Monograph No. 3, USDA-SCS, Washington, D.C. As of 8/2011 available via: http://pdf.usaid.gov/pdf_docs/PNAAQ982.pdf
(Nine pages -- only pages 3 – 11 are reproduced)

Van Wambeke, A. R. 2000. ***The Newhall Simulation Model for estimating soil moisture & temperature regimes.*** Department of Crop and Soil Sciences. Cornell University, Ithaca, NY.
(Nine pages)

Van Wambeke, A., Hastings, P., & Tolomeo, M. 1986. ***Newhall simulation model: a BASIC program for the IBM PC.*** Ithaca, NY: Department of Agronomy, Cornell University. Diskette and Booklet.
(Forty-two pages)

The following two pages are:

Kellogg, C. E. 1969. United States Department of Agriculture, Soil Conservation Service Memo dated March 5, 1969 Re: ***Soil temperature and soil moisture measurements.***

UNITED STATES DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE
Washington, D. C. 20250

March 5, 1969

Advisory SOILS-4

From: Charles E. Kellogg, Deputy Administrator
for Soil Survey

Re: Soil temperature and soil moisture measurements

The purpose of this Advisory is to explain the need for making useful records of soil moisture and temperature conditions over time.

We hope that your staff can help the soil scientists with this need. Some of their time and attention will be required. How much varies widely within States. Several of the cooperating experiment stations are interested in this problem and can help meet the needs of the Soil Survey.

The temperature and moisture regimes of soils are two of the most important properties needed for our interpretations. They directly determine the kinds of plants that can be grown and also limitations of soils for housing, recreation, highway design, and other engineering purposes. They affect the processes that go on in the soil. Thus these properties, along with others, are important to definitions of the classes in our soil classification system.

It would be virtually impossible to devise a system of soil classification useful for interpretations if we ignored these regimes. During the ice age, the climate over most of the United States alternated between periods something like the present and periods that were distinctly cooler and wetter. Vegetation changed with the climate. In the areas that were not covered by the ice or buried by loess, many of the soils developed properties that reflect climates that were cooler and wetter than the present. If we were to use those properties to define classes without regard to current temperature and moisture, we would group series in a way that would make many important interpretations impossible. For example, soils of the Appalachian plateau in New York would have to be grouped with soils that presently have permafrost. The evidences of the ancient permafrost persist in the soils even though the frost melted something

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more than 10,000 years ago. If we did not use soil moisture regimes to define classes, some soils in the Arizona deserts would be grouped with soils of the High Plains in Texas or Oklahoma simply because rainfall was once higher in Arizona and the soils retain the evidence of the older climate in their morphology. Soils that were wet during the ice age still have the colors of wet soils even though they were naturally drained many thousands of years ago.

Moisture and temperature records are not everywhere needed. In much of the country we can infer the regimes from meteorological data. We do need more soil temperature data in the mountains where weather stations are lacking, and in States where the soil temperatures are near the limits between classes. We particularly need soil moisture data in two situations: One is in the poorly and very poorly drained soils in which the water table fluctuates. For these, we need more records of the height of the water table throughout the year to compare with the morphology. These records will eventually permit more precise recognition of the water table fluctuations and better interpretations. The other situation is near the margins of the deserts where the rainfall is limiting. For these we need records of the duration of periods when the soils lack water available to useful plants.

Methods of measuring soil temperature are explained in SCS-TP-144, Soil Temperature Regimes--their characteristics and predictability, 1964.

Methods for ground-water studies are explained in a reprint of a note by R. B. Daniels and E. E. Gamble that was given general distribution. Additional copies are available from Soil Survey Investigations, SCS, Washington, D. C.

Methods that can be used in the field for determining the presence or absence of available water are currently under study.

Charles Kellogg

The following fifteen pages are:

Newhall, F., and C.R. Berdanier. 1996. ***Calculation of soil moisture regimes from the climatic record.*** Soil Survey Investigations Report No. 46, National Soil Survey Center, Natural Resources Conservation Service, Lincoln, NE.

Calculation of soil moisture regimes from the climatic record

Franklin Newhall and C. Reese Berdanier

Soil Survey Investigations Report No. 46

National Soil Survey Center
Lincoln, Nebraska

March 1996

Natural Resources Conservation Service
U.S. Department of Agriculture

FOREWORD

Early versions of this document were written before 1980 when products of the computer model described herein were being used in support of soil classification throughout the United States and in other countries. The process of review, approval, and publication was interrupted several times by retirements or transfers of the authors and other key people.

Now, the model has been used widely and is known in a general way by many people. Further, the original computer model is no longer operational and products in the original output format are no longer available. Accordingly, I have removed several sections of the early versions that are no longer pertinent. I have retained and revised sections that describe and explain how the computer model worked.

Ellis G. Knox
February 1996

CALCULATION OF SOIL MOISTURE REGIMES FROM THE CLIMATIC RECORD

By Franklin Newhall and C. Reese Berdanier [1]

INTRODUCTION

Soil moisture regimes (Soil Survey Staff, 1992) reflect seasonal patterns of variation in the moisture condition of the soil. They are used in Soil Taxonomy to differentiate many classes in the suborder, great group, and subgroup categories.

A model of moisture accretion and depletion, commonly known as the Newhall model, was developed to apply weather data to decisions about soil moisture regime in the application of Soil Taxonomy (Soil Survey Staff, 1975, page 53). It can be run for any weather station having adequate records of monthly precipitation and temperature. The model does not attempt a sophisticated simulation of water movement in and out of the soil. It is conceptually simple but tedious and suitable for computer use.

The model was used by the Soil Survey Staff in the Soil Conservation Service to predict the number of days in a year that parts of the soil moisture control section are moist or dry for thousands of locations in the United States and many locations in other countries.

The original model, written by Newhall in COBOL, is no longer available. It was revised and rewritten by van Wambeke (1981, 1982, 1985, 1986) with an output format in FORTRAN. A version in BASIC (FLEXNSM Program) was available in 1992 from Dr. A. van Wambeke, Department of Soil, Crop, and Atmospheric Sciences, Cornell University, Ithaca, New York.

This report documents the assumptions, logic, and procedure of the original model.

ASSUMPTIONS AND DEFINITIONS FOR THE SOIL MOISTURE MODEL

As in other soil moisture models, the soil is regarded as a reservoir with fixed capacity. In the model, water is added by precipitation, the amount exceeding the retention capacity of the soil is lost by deep leaching or runoff, and stored soil water is removed by evapotranspiration. This model uses Thornthwaite's procedure (1948) to estimate evapotranspiration (PE) from abundant data on temperature and day length. It differs from most previous models because of certain assumptions about the relationship of infiltration and rainfall intensity and about the amount of energy required to remove moisture from various layers of the soil.

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[1] Climatologist (retired) and Soil Scientist (retired), Soil Conservation Service, USDA.

The soil moisture profile

The soil moisture profile extends from the surface to that depth above which the water retention difference (WRD) is 200 mm. WRD (Burt, 1995) is the difference between the amount of moisture held in the soil horizon at a tension of 33 kPa (1/3 bar) and the amount held at 1500 kPa (15 bars). It can be expressed on a volumetric or a thickness basis. It is assumed that below this profile there is no active exchange of moisture with the atmosphere. The actual thickness of the soil moisture profile depends on the WRD of individual soil horizons. It ranges from less than 80 centimeters to more than 240 centimeters.

The soil moisture control section

The soil moisture control section (MCS) is defined in Soil Taxonomy (Soil Survey Staff, 1975, p. 53). Its upper boundary is the depth to which a dry soil (at a tension of more than 1500 kPa but not air dry) is moistened by 25 mm of water moving downward from the surface in 24 hours. The lower boundary is the depth to which the dry soil is moistened by 75 mm of water moving downward from the surface in 48 hours. These depths may be measured in the field but the necessary observations seldom are made. The boundaries may be approximated by calculating the depths of cumulative WRD of 25 and 75 mm. Thus, the moisture control section is the layer having 50 mm of WRD that lies below a surface layer having 25 mm of WRD. The thickness of the MCS depends on soil texture, bulk density, amount and size of rock fragments, and other soil properties that affect WRD. The soil moisture profile considered in this model has a third layer, below the MCS, that has 125 mm of WRD.

The soil moisture diagram

The conceptual diagram used in the computer model divides the soil moisture profile into 200 depth increments. Each increment has 1 mm of WRD. Each increment is divided into 200 segments; each segment represents 0.005 mm of WRD. The moisture tension of an increment ranges from 33 kPa, when all of the segments are filled, to 1500 kPa or dryer, when all of the segments are empty. The 199 parallel diagonals through this 200-by-200 grid are called slants. Depth increments, segments, and slants are the units manipulated by the computer. These concepts are illustrated for a 16-by-16 grid in Figure 1.

Accretion of moisture in the soil

Water from precipitation is added by depth increments. The model assumes that water from precipitation enters the soil from the top, filling all segments of each increment of soil before entering the next lower increment (Figure 2B). If the wetting front, the deepest increment filled by accretion, reaches the bottom of the soil moisture profile, excess moisture is assumed to be lost through deep percolation or by surface runoff.

The model divides total monthly precipitation (MP) into two parts. One half of MP is considered to be heavy precipitation (HP) that moves into any available water retention capacity. The other half of MP is considered to be light precipitation (LP) that is directly available for loss by evapotranspiration at the full rate of PE for the month. The difference between LP and PE is called net moisture activity (NMA). Only LP in excess of PE (positive NMA) is added into soil storage, up to the capacity for retention. By convention, the lowest increment to which moisture is added is made to be full at the end of the event.

Depletion of soil moisture

Water depleted by evapotranspiration is removed from the soil moisture profile by slants (Figure 2C, D). The model assumes that moisture is removed most readily from the depth increments most nearly filled and those nearest the top of the soil moisture diagram. That is, the energy required to remove water from the soil (expressed in units of PE) depends on moisture tension as well as depth in the profile. Accordingly, the model assumes that the requirement for removal of moisture is equal for the segments of one slant.

If all segments in the diagram are filled, depletion begins with slant 1 (Figure 1) and proceeds sequentially to the last slant. In early stages of depletion, one unit of PE removes one unit of moisture. As the soil profile becomes partially depleted of moisture, more units of PE are required to remove each unit of moisture as illustrated for the simplified diagram of Figure 1. In the computer model, using a 200-by-200 grid diagram with 399 slants, one unit of PE removes one unit of water in slants 1 to 60, the PE units required increase logarithmically from one to five from slants 69 to 320, and five units are required in slants 320 to 399.

PE is assumed to be uniformly distributed over the month. Only PE in excess of LP (negative NMA) is available to deplete water from the soil moisture profile.

OPERATIONS OF THE MODEL

Calculation of moisture states

The soil moisture regime is determined by moisture conditions in the MCS over a time period of one or more years. Moisture conditions of the MCS, in turn, are determined from the moisture states for the whole soil moisture profile. The computer model calculates three moisture states per month (two at mid month and one at the end of the month) from MP and normal monthly PE for each month of the selected climatic record.

Step 1. First half of month. This gives the moisture state at the middle of the month, just before step 2.

1.1. Compute light precipitation (LP).

LP = MP/2

1.2. Compute net moisture activity (NMA).

NMA = LP - PE

1.3. Add or remove water from the soil moisture profile.

If NMA > 0, apply NMA/2 to fill available segments by depth increments, starting at the top of the soil moisture diagram.

If NMA < 0, apply NMA/2 to exhaust filled segments by slants, starting with the lowest slant number.

Step 2. Mid month. This gives the moisture state in the middle of the month, just after accretion of HP.

2.1. Compute heavy precipitation (HP).

HP = MP/2

2.2 Apply HP to fill available segments by depth increments, starting at the top of the soil moisture diagram.

Step 3. Second half of the month. This gives the moisture state at the end of the month.

3.1. Compute LP. (Same as 1.1)

3.2 Compute NMA. (Same as 1.2)

3.3. Add or remove water from the soil moisture profile. (Same as 1.3.)

Moisture conditions of the moisture control section

For each moisture state generated, the MCS is classified dry in all parts (D), dry in some parts and moist in some (B), or moist in all parts (M). In terms of the soil moisture diagram (Figure 2), a part of the MCS is dry when all segments of at least one depth increment are empty. A part of the MCS is moist when one or more segments of at least one depth increment are filled.

Duration of moisture conditions

Periods between steps 3 and 1 (first half of the month) and between steps 2 and 3 (second half of the month) can be 14, 15, or 15.5 days. The interval between steps 1 and 2 is zero. If consecutive diagrams have the same moisture condition, the MCS is considered to have the same condition for all days in the period. When conditions change during a half-month period, the durations of the initial and subsequent conditions are computed through consideration of the NMA required to move from the initial moisture state to the state at the change to the next condition.

For example, when NMA is negative and the condition of the MCS changes from M to B or D during a half-month period, the duration (in days) of each condition is computed as follows (for one-half month = 15 days):

I = Initial soil moisture state
F = Final soil moisture state
PE available = -NMA/2
PE I to B = PE required to change from I to soil moisture state that initiates B
PE B to D = PE required to change from soil moisture state that initiates B to soil moisture state that initiates D

When I = M and F = B:

$$\text{Duration of M} = 15 \times \frac{\text{PE I to B}}{\text{PE available}}$$

$$\text{Duration of B} = 15 - \text{duration of M}$$

When I = M and F = D:

$$\text{Duration of M} = 15 \times \frac{\text{PE I to B}}{\text{PE available}}$$

$$\text{Duration of B} = 15 \times \frac{\text{PE B to D}}{\text{PE available}}$$

$$\text{Duration of D in days} = 15 - (\text{duration of M} + \text{duration of B})$$

Dates of change in moisture condition, derived from durations of D, B, and M during each half month, are converted to day numbers of the year. (Day numbers run from 001 to 365 for January 1 to December 31. February 29 is excluded.) For example, Table 1 lists day numbers of all changes in moisture condition for a 10-year period of record at Rosemont, Nebraska. Such information yields the number of days that the MCS exhibits specific moisture conditions as shown in Tables 2 and 3.

Table 2 relates to the ustic soil moisture regime. It shows the number of days that the MCS was dry in some or all parts (moisture conditions B or D) when the soil temperature was 5 ^{o}C or higher. The table shows a 70% probability (7 years out of 10) of meeting the ustic requirement of 90 or more days.

Table 3 shows the greatest number of consecutive days when the MCS was dry in all parts during the 120 days following the summer solstice. The requirement of 45 days or more for the xeric soil moisture regime was met in only 4 out of 10 years.

COMPARISONS WITH OBSERVED DATA

Data from direct observations of the soil moisture status or content of well characterized soils were available for few locations. Most commonly, water contents as a weight percent of oven-dry soil in several consecutive layers downward from the surface were measured at intervals during the year. From these data and water retention at 1500 kPa, it was possible by interpolation to count the number of days that the soil in given layers exceeded 1500 kPa tension. Then, using WRD values for the same layers, computer model results, expressed as in table 1, were obtained for the identical time period and the resulting numbers of days were compared.

Figure 3 shows the calculated and observed values of the number of days when the selected soil layer was dry in all parts during the period when the estimated soil temperature was 5 ^{o}C or higher. Data in the figure are for the layer that most closely approximates the MCS. The data reflect 128 station-years of observations at seven stations, mostly in the Great Plains between 1905 and 1930. Despite scatter, the correlation coefficient between calculated and observed values is 0.81.

This test was made for moisture condition D (dry in all parts) because it seemed plausible to attribute very low moisture content to all parts of the MCS. The two other moisture conditions cannot be tested in the same way because the distribution of moisture in parts of the observed layer cannot be assumed, and it is not possible to infer whether some parts are dry or not.

A different test used data taken at Rosemont, Nebraska. Moisture content was calculated for layers of a six-layer profile using an early version of the soil moisture diagram with 40 rather than 200 increments. The calculation was for the beginning, middle, and end of each month during which the soil moisture observations were made. The model explained about 40 percent of the variation of moisture in the surface layer, 60 percent in the second layer, and 50 percent in the third layer.

SUMMARY

The computer model described in this publication can be used to estimate aridic (torric), xeric, ustic, and udic soil moisture regimes as defined in Soil Taxonomy (Soil Survey Staff, 1992). Factors used in the model are precipitation and evapotranspiration. Results of the model should be applied judiciously because the calculated moisture regimes are estimates derived from climatic data, not soil data. However, the estimates are useful guides for the tentative classification of soils.

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Soil Survey Staff. 1975. Soil Taxonomy: A Basic System of Soil Classification for Making and Interpreting Soil Surveys. U.S. Department of Agriculture, Soil Conservation Service, Agriculture Handbook 436. U.S. Govt. Print. Off., Washington, D.C.

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Table 1. Day numbers when changes occurred in the calculated condition of MCS, Rosemont, Nebraska 1948-1957.

Year	Moisture Conditions and Day Numbers								
1948	M 043	B 192	M 196	B 215	D 223	B 349			
1949	M 062	B 226							
1950	D 177	M 196	B 225	D 240	B 256				
1951	M 045								
1952	B 252								
1953	M 045	B 196	D 217						
1954	M 135	B 179	D 184	B 227	D 254				
1955	B 015	D 125	B 135	D 161	B 166	D 193	B 196	D 213	B 258
1956	D 130	B 166	D 188	B 227	D 239				
1957	B 065	M 074	B 220	M 227	B 262				

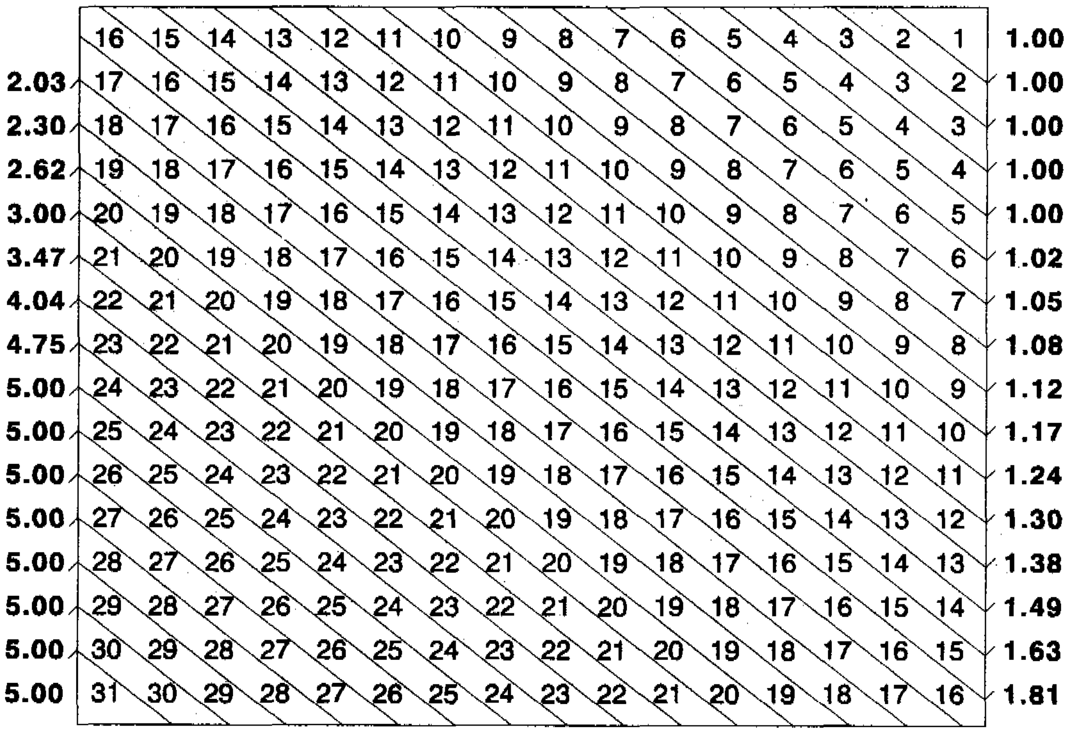
Table 2. Number of days when calculated condition of MCS was D or B from day 100 to day 326, the average period when soil temperature equals or exceeds 5 °C., Rosemont, Nebraska 1948-1957.

Year	Duration of Conditions D and B (day numbers and consecutive days)	Number of Days of D or B
1948	196 - 192 = 4, 326 - 215 = 111	115
1949	326 - 226 = 100	100
1950	196 - 100 = 96, 326 - 225 = 101	197
1951	none	0
1952	326 - 252 = 74	74
1953	326 - 196 = 130	130
1954	135 - 100 = 35, 326 - 179 = 147	182
1955	326 - 100 = 226	226
1956	326 - 100 = 226	226
1957	227 - 220 = 7, 326 - 262 = 64	71

Table 3. Greatest number of consecutive days of calculated condition D in MCS from day 172 to day 292, the 120-day period that begins with the summer solstice, Rosemont, Nebraska, 1948-1957

Year	Duration of Condition D (day numbers and consecutive days)		Greatest Number of Consecutive days
1948	292 - 223 = 69		69
1949	none		0
1950	177 - 172 = 5,	256 - 240 = 16	16
1951	none		0
1952	none		0
1953	292 - 217 = 75		75
1954	227 - 184 = 43,	292 - 254 = 38	43
1955	196 - 193 = 3,	258 - 213 = 45	45
1956	227 - 188 = 39,	292 - 239 = 53	53
1957	none		0

Surface



	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	1.00
2.03	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1.00
2.30	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	1.00
2.62	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	1.00
3.00	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	1.00
3.47	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	1.02
4.04	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	1.05
4.75	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	1.08
5.00	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	1.12
5.00	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	1.17
5.00	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	1.24
5.00	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	1.30
5.00	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	1.38
5.00	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	1.49
5.00	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	1.63
5.00	31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	1.81

Figure 1. Simplified soil moisture diagram with 16 depth increments, 16 segments in each increment, and 31 slants identified by number. Bold numbers to the right and the left indicate the number of PE units to remove a unit of moisture.

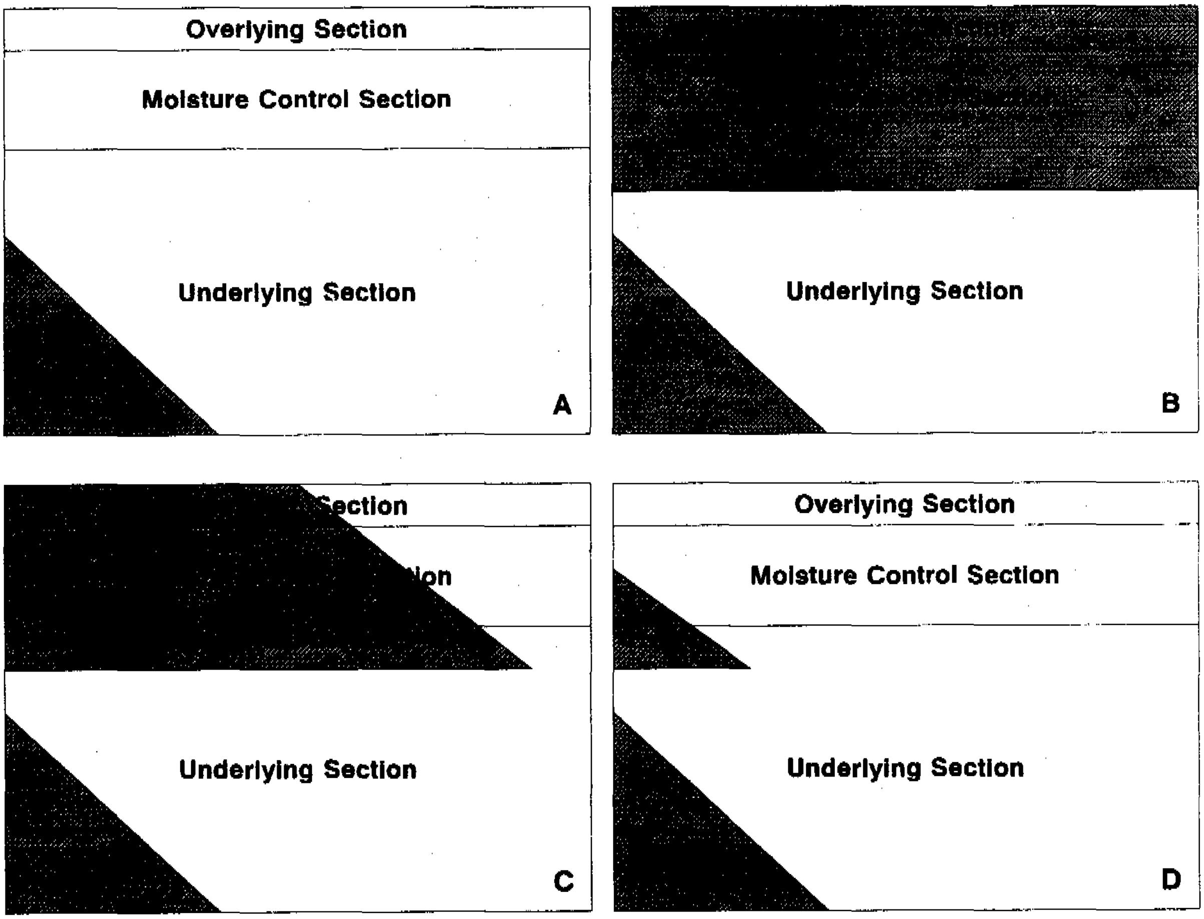


Figure 2. Simplified soil moisture diagrams showing the three sections of the soil moisture profile. The diagrams illustrate four moisture states and three moisture conditions of the moisture control section (MCS).

A. Water has been depleted by slants to below the MCS.
The moisture condition is D.

B. Water has filled increments from the top to below the MCS.
The moisture condition is M.

C. Water has been depleted by slants but all parts of the MCS are still moist.
The moisture condition is M.

D. Further water depletion by slants has made part of the MCS dry.
The moisture condition is B.

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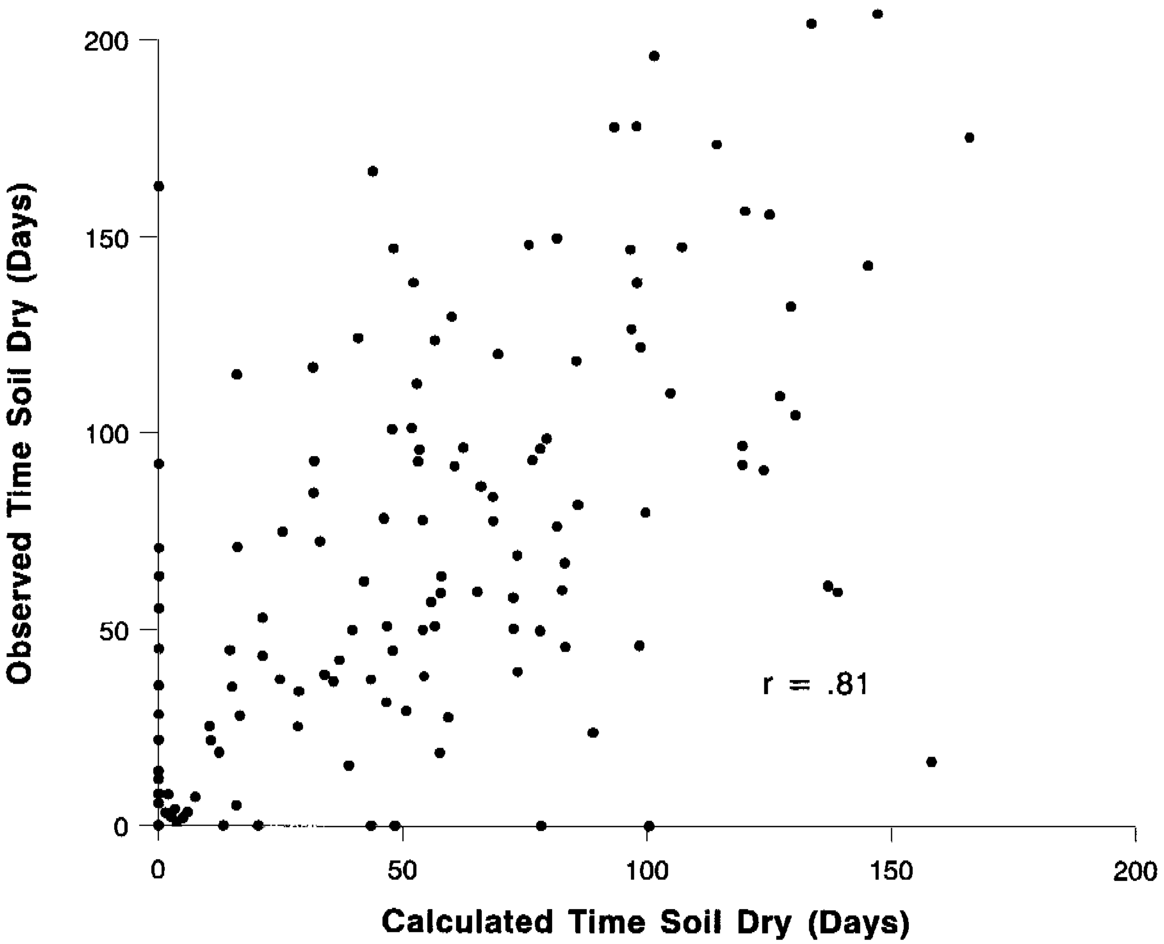

Figure 3. Number of days that soil layer is dry in all parts during period when soil temperature is estimated to be 5 °C or higher.

The following sixteen pages are:

USDA Soil Conservation Service. 1964. ***Soil-Temperature Regimes -- their characteristics and predictability.*** SDS-TP-144 April 1964. 14 pages.

Soil-Temperature Regimes--
their characteristics and predictability

U. S. Department of Agriculture
Soil Conservation Service

SCS-TP-144
April 1964

CONTENTS

SOIL-TEMPERATURE REGIMES
THEIR CHARACTERISTICS AND PREDICTABILITY

by Guy D. Smith, Soil Scientist; Franklin Newhall, Climatologist;
Luther H. Robinson, Soil Scientist; and Dwight Swanson, Climatologist,
Soil Conservation Service

The temperature of a soil is one of its important properties. Within limits, it controls the possibilities of plant growth and soil formation. Below freezing there is no biotic activity, water no longer moves as a liquid, and unless there is frost heaving, time stands still for the soil. Between temperatures of 32° and 42° F. root growth of most plants and germination of most seeds is impossible. A horizon as cold as 40° F. is a thermal pan to roots of most plants. The soil does not really come to life until its temperature exceeds 42° F., and the pace quickens rapidly as the temperature rises above 45° F.

Biological processes in the soil are controlled in large measure by soil temperature and moisture. Each plant species has its own temperature requirement. In the Antarctic, for example, there is a microscopic plant that grows only at temperatures below 45° F., temperatures at which most other plants are inactive. At the other extreme, germination of seeds of many tropical plants requires a soil temperature of 75° F. or more. Plants have one or more soil-temperature requirements that are met by the soils of their native environment. Similarly, soil fauna have temperature requirements for survival. Soil temperature, therefore, has an important influence on biological, chemical, and physical processes in the soil and on the adaptation of introduced plants. Relations of soil temperature to plant growth are not discussed here because they have been reviewed recently (Richards et al. 1952).

As we progress with the national cooperative soil survey and improve our soil classification, we are called on for interpretations to serve more and more uses. We must be able to make quantitative statements about our soils to meet many of these demands. Soil temperature is one basic soil property we should know.

The taxa of our older classifications of soils are partly defined by environment and genesis, giving some control of the variability in soil temperature. Latosols, for example, were confined to the Tropics, Tundra soils to the Arctic regions, Alpine Meadow soils to high elevations and thus to cold climates, and so on. We have been able to restrict the environment of a given soil series so that a soil series of Puerto Rico does not occur in Oregon or Alaska and one in Ohio does not occur in Arizona. But the new soil-classification system that we are developing must be cut loose from the natural landscape if it is to include soils whose properties have been changed by man. In doing this we lose some of the old relationship between soils and their environment, particularly if horizons are very thin, weak, or absent.

Recent alluvium having the same range in texture, mineralogy, reaction, organic matter, and color could occur in Hawaii, Nevada, and Alaska in widely different temperature and moisture regimes. The soil in Alaska would probably be forested and have a thick O horizon. The soil in Nevada might have a cover of scattered shrubs and a vesicular surface crust. The soil in Hawaii would have neither an O horizon nor a vesicular crust. No one would mistake one virgin soil for either of the others. But we need to substitute permanent properties for the distinctive surface horizons that are mixed or destroyed by cultivation.

The environment of a county without mountains is usually uniform enough for differences in genesis due to climate to be disregarded for purposes of a soil survey, but if we classify the soils of the United States or even those of a mountainous county, we cannot disregard the environment entirely. It must be brought into the classification at the phase or some higher level, and soil temperature offers a mechanism to accomplish part of this.

At any one moment, temperature varies from soil horizon to soil horizon. It fluctuates with the hour of the day and with the season of the year, and the fluctuations may be very small or very large according to the environment. Because temperature is so variable or perhaps because it is not preserved in samples, some soil scientists have felt that temperature is not a property of a soil horizon. Most of us who work with soils in limited geographic areas take soil temperature for granted because the temperature of all the soils is about the same. We are all inclined to notice the properties that differ among soils and to focus our attention on them. Yet if one travels, he is impressed by the coldness of soils he examines in high mountains or in boreal forests but not by the coldness of soils in tropical lowlands.

Each pedon has a characteristic temperature regime that can be measured and described. For most practical purposes, the temperature regime can be described by the mean annual soil temperature, the average seasonal fluctuations from that mean, and the mean warm or cold seasonal soil-temperature gradient within the main root zone, the 5- to 100-cm. depth. In this paper, the seasons in the northern hemisphere are winter--December, January, and February; spring--March, April, and May; summer--June, July, and August; autumn--September, October, and November. In temperate regions, we have used the mean summer and winter soil-temperature gradients. In tropical regions with pronounced dry seasons, the temperature regime can be better characterized by using the mean dry and wet seasonal soil-temperature gradients.

We have prepared this review of available information to emphasize the kinds of soil-temperature regimes and their relation to environmental factors. Primary emphasis is on soil temperatures in the United States and Puerto Rico, but we have drawn on the literature of many countries for illustrations. The measurements of soil temperature reported have commonly required complex instruments and daily or hourly observations. We will show, however, that most of the relevant parameters can be measured by simple equipment and with little effort.

Data that adequately describe temperature regimes of soils and their relation to environment are scarce because (1) details of the site conditions often are not reported, (2) the observations are not from deep enough layers, (3) the record is not kept throughout the year, or (4) the method of observation results in biased data. The picture we present is as we see it today. Additional data may require some modification in our opinions.

Mean Annual Soil Temperature

Each pedon has a mean annual temperature that is essentially the same in all horizons at all depths in the soil and at depths considerably below the soil. The measured mean annual soil temperature is seldom the same at successive depths at a given location, but the differences are so small that it seems valid and useful to take a single value as the mean annual temperature of a soil. Some representative measurements of the mean annual temperature at various depths in and below selected soils are given in table 1.

Many data show differences in the annual averages of measured temperatures in the first few inches and at depths of more than 20 inches. Some of the data were obtained by daily readings at the same hour, for example, 0800 or at 0800, 1200, and 1800. This method does not give a true average for depths having a daily temperature cycle and thus often introduces a systematic error or bias into the records. Other records are ambiguous because the methods of computing the mean temperature were not given in the references available. The data in table 1 are considered reasonably representative of the most reliable measurements.

TABLE 1.--Mean annual temperature at various depths in soils and substrata in selected locations[1]

[---indicates no record]

Depth (feet)	Bozeman, Mont.	Seattle, Wash.[2]	Urbana, Ill.	Colombo, Ceylon	Jaipur, India	Irkutsk, U.S.S.R.[2]	Belgrade, Yugoslavia[2]
	° F.	° F.	° F.	° F.	° C.	° C.	° C.
1---------	43.2	---	53.2	85.5	26.9	---	---
2---------	43.4	52.4	53.0	85.7	---	0.7	---
3---------	42.7	---	53.3	85.6	26.9	0.8	12.9
4---------	43.3	51.9	---	85.6	---	1.1	12.8
5---------	43.4	52.2	---	85.7	---	1.5	12.6
10--------	43.9	53.1	---	85.2	27.2	2.0	12.7
20--------	---	52.8	---	---	27.1	2.5	12.6
30--------	---	52.6	---	---	---	---	12.8
50--------	---	---	---	---	---	---	12.9
Mean annual air temperature.	42.9	51.4	50.9	80	25	-2	12.2
Length of soil-temperature records (years).	5	2	20	15	20	18	4

[1] Data from Chang (1958b).
[2] Depths are approximate.

Mean annual soil temperature and mean annual air temperature

A comparison of mean annual soil and air temperatures at selected sites in the United States is given in table 2. In computing these averages, we have given the greatest weight to measurements made below the depth of the daily temperature cycle.

IN HUMID TEMPERATE UNITED STATES

In most of the United States, the mean annual air temperature is a consistently good indication of the mean annual soil temperature although the latter is usually a little higher. Examination of the data in table 2 and numerous other data shows that if the mean annual air temperature is 47° F. or higher and

TABLE 2.--Relation of mean annual soil temperature to mean annual air temperature at selected sites in the United States

[Additional information on most of the sites in this table and other sites is given in U.S. Weather Bur. (1961). --- indicates no record]

Location	Depth	Years	Cover	Mean annual soil temperature A	Mean annual air temperature[1] B	A minus B
	In.	No.		° F.	° F.	° F.
Barrow, Alaska[2]---------	0-264	1	Tundra	16.2	[3] 9.8	6.4
Tanana, Alaska[2]---------	12	7	Swamp veg.	32.7	[3] 22.6	10.1
Fairbanks, Alaska[2]-----	1-24	2	---	35.0	[3] 26.0	9.0
Galena, Alaska[2]---------	6-12	6	Moss	37.8	[3] 23.8	14.0
Anchorage, Alaska[2]------	6-48	5	Bare	39.1	[3] 33.4	5.7
Bozeman, Mont.[2]---------	12-120	5	---	43.3	[4] 42.9	.4
Rainbow Dam, Wis.[3]------	1-6	5	Grass	44.9	41.0	3.9
Moscow, Idaho[2]----------	0-72	3	---	47.1	[3] 47.6	-0.5
Mount Vernon, Wash.[2]---	6	5	Grass	48.6	[4] 50.6	-2.0
Squaw Butte Expt. Sta., Oreg.[3]---------------	2-24	3	Bunch grass	48.8	46.3	2.5
Ithaca, N.Y.[2]-----------	0-96	5	Grass	48.9	[4] 47.1	1.8
Flagstaff, Ariz.[2]------	6	3	Park-pine	49.2	[4] 44.6	4.6
Burlington, Vt.[3]--------	0-10	5	Grass	49.3	44.3	5.0
East Lansing, Mich.[5]---	2-18	2	Bare	50.3	[3] 46.8	3.5
Fort Collins, Colo.[2]---	3-72	41	Grass	50.6	[4] 48.1	2.5
Ames, Iowa[6]-------------	1-72	20	Grass	50.9	[4] 48.9	2.0
Wooster, Ohio[2]----------	3.5	7	Grass	51.4	[4] 50.1	1.3
Coshocton, Ohio[2]--------	5-24	14	Crops	51.9	[4] 52.2	-0.3
Lemont, Ill.[7]-----------	0.4-348	3	Grass	52.3	49.1	3.2
Seattle, Wash.[2]---------	0-360	2	Grass	52.5	[3] 51.4	1.1
Prosser, Wash.[2]---------	0.5-12	20	Bare	53.1	[4] 51.0	2.1
Urbana, Ill.[2]-----------	0-36	20	Sedge-grass	53.2	[4] 50.9	2.3
Pullman, Wash.[2]---------	1-6	9	Grass	54.6	52.2	2.4
Conception, Mo.[3]--------	1-6	5	Grass	54.9	[3] 53.0	1.9
Lexington, Ky.[2]---------	3-36	8	---	55.6	[4] 54.9	0.7
Corvallis, Oreg.[3]-------	2-40	1	Grass	56.0	52.6	3.4
Union, S.C. (Calhoun)[3]-	1-12	3	Grass	59.5	59.6	-0.1
Auburn, Ala.[2]-----------	3-48	1	(Streambank)	65.6	[3] 61.5	4.1
Indio, Calif.[8]----------	12-72	1	Date grove	68.6	71.9	-3.3
Temple, Tex.[2]-----------	1-48	7	Grass	70.5	[3] 68.0	2.5
Tifton, Ga.[2]------------	3-6	2	Grass	71.2	[3] 71.3	-0.1
Tucson, Ariz.[2]----------	3-72	1	Bare	73.2	[3] 68.4	4.8

[1] Values are for periods when soil temperature was measured except those from Climate of the States[4], which are normal air temperatures. Air temperatures were not always measured at the exact site of the soil-temperature measurements, and the effects of microclimate are not controlled.
[2] Data from Chang (1958b).
[3] U.S. Weather Bureau climatological data (1895-1963).
[4] Data from U.S. Weather Bureau Climate of the States (1959-1960).
[5] Data from Bouyoucos (1916).
[6] Data from Elford and Shaw (1960).
[7] Data from Carson (1961).
[8] Data from Bliss (1942).

if rainfall is generally adequate in all seasons, level or gently sloping soils have a mean annual temperature about 2° F. higher than the air. Table 2 includes 16 stations that more or less meet these conditions. If we were to estimate the mean annual soil temperature by adding 2° to the measured mean annual air temperature, we would on the average miss the measured soil temperature by only a little more than 1°.

IN COLD CLIMATES

As the mean annual air temperature decreases, the difference between soil and air temperatures tends to increase. At low elevations this is largely, if not entirely, because snow insulates the soil in cold weather. Relations at high elevations are discussed later.

Table 2 shows that the soils of Alaska range from about 6° to 14° F. higher than the air. The mean annual soil temperatures in the U.S.S.R. cited by Golovin (1962) are higher than air temperatures. He cites Shul'gin as showing that the soil is 1° C. warmer than the air in the southern part of European U.S.S.R. and 3.5° C. warmer in the northern part. In the Amur region of southeastern Siberia, the soils are 3 to 6° C. (5 to 11° F.) warmer than the air. There the mean annual soil temperatures are reported to range from almost 31° to 40° F. (-0.3° to 4.3° C.), and the mean annual air temperature ranges from about 25° to 32° F. These data, shown in table 3, are consistent with the data from Alaska in table 2.

IN HUMID OCEANIC CLIMATES

In contrast to most of the United States, some data from western Europe show soil temperatures to be lower than air temperatures (Chang 1958a, p. 60). This relation has been attributed to the cold rains and to evaporation, but the reduction of solar radiation by the cloud cover may also be an important factor. A similar relation may exist in parts of southern Alaska and in coastal areas of Washington and Oregon, but the only measurements of soil temperature in this region that we have found were made at Seattle, Wash., and Corvallis, Oreg. (table 2). At Seattle, which has about 32 inches of rain, the soil is 1.1° F. warmer than the air. At Corvallis in 1961, the soil was 3.4° warmer than the air. Nevertheless, it is possible that as rain increases, soil temperatures may drop below air temperatures. Both Seattle and Corvallis have very dry sunny summers, thus the climate is not strictly comparable to that of western Europe.

TABLE 3.--Relation of average annual soil temperature to air temperature in the Amur region, U.S.S.R.[1]

Place	Average annual temperature		Temperature difference
	Soil at a depth of 20 cm.	Air	
	° C.	° C.	° C.
Ul'minsk Experimental Field-------------	1.2	-2.9	4.1
Blagoveshchensk-------------------------	4.3	0.0	4.3
Amur Agricultural Experiment Station----	3.2	-1.3	4.5
Kukhterin Lug---------------------------	-0.3	-4.2	3.9
Komissarovsk grain crop sovkhoz---------	1.6	-1.6	3.2
Belogorsk-------------------------------	3.5	-2.0	5.5
Tarbagatay------------------------------	1.7	-2.8	4.5
Gosh------------------------------------	1.7	-3.7	5.4
Norskiy Sklad---------------------------	2.2	-4.0	6.2
Paykanskiy Sklad------------------------	1.4	-2.8	4.2
Verkhnyaya Tom'-------------------------	0.8	-4.2	5.0

[1] Golovin (1962) p. 216.

IN DRY CLIMATES

The soil at Tucson, Ariz. (table 2), is about 5° F. warmer than the air. Similar differences have been reported (Smith 1932) at Davis, Calif., where the difference is 7.2° F. It must be noted that both soils were bare. It must also be pointed out that irrigation can have a drastic effect on soil temperature. For example, an irrigated soil at Vauxhall, Alberta, was 13° F. colder than the air during the summer and 3° colder than the air during the year 1961.[1] An irrigated soil at Indio, Calif., (table 2) was also 3° colder than the air. This is presumably an effect of evaporation.

Mean annual soil temperature and kind of cover

Measurements of the relation of mean annual soil temperature to cover in mid-latitudes are given in table 4.

TABLE 4.--Effect of cover on mean annual soil temperature[1]

Location	Depth	Years	Cover	Mean annual soil temperature A	Mean annual air temperature B	A minus B
	In.	No.		° F.	° F.	° F.
Huntley, Mont.----	2-60	2	Sod	49.9	47.0	+2.9
Huntley, Mont.----	2-60	2	Bare	49.2	47.0	+2.2
New Brunswick, N.J.	1-32	6	Sod	52.9	53.0	-0.1
New Brunswick, N.J.	1-8	2	Bare	53.6	52.3	+1.3
Union, S.C.-------	0-72	3	Pine	61.2	61.7	-0.5
Union, S.C.-------	0-12	3	Sod	59.5	59.6	-0.1
Union, S.C.-------	0-72	3	Lespedeza	57.2	61.7	-4.5

[1] U.S. Weather Bureau climatological data (1956 and later).

In mid-latitudes it would appear that the kind of cover has at best only a slight influence on the mean annual soil temperature. Other data showing somewhat greater differences have not been included in table 4 because they may have been biased by the time of the temperature readings, which were taken at a shallow depth once a day at a fixed hour.

In high latitudes it is possible that a thick O horizon of needles and moss has a significant effect on the mean annual soil temperature. The O horizon is a permanent layer of insulation; snow is present only in cold weather. An O horizon therefore reduces the relative importance of snow as an insulator. If an O horizon is present, the mean annual soil temperature could be as low as or lower than the mean annual air temperature. The insulating effect of snow cover is discussed more fully later.

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[1] Meteorological observations in Canada monthly record, 1961.

Mean annual soil temperature and slope

Few data have been found on the relation of slope gradient and direction to mean annual soil temperature. The mean annual soil and air temperatures of north- and south-facing slopes of 20° (36 percent) were studied under light-shade conditions in a deciduous forest in New Jersey (Cantlon 1953). Over the year the soil at a depth of 4 cm. on the south-facing slope was 4.8° F. warmer than that on the north-facing slope (fig. 10, p.10). The air 5 cm. above the soil was 6° F. warmer on the south- than on the north-facing slope; 1 meter above the soil it was 1.7° F. warmer, but at a height of 2 meters there was virtually no difference.

Soil Conservation Service (SCS) staff members measured soil temperatures under grass at Waterford, Calif., at monthly intervals in 1962. The 20- to 30-percent south-facing slope was 6.4° F. warmer than the 20- to 30-percent north-facing slope. The mean annual soil temperature on the north-facing slope was 66.4° F. and on the south-facing slope, 72.8° F.

These observations of soil temperature probably show almost the maximum effect of slope aspect in the United States. The effect of slope depends on sunshine duration. Only in deserts where the soil is bare and sunshine is at a maximum would we expect a greater difference on equivalent slopes. It must be noted that the effect of slope varies with latitude.

Mean annual soil temperature and elevation

Differences in soil temperature related to elevation are relatively complex. With increased elevation, intensity of radiation increases, air temperature decreases, and rainfall and snow may vary erratically.

The mean annual air temperature tends to decrease about 2.7° F. per 1,000-foot increase in elevation of the earth's surface. The temperature reduction with elevation is greatest in summer when it averages about 3.6° F. per 1,000 feet; in winter it averages only 2.2° F. per 1,000 feet.

The difference between air and soil temperature increases with elevation. Carson (1961, p. 46) attributed this to increased radiation, but snow cover often increases and is certainly a factor. We can assume, therefore, that soil temperature may not decrease as much as air temperature.

Mean annual soil temperature and organic-matter content

Bouyoucos (1916) found that there was virtually no difference in the mean annual soil temperature between drained peat and medium- to fine-textured mineral soils at East Lansing, Mich.

Few other comparisons are available between the mean annual temperatures of organic and mineral soils. Records at Flahult, Sweden (Chang 1958b), show that the mean annual temperatures of a wet bog and a well-drained sand are practically identical (fig. 14, p. 12). From these examples it seems that neither ground water nor organic-matter content influences the mean annual soil temperature appreciably.

Mean annual soil temperature and soil color or texture

Bouyoucos (1916) in his studies of the effect of color and texture on the mean annual soil temperature recorded the following mean annual soil temperatures (6-inch depth).

Soil texture	Not covered with sand	Covered with sand
	° F.	° F.
Gravel	51.1	51.9
Sand	51.3	52.0
Loam	49.4	51.5
Clay	50.0	51.9
Peat	49.4	52.5

He concluded that coarse-textured soils are warmer because they hold less water that can evaporate and cool them. After covering all the soils with sand to reduce evaporation, he found no differences in soil temperature. The main conclusion he reached, however, was that color and texture have a very minor effect on the mean annual soil temperature.

Fluctuations of Soil Temperature With Time

The mean annual temperature of a soil is not, of course, a single reading but an average of a series of readings. Near the surface this series may fluctuate from the mean fully as much as air temperature, especially if there is no insulating cover. The fluctuations occur as daily and annual cycles, which in most places are made somewhat irregular by weather events. The fluctuations decrease and are ultimately damped out with increasing depth in the substrata in a zone of constant temperature that is the same as the mean annual temperature.

Short-term temperature fluctuations

DAILY FLUCTUATIONS

Daily changes in air temperature have a significant effect on surface-soil horizons to a depth of about 20 inches (50 cm.). The fluctuations may be very large, particularly in soils of dry climates where the daily range in temperature of the upper inch may approach 100° F. Sutton (1953) has pointed out that for middle and high latitudes a representative daily range on a sunny summer day is 25° C. (45° F.). At the other extreme under melting snow the surface temperature may be constant throughout the day.

Daily soil-temperature fluctuations are affected by clouds, vegetation, length of day, soil color, soil slope, soil moisture, air circulation near the ground, and the temperature of any rain that falls. Moisture can be exceedingly important in reducing fluctuations in soil temperature. The specific heat of water is roughly five times that of soil minerals and twice that of dry organic matter. The specific heat of water is roughly four times that of dry surface horizons, and the specific heat of medium-textured surface horizons at field capacity is roughly twice that at the wilting point. Water increases thermal conductivity, and it can also absorb or liberate heat by thawing and freezing or by evaporating and condensing. All effects reduce fluctuations at the surface.

To illustrate the daily temperature fluctuations that can be expected over much of the United States, two examples from the more extensive foreign literature are reproduced. Figure 1, taken from Chang (1958a), shows the change in temperature with depth at various hours during a summer day at Griffith, Australia. Between 0600 and 1200, the surface temperature is rising but the temperature at 24 cm. is falling. The daily maximum at the surface comes at or before 1500, but the maximum at 24 cm. is not reached until between 2000 and 2200.

Figure 2 (Rode 1955, after Homen 1897) shows the daily temperature cycle in a soil in Finland by lines connecting points of equal temperature. The hours of the day for 2 days are shown by vertical lines. To determine temperatures at any hour, locate the hour and read down. To determine the temperature changes over time at any given depth, locate the depth and read across. At a 30-cm. depth on August 12, for example, the soil temperature fell until about 1100; from 1100 to 2200 the temperature rose about 2° C. The temperature at a 10-cm. depth fluctuated between about 14° C. and 21.5° C. on August 12 and between 14° C. and 19° C. on August 13. The dashed lines indicate the boundaries between the heating and cooling cycles. At a 50-cm. depth, the fluctuation is only a fraction of a degree and the time lag is about 18 hours. At 60 to 70 cm. the cycle disappears.

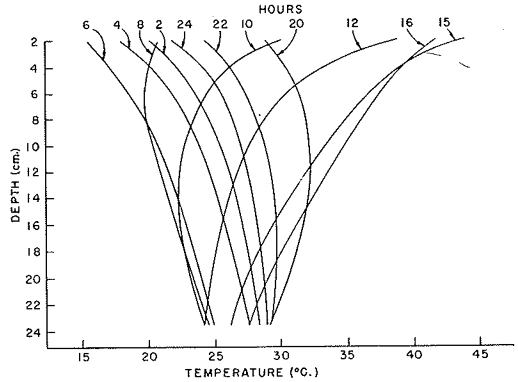


Figure 1.--Variation of soil temperature with depth at each of several hours during the course of a summer day at Griffith, Australia (from Chang 1958a).

FLUCTUATIONS DUE TO CHANGES IN WEATHER

Soil temperatures also fluctuate with weather that brings below-average or above-average air temperatures for short periods. The weather fluctuations extend to a greater depth than the diurnal cycle. Weather changes tend to last a few days to a week in most of the United States but, like weather patterns in general, occur at irregular intervals.

Figure 3, after Carson (1961), shows that the soil temperature at a depth of 1 cm. is closely related to insolation and air temperature. Changes in soil temperature at this depth reflect hourly variations in insolation (April 16 and 17). Temperatures at 1 cm. were also affected by the warm air mass that moved in on April 20. The soil temperature at a depth of 50 cm.

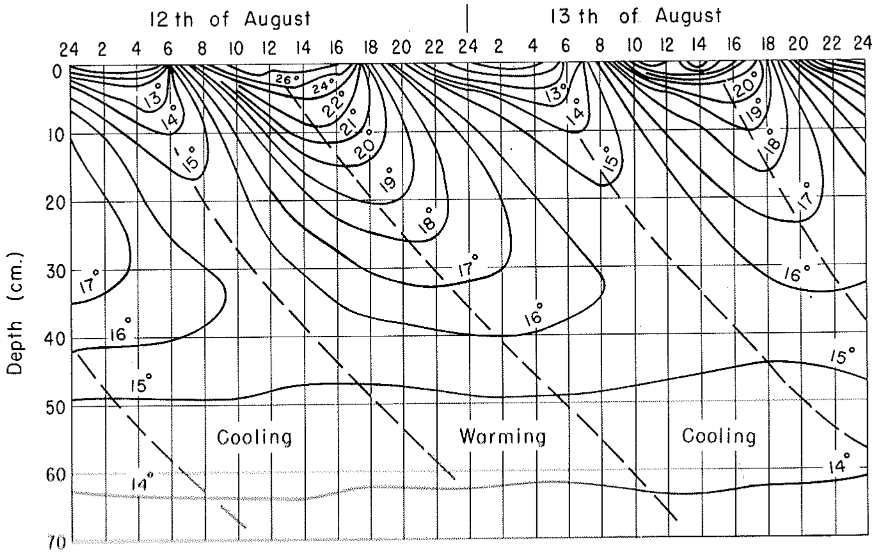
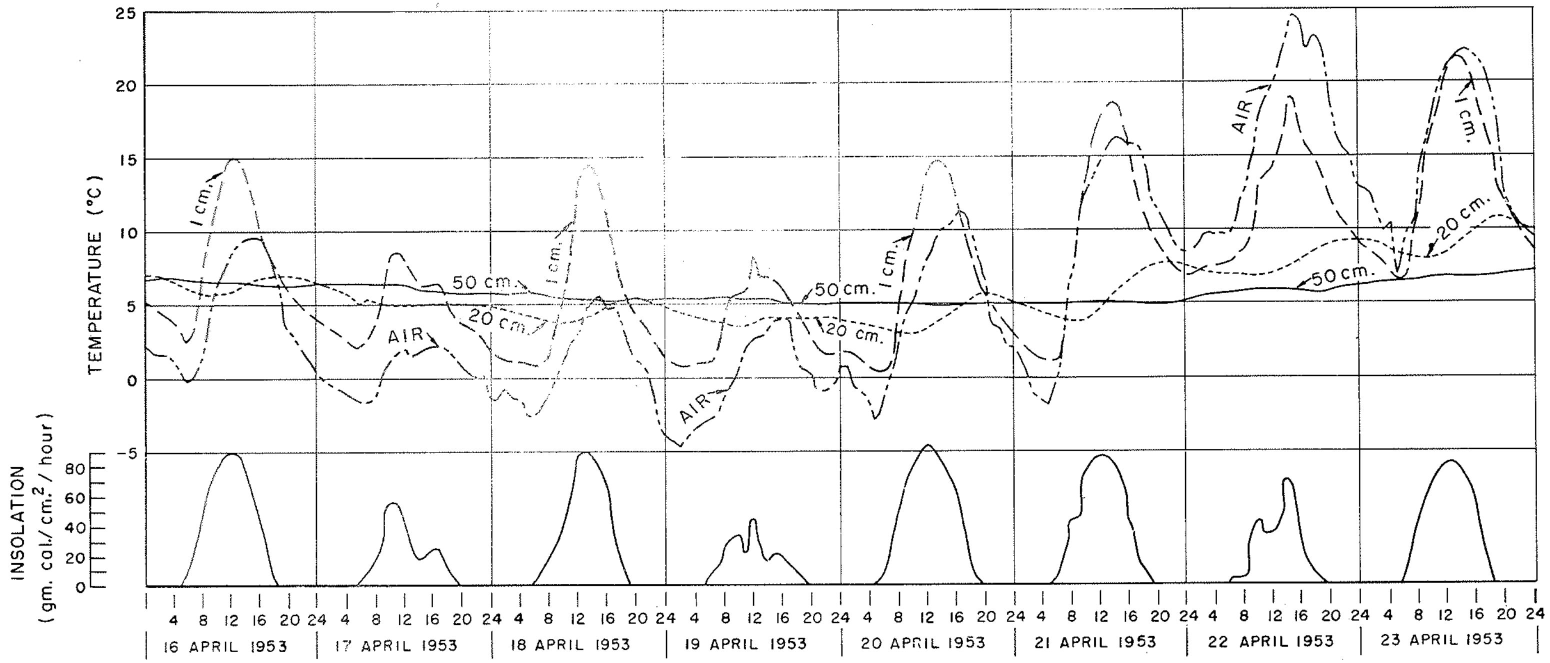


Figure 2.--Daily temperature waves (°C.) in a sandy heath soil at Mustiala, Finland (from Rode 1955, after Homen 1897).



	16 April 1953	17 April 1953	18 April 1953	19 April 1953	20 April 1953	21 April 1953	22 April 1953	23 April 1953
TOTAL DAILY SUNSHINE, (gm cal / cm ^{2})	688	296	600	254	736	685	355	673
TOTAL DAILY PRECIPITATION (INCHES)	.03	NONE	NONE	TRACE	NONE	NONE	NONE	NONE

Figure 3.--Soil temperature and air temperature during a spring period with variable sunshine at Lemont, Ill. (after Carson 1961).

shows almost no daily fluctuation, but the warm period from April 20 to 23 caused a rise of about 2° C. over a 72-hour period. The soil temperature at this depth reflects short-time weather patterns but is essentially independent of the daily temperature cycle.

Cold or warm rains may bring about rapid and marked changes in the temperature of surface horizons, which is part of the influence of weather. Generally the direct temperature effect of a rain is not measurable 48 hours after the rain ends.

Seasonal temperature fluctuations and soil-temperature gradients

SEASONAL FLUCTUATIONS IN THE TROPICS

Seasonal fluctuations of soil temperature are generally small in the Tropics--the zone between the Tropics of Capricorn and Cancer. Mean annual soil temperatures vary with elevation, but seasonal temperatures vary primarily with clouds and rain. The warmest seasons may be the dry seasons, for clouds and rain may outweigh the effect of the angle of the sun's rays.

We have plotted soil temperature, air temperature, rainfall, and percentage of possible sunshine for two stations (I.N.É.A.C. 1953) a little north of the Equator in the Republic of the Congo (Leopoldville). One is Nioka at an elevation of about 5,000 feet (fig. 4); the other is Yangambi at an elevation of about 1,200 feet (fig. 5). These figures show that the soil temperature is higher in "winter" than in "summer." Actually, the soil temperature fluctuates with cloud cover and rain and appears to be most closely correlated with the amount of sunshine. In the Tropics, differences between summer and winter temperatures are small and may be in either direction. The average temperature over a 3-month season is virtually the same at all depths within the upper meter of soil.

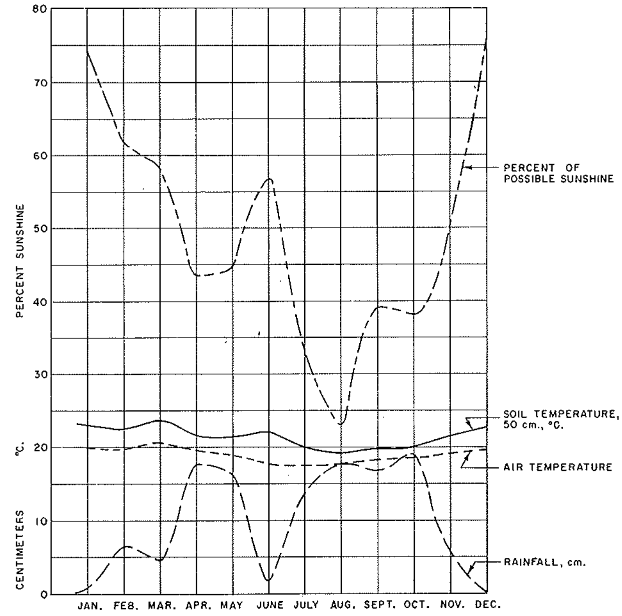


Figure 4.--Mean monthly soil temperature at 50 cm. for 1952 at Nioka, Rep. Congo, and major climatic factors that affect it.

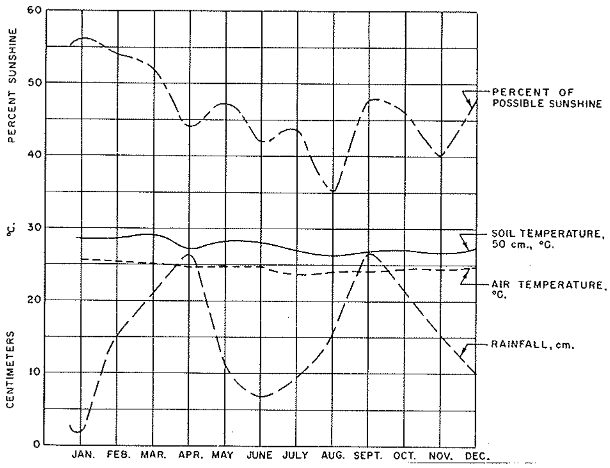


Figure 5.--Mean monthly soil temperature at 50 cm. for 1952 at Yangambi, Rep. Congo, and major climatic factors that affect it.

As the temperate region is approached, near the Tropic of Cancer for example, summer soil temperatures are likely to be higher than those in winter, but the differences between the mean summer and the mean winter temperature of the upper meter of soil are usually less than 5° C. (9° F.). Tropical conditions in the United States are restricted to Hawaii and Puerto Rico.

SEASONAL FLUCTUATION AND GRADIENTS IN MID-LATITUDES

Soil temperatures in the 48 coterminous States generally show marked seasonal fluctuations. To illustrate seasonal changes under a mid-latitude continental climate such as that in much of the United States, a good record of soil temperatures from Belgrade, Yugoslavia, has been selected. The mean monthly temperatures cited by Chang (1958b) are given in table 5 and are shown graphically in figure 6. The annual cooling and heating waves extend to 12 meters (40 feet), but the amplitude of variation at this depth is only 0.1° C. At a 14-meter depth, the temperature is constant and is the same as the mean annual soil temperature. These records show clearly that seasonal temperature fluctuations penetrate deep into the earth, well below the lower limit of soil.

The depth to the stratum with constant temperature is not the same in all soils. It is reduced by shallow ground water with its high specific heat. Records of well-water temperature in the 48 coterminous States show that in the presence of ground water the stratum of constant soil temperature occurs at about 30 feet.

TABLE 5.--Mean monthly and annual ground temperatures at Belgrade, Yugoslavia, 1902-06[1]

Latitude: 40°48' N. Longitude: 20°28' E. Elevation: 139 meters

Time of observation: every hour

Depth	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
	° C.	° C.	° C.	° C.	° C.	° C.	° C.	° C.	° C.	° C.	° C.	° C.	° C.
90 cm.	5.0	4.3	6.4	9.8	14.3	17.8	20.6	21.9	20.3	16.0	11.3	7.1	12.9
1.2 m.	6.9	5.8	6.8	9.2	12.7	15.8	18.4	20.0	19.3	16.3	12.6	9.1	12.8
1.5 m.	7.2	6.1	6.9	9.1	12.2	15.4	17.9	19.5	19.1	16.2	12.8	9.5	12.6
2 m.	9.0	7.7	7.7	9.0	11.4	14.0	16.2	17.9	18.1	16.4	13.8	11.3	12.7
3 m.	11.3	10.0	9.5	9.7	10.7	12.2	13.8	15.2	16.4	16.1	14.5	12.8	12.7
4 m.	12.5	11.4	10.6	10.4	10.8	11.6	12.9	14.0	14.8	15.1	14.6	13.6	12.7
5 m.	12.9	12.1	11.4	11.0	11.1	11.6	12.2	13.1	13.8	14.3	14.2	13.7	12.6
8 m.	13.0	12.9	12.8	12.7	12.5	12.4	12.5	12.5	12.5	12.7	12.8	12.9	12.7
10 m.	12.9	12.9	12.9	12.9	12.9	12.8	12.7	12.7	12.7	12.7	12.7	12.8	12.8
12 m.	12.8	12.9	12.9	12.9	12.9	12.9	12.9	12.9	12.8	12.8	12.8	12.8	12.9
14 m.	12.9	12.9	12.9	12.9	12.9	12.9	12.9	12.9	12.9	12.9	12.9	12.9	12.9
18 m.	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0
20 m.	13.1	13.1	13.1	13.1	13.1	13.1	13.1	13.1	13.1	13.1	13.1	13.1	13.1
24 m.	13.3	13.3	13.3	13.3	13.3	13.3	13.3	13.3	13.3	13.3	13.3	13.3	13.3
Air temperature[2]	-0.9	0.8	6.7	11.3	16.7	19.5	21.8	21.3	17.2	12.5	5.7	1.8	11.2

[1] Meteorologische Zeitschrift 1911, p. 297, in Chang (1958b).

[2] Normal mean monthly air temperature after Kendrew (1942, p. 295).

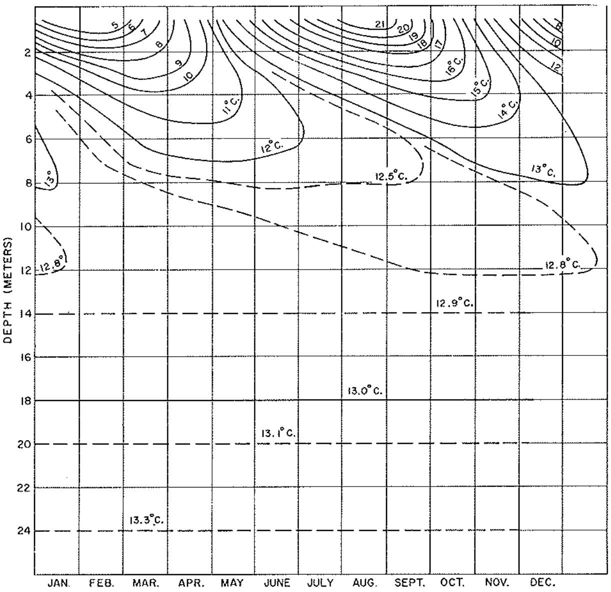


Figure 6.--Mean monthly isotherms of ground temperature at Belgrade, Yugoslavia.

Chang (1958a, p. 93) has estimated that in the absence of ground water seasonal fluctuations of soil temperature penetrate to a depth of 20 meters (66 feet) in Alaska, 15 meters (50 feet) in humid latitudes, and 10 meters (33 feet) in the Tropics. In dry soils thermal conductivity is low and, although seasonal fluctuations in temperature may be very large, the depth of penetration is not increased. At Jaipur, India (27° N. Lat.), the seasonal range in soil temperature at a depth of 20 feet was 2.7° C., but at 45 feet it was only 0.2° C. (Chang 1958b).

The amplitude of seasonal fluctuations and the months of warm and cool periods of soil temperature are primarily functions of latitude and climate. In mid-latitudes the angle of the sun's rays is most important, but clouds, rain, irrigation water, snow cover, bodies of water, direction and angle of slope, and presence or absence of shallow ground water and thick O (organic) horizons can all affect the amplitude of fluctuation. Seasonal fluctuations in mid-latitudes are generally in excess of 5° C. (9° F.). That is, the average summer soil temperature in the upper meter is more than 9° F. higher than the average winter soil temperature.

Since the temperatures of soils at high elevations tend to resemble those of soils at high latitudes, the discussion in this section is confined to soils having mean annual temperatures of 47° F. or higher. The cold soils at high elevations in the mid-latitudes are discussed with the soils of high latitudes.

Outside the Tropics soil temperature tends to decrease with depth in summer and to increase with depth in winter. In mid-latitudes the mean annual soil temperature at any given depth is very close to the average of the mean summer and winter temperatures at that depth. At a given depth in level soils the mean monthly temperature fluctuates about the mean annual temperature in an approximate sine curve.

Effect of Depth.--In a given soil the closer to the surface, the greater the amplitude of fluctuation. This relation is shown graphically in figure 7 (data from Elford and Shaw 1960). The use of long-time averages eliminates the irregularities in the temperature curves at 4 inches and 20 inches caused by the vagaries of weather.

Seasonal variations of soil temperature are greatest at the surface and decrease with depth until, at a depth of 30 feet or more, they disappear (fig. 6). The mean summer, winter, and annual soil temperatures (Chang 1958b) are plotted in figure 8 as a function of

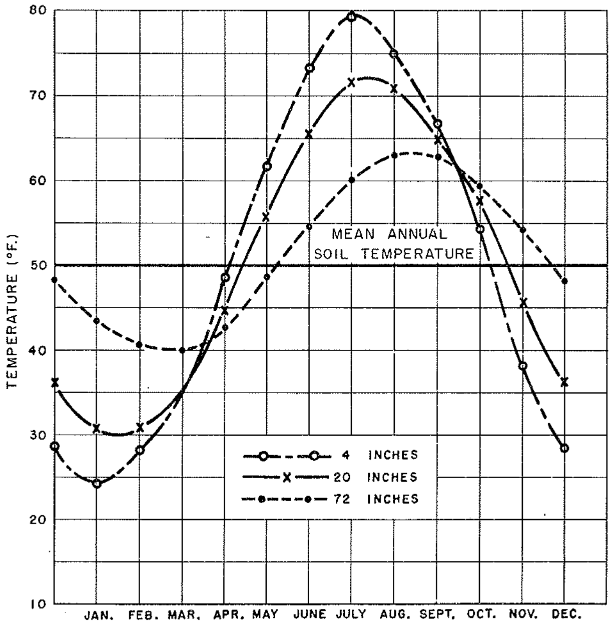


Figure 7.- Mean monthly soil-temperature curves for various depths in a soil at Ames, Iowa.

depth together with air temperatures for two stations in the mid-latitudes. If we disregard the upper inch or two, the changes with depth of the mean seasonal soil temperature are nearly linear, so nearly so that one must conclude that the mean seasonal temperature of soil to any depth *within the solum* is very closely approximated by the mean temperature at the midpoint in depth. The temperature gradient is positive in winter and negative in summer. It is approximately 0.6° C. per 10 cm. (1° F. per 4 inches) at Kutakya, Turkey; Odessa, U.S.S.R.; and Ames, Iowa; and 0.5° C. per 10 cm. at Fort Collins, Colo. The gradients seem very similar in most mid-latitude soils where records are available, even on undrained peats as we show later.

The graphs show that the mean summer air temperature at Ames and Kutahya exceeds the mean summer soil temperature at 50 cm. by about 1° F. Thus, the mean summer air temperature is about 1° F. higher than the average temperature of the soil to a depth of 1 meter, for the 50-cm. temperature is virtually the same as the average for the upper meter.

Mean winter soil and air temperatures do not show such a close relationship. The mean winter air temperature is 9° F. lower than the soil temperature at Ames and 7° F. lower at Kutahya. During the winter, snow insulates the soil for variable periods in mid-latitudes. The more continuous and the thicker the snow cover, the greater the difference one would predict between the mean winter air and soil temperatures.

Effect of Vegetative Cover and Irrigation.--In the humid mid-latitudes, cover can have an important influence on seasonal fluctuations of soil temperature. The differences between grass, crops, and trees in shading or insulating the soil are minor if O horizons are transient or absent.

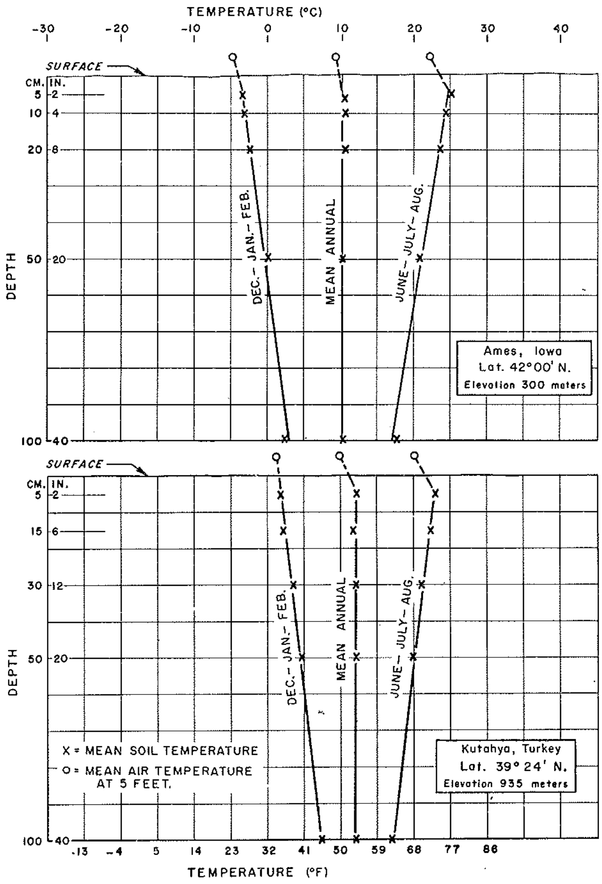


Figure 8.--Soil-temperature gradients with air temperatures for winter and summer in relation to mean annual temperatures at Ames, Iowa, and Kutahya, Turkey.

SCS staff members measured soil temperature at monthly intervals from May to October in 1962 to compare soil temperature under forest with that in cultivated fields. The mean summer soil temperatures at 24 inches are tabulated in table 6. Conifers caused a marked reduction in summer soil temperature, whereas hardwoods had only a minor influence except at Knoxville. Table 6 shows that cultivated soils of mid-latitudes were cooler at a depth of 24 inches

TABLE 6.--Mean summer temperature at 24-inch depth in cultivated and forest soils during 1962

Location	Type of forest	Mean summer temperature			
		Air at 5 feet[1]	Soil at 24-inch depth		
			Under forest	Cultivated	Difference
		° F.	° F.	° F.	° F.
Knoxville, Tenn.-----	Hardwoods	76.2	68	77	9
Urbana, Ill.---------	Hardwoods	72.6	65	69	4
Ithaca, N.Y.---------	Conifers	66.6	58	68	10
Steele Co., Minn.----	Mixed hardwoods	67.3	57	62	5
Beltrami Co., Minn.--	Mixed hardwoods	63.5	55	58	3
Palmer, Alaska-------	Mixed conifers and hardwoods.	54.6	35	51	16

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[1] U.S. Weather Bureau climatological data.

than the air at the nearest weather station. The average difference was between 1 and 2° F. for the summer. On the average soils under forest were about 9° F. cooler than the air.

Since in dry regions under natural conditions soils are partly bare or mostly bare, irrigated close-growing crops can have a very marked effect on seasonal fluctuations of soil temperature. Evaporation of irrigation water can also have a marked affect. It was pointed out earlier that data from Vauxhall, Alberta, show that an irrigated soil was 13° F. colder than the air during the summer. The mean annual soil temperature at both Vauxhall, Alberta, and Indio, Calif. (Bliss 1942), was 3° F. lower than the mean annual air temperature.

Effect of Ground Water.--Because of its large latent and specific heat, shallow ground water greatly affects seasonal fluctuations of soil temperature in mid-latitudes. The principal effects are during periods when the soil is freezing or thawing because the latent heat of freezing of water is about 80 times the specific heat.

In figure 9 we have plotted from unpublished SCS data the mean summer temperature for two soils in Steele County, Minn.--one an undrained peat and the other a cultivated Gray-Brown Podzolic soil. The undrained peat soil was about 7° F. cooler. The slope of the seasonal soil-temperature gradient is nearly the same for both soils--approximately 1° F. per 4 inches of depth. Since temperature was measured only monthly, one might question the reliability of so few observations. But the soil temperature at a depth of 2 feet or more usually changes very slowly. Moreover, we compared monthly averages of daily measurements with those made on the first day of each month at several stations and found the average error less than 2° F., an error well within the range of fluctuation caused by day-to-day weather. The straight-line relation of temperature to depth is a further indication of the probable reliability of the data.

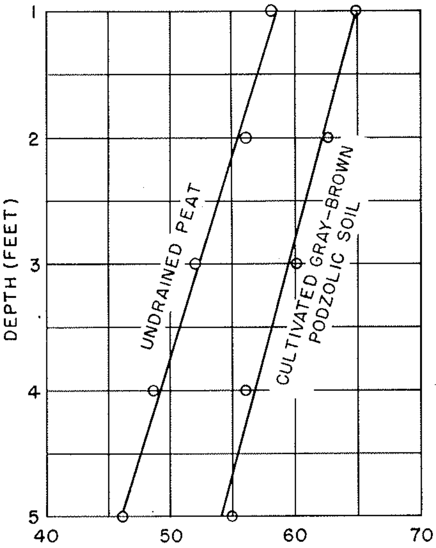

Figure 9.--Mean summer soil-temperature gradients for an undrained organic soil and a cultivated Gray-Brown Podzolic soil, Steele County, Minn.

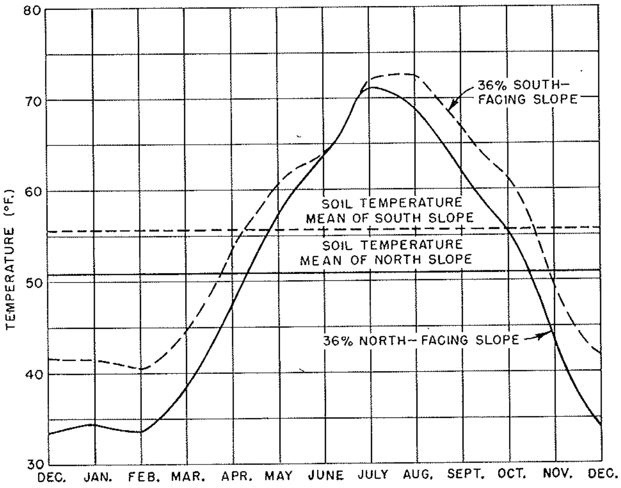

Figure 10.--Mean monthly and annual soil temperatures at a 4-inch depth on north- and south-facing slopes of Cushetunk Mountain, N.J.

Effect of Slope Aspect and Steepness.--The aspect (direction) and steepness of slope may affect the deviation of the mean monthly soil temperatures from the annual mean. In figure 10 we have plotted the mean monthly temperatures at a 4-cm. depth for north- and south-facing slopes of 36 percent in New Jersey reported by Cantlon (1953). The effect in winter was large compared to that in summer. The readings were made weekly with a high-low thermometer for a year, so they include not only the effects of slope and day-to-day weather but also an uncertain effect of the asymetrical nature of the daily temperature cycle at that depth. Nevertheless, as pointed out by Cantlon, the maximum difference in the mean monthly temperatures at the two sites occurs in winter and coincides with the maximum difference in the angle of the sun's rays. Thus, the relation is probably significant. The south-facing slopes have smaller seasonal fluctuations from the annual mean than the north-facing slopes.

TABLE 7.--Mean summer soil temperature during 1962 under various vegetative covers on north- and south-facing slopes of 20 to 30 percent

Location	Cover	Mean summer temperature at 24 inches		
		N slope	S slope	Difference
		° F.	° F.	° F.
Waterford, Calif.------	Range grass	82	87	5
Lincoln, Nebr.---------	Pasture	66	68	2
Urbana, Ill.-----------	Deciduous forest	70	72	2
Steele Co., Minn.------	Deciduous forest	63	64	1
Ithaca, N.Y.-----------	Pasture	64	68	4
Knoxville, Tenn.-------	Pasture	76	78	2

SCS staff members made measurements of soil temperature in 1962 on north- and south-facing slopes of 20 to 30 percent. The mean summer temperatures at a 24-inch depth listed in table 7 indicate differences between north- and south-facing slopes comparable to those observed in New Jersey.

SEASONAL FLUCTUATIONS IN HIGH LATITUDES

Soils in high latitudes are cold, and the seasonal soil-temperature fluctuations do not approximate a simple sine curve as those in mid-latitudes. We have plotted in figure 11 the mean monthly soil and air temperatures at Mustiala, Finland (Chang 1958b). The air temperature follows a simple sine curve and is above the mean for about 6 months of the year. The soil temperature at 50 cm., however, is above its mean only 5 months and below it for 7 months. The asymmetrical soil-temperature fluctuations reflect the combined influence of snow as an insulator during the winter and the relatively high insolation during the summer months when the sun is above the horizon all or most of the time.

In figure 12 we have plotted the mean annual seasonal soil temperature (Chang 1958b) as a function of depth for two high-latitude stations--Cape Chelyuskin, U.S.S.R., and Mustiala, Finland. The skewed seasonal fluctuations are indicated by the closeness of the winter and the mean annual temperature lines.

In these latitudes summer soil temperatures are appreciably lower than the air temperature. At Cape Chelyuskin, the mean summer air temperature is about 8° F. higher than the soil temperature at 50 cm. At Mustiala, Finland, the air temperature is 3° F. higher. The temperature gradients with depth are similar to those in mid-latitudes.

To determine whether permafrost at depth affects the temperature gradient, we also plotted the mean July soil temperature at Cape Chelyuskin. During this month the permafrost stood at about 16 inches, but the soil temperature changed as a straight-line function of depth below 4 inches.

Effect of Snow Cover.--The effect of snow cover on soil temperature at various depths (after Molga 1958) is shown in figure 13. Here we have plotted the temperature difference between soil kept bare and soil covered with snow (bare plot minus snow-covered plot). From November through March, the snow-covered plot was warmer at all depths and the average temperature difference for the three winter months (December through February) was 4° C. at the 50-cm. depth. In April when air temperatures were rising and snow was melting, the bare soil warmed more rapidly and was warmer than the snow-covered plot to a depth of 40 cm.

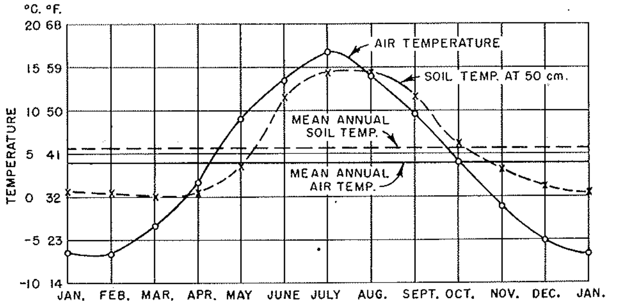

Figure 11.--Mean monthly and annual soil and air temperatures at Mustiala, Finland.

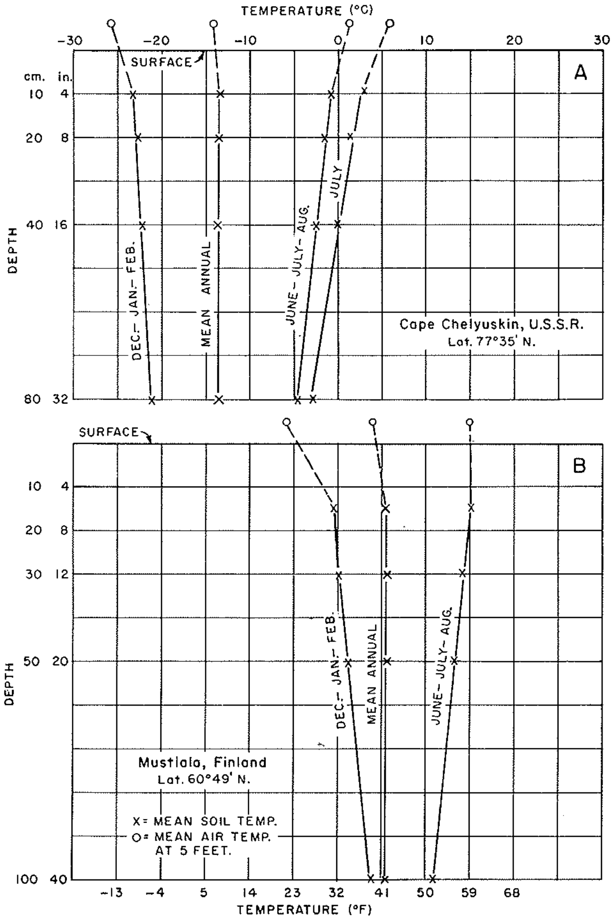

Figure 12.--Soil-temperature gradients and air temperatures for winter and summer in relation to mean annual temperatures at A, Cape Chelyuskin, U.S.S.R., and B, Mustiala, Finland.

The effect of snow on soil temperature is not limited to high latitudes and high altitudes. Snow covers are common but intermittent for the most part in mid-latitudes where mean annual soil temperatures are less than 55° F.

Effect of Vegetative Cover.--Covers of litter and moss commonly are thicker in the colder climates. As they thicken, they reduce seasonal fluctuations of soil temperature because they insulate the soil during the entire year. Table 6 includes two observations on the effect of cover on summer temperatures in the

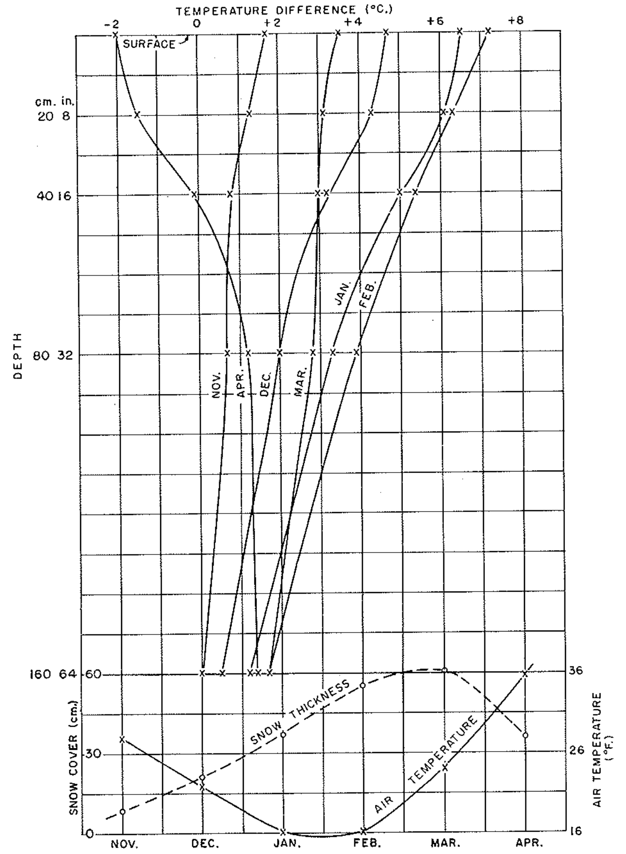

Figure 13.--Monthly soil-temperature differences between bare and snow-covered plots at Leningrad, U.S.S.R., and mean monthly air temperature and snow thickness.

colder soils--one under hardwoods and the other under mixed hardwoods and conifers. The hardwood litter had little effect in Beltrami County, Minn., but the mixed litter at Palmer, Alaska, apparently had a very large effect--a 16° F. reduction in summer soil temperature at a depth of 24 inches. A small part of this difference is due to our convention of measuring depth from the contact between the O horizon and the mineral soil. The difference would have been a little less had depth been measured from the surface of the O horizon. The mean annual air temperatures at Palmer and Beltrami County are nearly the same.

Inland in Alaska we have only fragmentary unpublished SCS data, but July temperatures of well-drained soils at a 24-inch depth at Fairbanks are about 15° to 20° F. lower under forest than under cultivation. Under much of the forest at Fairbanks there is permafrost that melts if the soils are cleared, but we cannot simply assume that removal of the forest and the O horizon has increased the mean annual temperature. The melting and retreat of permafrost could be the result of increasing either the seasonal fluctuations or the mean annual temperature or both. No matter what other effect forest cover has, it keeps the soils cold during the summer at Fairbanks. The maximum temperature recorded at a 24-inch depth was 48° F.

Effect of Ground Water.--Because of its specific and latent heat, ground water reduces seasonal fluctuations of soil temperature. We have plotted in figure 14 the soil temperature at the 50-cm. depth for two soils at Flahult, Sweden (Chang 1958b), where mean annual soil temperatures are about 6° C. (42.8° F.).

The wet bog was warmer in winter and cooler in summer than the sandy soil. The amplitude of fluctuations in the wet bog at the 50-cm. depth was 4° C. less than in the sand.

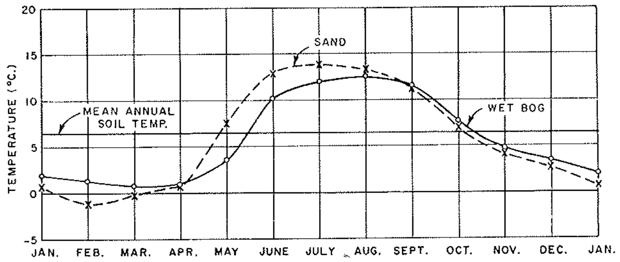

Figure 14.--Mean monthly soil temperature at 50 cm., Flahult, Sweden.

Unpublished SCS records show that in the Tanana Valley of Alaska, where mean annual soil temperatures are about 32° F., an imperfectly drained soil under forest never reached a temperature above 36° F. at the 24-inch depth in 1962. Where cleared the soil at 24 inches had a maximum temperature of over 60° F. This is, of course, the combined effect of cover and ground water.

Effect of Slope Aspect and Steepness.--Only very fragmentary data are available from high latitudes to indicate the importance of slope aspect and steepness on seasonal soil-temperature fluctuations. Measurements made during the summer of 1962 by SCS staff in the Matanuska Valley, Alaska, compared a 28-percent SW slope with a 27-percent NNW slope under grass. On June 1, the frost was 22 inches below the surface on the NNW slope and 4 feet below on the SW slope. From July 1 through September, the temperature difference was 2° F. or less at the 24-inch depth, the SW slope remaining only slightly warmer. These observations are consistent with those reported for mid-latitudes.

Measurement of Soil Temperature

From the evidence presented, it can be seen that soil temperature can often be estimated from climatological data with a precision that is adequate for the present needs of the soil survey. If we cannot make reasonably precise estimates, we can see that the measurement of soil temperature need not be a difficult or a time-consuming task.

We have seen that for much of the United States we can estimate the mean annual soil temperature by adding 2° F. to the mean annual air temperature (table 2). We have seen that the average summer temperature of the upper 40 inches of level, well-drained, cultivated or grass-covered soils can often be approximated by subtracting 1° F. from the mean summer air temperature (fig. 8).

The mean summer temperature for a specific depth can also be estimated. To do this, we can take the average summer temperature of the upper 40 inches and correct for the temperature-depth gradient by adding or subtracting 1° F. for each 4 inches above or below 20 inches. The mean winter temperature of many mid-latitude soils can be estimated from the difference between the mean annual and the summer temperature because the differences are of the same magnitude but have opposite signs.

We have seen in figure 6 that the cooling wave at Belgrade extends to 12 meters (40 feet) and that at this depth the minimum temperature is reached about 10 months later than at 1 meter. The amplitude of variation at the 40-foot depth is less than 0.1° C. This means that the mean annual temperature of a soil in mid-latitude can be determined at any time by a single reading at a depth of 13 meters. A single reading at a depth of 10 meters is within 0.1° C. of the mean annual soil temperature. A single reading at a depth of 6 meters (20 feet) is within 1° C. of the mean annual temperature.

The mean annual temperature of soils underlain by deep regolith can therefore be very closely approximated at any season by using auger extensions. In some places there is an even simpler method of determining the mean annual soil temperature. Dug wells generally range from 20 to 60 feet in depth. If the water table stands between 30 and 60 feet, the well-water temperature, which is in equilibrium with the soil temperature, gives the mean annual soil temperature with an error of less than 1° C. Unfortunately, this method is suited only to humid regions where ground water is shallow and is not frozen. Extensive records of well-water temperature have shown that the water temperature between 30 and 60 feet is essentially constant throughout the year. At these depths it bears the same relation to air temperature as the soil-temperature measurements given in table 2. One precaution is necessary in using well-water temperature--the well must be in use so that water is moving into the well from the ground around.

If the soil is shallow and there are no wells, the mean annual soil temperature can be measured only over the four seasons by taking several readings at regular intervals of time. If the soil is expected to be frozen deeply at the time of one or more readings, a special thermometer can be buried or a thermocouple can be used. If the temperature of a soil is measured at a depth below the influence of the daily cycle of fluctuations, say at 20 inches, four readings equally spaced throughout the year give a very close approximation of the mean annual temperature. For example, the average of readings taken at the 50-cm. depth at Vauxhall, Alberta, on January 1, April 1, July 1, and October 1, 1962, differs from the average of two readings each day of the year by only 0.6° F. Greater precision can be had by increasing either the number or the depth of the readings. The mean annual soil temperature computed for any 1 year will also be close to the long-term mean annual, that is, the "normal." At Ames, Iowa, for example, the standard deviation of this value for a 13-year record at the 20-inch depth is only 1° F.

Seasonal temperatures, we have seen, bear an almost linear relation to depth within the depth limits that usually concern us as soil scientists. By selecting a suitable depth and measuring the temperature on the 15th of June, July, and August, we can derive the average soil temperature for the 3-month summer period. The error will be small only if measurements are made at a depth below the daily temperature fluctuations--20 inches or more. Measurements made at a 20-inch depth give the average temperature of the upper 40 inches. A test of this method for the station at Vauxhall, Alberta, showed that the average of three daily values taken at a 50-cm. depth on June 15, July 15, and August 15, 1962, is within 1° F. of the mean summer temperature computed from daily readings.

Greater precision can be had mainly by increasing the number of readings, but readings of soil temperature should not be made at depths as shallow as 20 inches for at least 48 hours after a heavy rain.

We have also seen that the average temperature for a 3-month season varies as a linear function of depth. If we determine the mean summer temperature at several depths, say 20, 30, and 40 inches, we can estimate the mean summer temperature at any depth below the surface within the normal root zone.

Seasonal temperatures are affected by cover, slope direction and steepness, snow, ground water, rain, and clouds. Available data are inadequate to permit close estimation of the seasonal temperature of soils other than those at freely drained, cultivated or grass-covered, level sites. If we want to know more, we must make more measurements; the time required to make them is very small. The need for additional information is greatest in the colder climates because most roots cannot grow in a horizon having a temperature of 42° F. or less. The average depth of rooting is fixed by the depth having this average temperature. We also have a general need for more information on the temperature of sloping soils to help understand the differences in adaptation of north- and south-facing slopes.

Summary

Soil temperature is a parameter important to both soil genesis and soil use. It was taken into account in older soil classification systems, and it must not be forgotten in any new systems to be used in our national cooperative soil survey.

Each horizon in a pedon has the same mean annual temperature, but the temperature is rarely the same in any two horizons at a given moment because of daily, short-term, and seasonal fluctuations. At depths below about 50 cm. soil temperature changes slowly, and at depths below about 30 feet temperature is nearly constant and is the same as the mean annual soil temperature. The mean annual soil temperature is higher than the mean annual air temperature over most of the United States. The difference is usually about 2° F. in the humid Southern and Central States, but it is more in the colder regions.

The mean annual soil temperature is largely independent of color, texture, drainage, and organic content. It is affected to a few degrees by slope steepness and direction and in some places by cover.

Seasonal fluctuations are affected by latitude, soil moisture, ground water, air movement near the ground, clouds, rain, and cover, but the effect of latitude is dominant over most of the United States. Daily fluctuations are affected by all these except latitude, but the influence of moisture and cover is dominant.

Mean annual soil temperatures and seasonal fluctuations can in general be predicted from meteorological records of air temperature, but with our present knowledge we cannot make precise estimates for many soils. We need to make more measurements of annual and seasonal soil temperatures. They do not require much time or expensive instruments. An average of four measurements a year, made at a depth of 20 inches near the 15th of the month at 3-month intervals, is very close to the mean annual soil temperature. Or a single measurement of ground- or well-water temperature at a depth between 30 and 60 feet gives the mean annual soil temperature.

The mean summer or winter temperature of the horizons of a pedon has a linear relation to depth within normal root zones. The average temperature of the upper 40 inches of soil over a 3-month season can be measured by three readings made on the 15th of each month at a depth of 20 inches. The temperature gradient with depth in mid-latitude is usually nearly 1° F. per 4 inches. It can be determined by readings at 30 and 40 inches in addition to the reading at 20 inches. Knowledge of the soil-temperature gradient permits close estimation of summer temperatures at any depth within the root zone.

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[Only pages 3 – 11 are reproduced below.]

The Use of Soil Temperature and Moisture Regimes in Soil Classification

The definitions of the taxa in Soil Taxonomy (1975) include a numbe of climatic parameters of soils which are used at different categorical levels.

The primary reason for using soil climates is that they are the causes of many other properties. Climate is one of the major pedogenic factors. Furthermore, some soil characteristics are only meaningful when they are considered in a limited area restricted to a defined soil climate; therefore it has a powerful differentiating effectiveness and climatic regimes are often more suitable than other properties for creating kingdoms within the classification system.

Another but no less important reason for the use of soil climatic data is to make the taxa meaningful for interpretation purposes by defining units in such a way that major soil limitations for plant growth are implied in the system.

A third advantage of introducing soil climate data into classification is that uniform, extensive geographic areas may be recognized on small scale maps. This facilitates the preparation of generalized soil maps that can be easily interpreted, particularly for crops which are climatically restricted to certain areas.

In spite of these reasons to introduce soil climatic properties into the system, many disadvantages exist. The difficulties are mainly operational and relate to the limited amount of information on climate usually available to soil surveyors. Field observations of soil temperature and moisture conditions are often lacking and many criteria for differentiating soil climate regimes depend on seasonally changing variables which require observations for extended periods of time.

The lack of precision in the data on soil moisture regimes should not be a barrier to prevent existing information, although sketchy, from reaching users who must make decisions on land use. The purpose of using incomplete data is to reduce the risks of making errors, not to eliminate them completely. Information with known limitations may perhaps lead to better decisions than those made with no information at all. The objective of this study is to extract from climatic observations what is useful for predicting soil moisture regimes and to delineate the geographic areas where comparable soil climatic conditions may occur.

One of the methods used to achieve this purpose is based on mathematical models which simulate the water movement in soils under changing weather conditions.

Franklin Newhall's Method of Computation of Soil Moisture Regimes

The model which is used to compute moisture regimes according to Soil Taxonomy is practically identical to the model developed by Dr. Franklin Newhall (1972). It considers an hydrological profile retaining 200 ml of available water divided into 8 layers. The second and the third layer form what is called the moisture control section.

Newhall's system is designed to serve the preliminary identification of moisture regimes in areas where climatic data are limited and where information on temperature and rainfall are available only on a monthly basis. Potential evapotranspiration is introduced into the model following Thornthwaite's method for its calculation.

The lack of detailed input data does not allow accurate estimates of soil potentials for crop production. The model cannot predict crop growth during various development stages. These prediction models need almost daily or hourly inputs.

Newhall's model nevertheless provides an approximate method to determine moisture regimes, especially for areas where only preliminary estimates are needed. It should be pointed out that the criteria and the soil moisture regime classes are only intended to be used for subdividing soil taxa at different levels of Soil Taxonomy, and not to create a new climatic classification.

The model used in this study differs from Newhall's 1972 method in that it does not calculate probabilities. Therefore it is not possible to place statistical confidence limits on the predicted values.

Definitions of Soil Moisture Regimes

The definitions of the soil moisture regimes which are used in this publication are those of the original text of Soil Taxonomy (1975). The computation does not consider soils that have restricted drainage and therefore the aquic moisture regime is not included in this study.

The subdivisions of the moisture regimes are only tentative. They have no official status, and are not an integral part of Soil Taxonomy. They are only given as guidelines to assist in the definition of new subgroups or other taxa.

Limitations of the Model

The present computations used temperature and rainfall data obtained from various sources. The monthly data are usually averages over many years. This type of input tends to reduce the intensity of the extremes which occur when data of individual years are used. Therefore conclusions drawn from these calculations should be made with care, after checking probabilities of occurrence for stations where monthly rainfall data over several years are available.

In the present model, Thornthwaite's potential evapotranspiration was used to estimate the removal of water from the soil. In all instances the soil temperature was calculated by adding 2.5°C to the mean annual air temperature. The amplitude of temperature variation at 50 cm depth between winter and summer was reduced by 33% of the difference between air temperatures for the same seasons. The season's months were December, January, and February or June, July, and August for winter or summer depending on the hemisphere.

Moisture regimes are defined on the basis of conditions existing in the moisture control section which is located well below the surface horizons in the profile. The topsoil is not considered. For this reason immediate interpretation on the availability of water for plants at a certain time of the year is not recommended without additional information on the moisture conditions prevailing in the topsoil. In other cases, consideration of deep horizons from which crops may extract water is essential to determine the water supplying power of soils; they have not been considered in this mathematical model.

All rainfall is considered effective; percolation of water through the profiles is unrestricted. Storage of water as snow on top of the soil is not considered in the model.

Tentative Subdivision of the Moisture Regimes

Claims have been made that the five moisture regime classes recognized in Soil Taxonomy are not sufficiently uniform for interpretation purposes.

A tentative subdivision of moisture regimes was developed in 1976 and included in the Fortran computer program. A map showing the distribution of these subdivisions is included. The map provides a means to examine new critical limits and test the definitions on the basis of possible correlations with vegetation or cropping areas.

The tentative key for the subdivisions accepts without any changes the criteria used for defining the five highest level classes. No attempt has been made to change the present definitions of the five moisture regimes: aridic, xeric, ustic, udic and perudic. The subdivisions, therefore, are to be evaluated keeping this restriction in mind. Perhaps better subdivisions could be devised if major modifications to Soil Taxonomy were considered.

The subdivisions have no official status in Soil Taxonomy.

The key leading to subdivisions of the existing moisture regimes is given on a tentative basis. The criteria that are used are assumed to occur in most years, that is, at least six out of ten.

The ustic moisture regime has been separated into two subclasses, depending on whether or not an iso-temperature regime is present. Thus, tropustic and tempustic regimes, respectively, are recognized. The tempustic and tropustic regimes are subdivided according to separate criteria. In the tempustic subclass the concentration of rainfall in summer or winter is taken into account, as well as the wetness of the seasons.

The udic moisture regime is also separated into tempudic and tropudic but only when the period of dryness in the moisture control section exceeds one month. All other udic regimes, except perudic, are called typic udic.

Classes of Soil Moisture Regimes (Soil Taxonomy, 1975)

The following descriptions of the soil moisture regime classes are taken verbatim from Soil Taxonomy (1975).

"The moisture regimes are defined in terms of the groundwater level and in terms of the presence or absence of water held at a tension <15 bars in the moisture control section by periods of the year. It is assumed in the definitions that the soil supports whatever vegetation it is capable of supporting. In other words, it is in crops, grass, or native vegetation; it is not being fallowed to increase the amount of stored moisture, nor is it being irrigated by man. These cultural practices affect the soil moisture condition as long as they are continued.

It has been conventional to think in terms of three soil moisture regimes. In one, the soil is saturated. In another, the amount of water is enough to cause leaching and, in the third, no leaching occurs. In the leaching regime some water moves through the soil at some time during the year and moves on down to the moist substratum. In the nonleaching regime, water moves into the soil but is withdrawn by evapotranspiration, leaving precipitated carbonates and more soluble salts. Between these two regimes there is another possible one in which there is alternation from year to year; leaching occurs in some years but not in all. For consideration of the losses of soluble materials or their accumulation in ca, cs, or sa horizons, these concepts are adequate. For the understanding of biological processes, they leave much to be desired. A soil can be subject to leaching in the winter when it is too cold for optimum biologic activity, and it can be too dry in most of the summer for significant biologic activity. The result is a relatively wide carbon-nitrogen ratio.

The soil moisture regime, as the term is used here, refers to the presence or absence either of ground water or of water held at a tension <15 bars in the soil or in specific horizons by periods of the year. Water held at a tension of 15 bars or more is not available to keep most mesophytic plants alive. The availability of water also is affected by dissolved salts. A soil may be saturated with water that is too salty to be available to most plants, but it would seem better to call such a soil salty rather than dry. Consequently, we consider a horizon to be dry when the moisture tension is 15 bars or more. If water is held at a tension of <15 bars but more than zero, we consider the horizon to be moist. A soil may be continuously moist in some or all horizons throughout the year or for some part of the year. It may be moist in winter and dry in summer or the reverse. In the northern hemisphere, summer refers to the months of June, July, and August, and winter means December, January and February. A soil or a horizon is considered to be saturated with water when water stands in an unlined borehole close enough to the soil surface or to the horizon in question that the capillary fringe reaches the surface or the top of the horizon."

Aquic

Although the aquic moisture regime is not considered in this study, its definition of Soil Taxonomy (1975) is given below.

"The aquic (L. *aqua*, water) moisture regime implies a reducing regime that is virtually free of dissolved oxygen because the soil is saturated by ground water or by water of the capillary fringe. An aquic regime must be a reducing one. Some soil horizons, at times, are saturated with water while dissolved oxygen is present, either because the water is moving or because the environment is unfavorable for micro-organisms, for example, if the temperature is <1°C such a regime is not considered aquic."

Aridic and Torric

"These terms are used for the same moisture regime but in different categories of the taxonomy.

In the aridic (torric) moisture regime, the moisture control section in most years is

1. Dry in all parts more than half the time (cumulative) that the soil temperature at a depth of 50 cm is above 5°C; and
2. Never moist in some or all parts for as long as 90 consecutive days when the soil temperature at a depth of 50 cm is above 8°C.

Soils that have an aridic or a torric moisture regime are normally in arid climates. A few are in semiarid climates and either have physical properties that keep them dry, such as a crusty surface that virtually precludes infiltration of water, or they are very shallow over bedrock. There is little or no leaching in these moisture regimes, and soluble salts accumulate in the soil if there is a source of them.

The limits of soil temperature exclude from these moisture regimes the very cold and dry regions of Greenland and adjacent islands. Such fragmentary data are available on the soils of those regions that no provision is made for their moisture regimes in this taxonomy."

Udic

"The udic (L. *udus*, humid) moisture regime implies that in most years the soil moisture control section is not dry in any part for as long as 90 days (cumulative). If the mean annual soil temperature is lower than 22°C and if the mean winter and mean summer soil temperatures at a depth of 50 cm differ by 5°C or more, the soil moisture control section is not dry in all parts for as long as 45 consecutive days in the 4 months that follow the summer solstice in 6 or more years out of 10. In addition, the udic moisture regime requires, except for short periods, a three-phase system, solid-liquid-gas, in part, but not necessarily in all, of the soil when the soil temperature is above 5°C.

The udic moisture regime is common to the soils of humid climates that have well-distributed rainfall or that have enough rain in summer that the amount of stored moisture plus rainfall is approximately equal to or exceeds the amount of evapotranspiration. Water moves down through the soil at some time in most years.

If precipitation exceeds evapotranspiration in all months of most years, there are occasional brief periods when some stored moisture is used, but the moisture tension rarely becomes as great as 1 bar in the soil moisture control section. The water moves through the soil in all months that it is not frozen. This extremely wet moisture regime is called "perudic" (L. *per*, throughout in time, L. *udus*, moist). The formative element *ud* is used in the names of most taxa to indicate either a udic or a perudic regime. The term perudic is not used in names of taxa, but is used in the text if it is relevant to the genesis of the soils.

Note that on the monthly basis, the perudic regime shows a surplus every month of the year. Obviously, if calculations were made on a daily basis, there would be short periods of withdrawal."

Ustic

"The ustic (L. *ustus*, burnt, implying dryness) moisture regime is intermediate between the aridic and the udic regime. The concept is one of limited moisture, but the moisture is present at a time when conditions are suitable for plant growth. The ustic moisture regime is not applied to soils that have cryic or pergelic temperature regimes, which are defined later.

If the mean annual soil temperature is 22°C or higher or if the mean summer and winter soil temperatures differ by <5°C at a depth of 50 cm, the soil moisture control section in the ustic moisture regime is dry in some or all parts for 90 or more cumulative days in most years. But the moisture control section is moist in some part for more than 180 cumulative days, or it is continuously moist in some part for at least 90 consecutive days.

If the mean annual soil temperature is lower than 22° C and if the mean summer and winter soil temperatures differ by 5°C or more at a depth of 50 cm, the soil moisture control section in the ustic regime is dry in some or all parts for 90 or more cumulative days in most years. But it is not dry in all parts for more than half the time that the soil temperature is higher than 5°C at a depth of 50 cm (the aridic and torric regimes). Also, it is not dry in all parts for as long as 45 consecutive days in the 4 months that follow the summer solstice in 6 or more years out of 10 if the moisture control section is moist in all parts for 45 or more consecutive days in the 4 months that follow the winter solstice in 6 or more years out of 10 (xeric regime).

In tropical and subtropical regions that have either one or two dry seasons, summer and winter have little meaning. In those regions, the ustic regime is that typified in a monsoon climate that has at least one rainy season of 3 months or more. In temperate regions of subhumid or semiarid climates, the rainy seasons are usually spring and summer or spring and fall, but never winter. Native plants are mostly annuals or they have a dormant period while the soil is dry."

Xeric

"The xeric moisture regime (Gr. *xeros*, dry) is that typified in Mediterranean climates, where winters are moist and cool and summers are warm and dry. The moisture, coming in winter when potential evapotranspiration is at a minimum, is particularly effective for leaching. In a xeric moisture regime, the soil moisture control section is dry in all parts for 45 or more consecutive days within the 4 months that follow the summer solstice in 6 or more years out of 10. It is moist in all parts for 45 or more consecutive days within the 4 months that follow the winter solstice in 6 or more years out of 10. The moisture control section is moist in some part more than half the time, cumulative, that the soil temperature at a depth of 50 cm is higher than 5°C, or in 6 or more years out of 10 it is moist in some part for at least 90 consecutive days when the soil temperature at a depth of 50 cm is continuously higher than 8°C. In addition, the mean annual soil temperature is lower than 22°C, and mean summer and mean winter soil temperatures differ by 5°C or more at a depth of 50 cm or at a lithic or paralithic contact, whichever is shallower."

Classes of Soil Temperature Regimes (Soil Taxonomy, 1975)

The following soil temperature regimes are used in defining classes at various categoric levels in the taxonomy. All definitions are taken verbatim from Soil Taxonomy (1975).

Pergelic. (L. *per,* throughout in time and space, and L. *gelare,* to freeze; connoting permanent frost).— Soils with a pergelic temperature regime have a mean annual temperature lower than 0°C. These are soils that have permafrost if they are moist, or dry frost if excess water is not present. It seems likely that the moist and the dry pergelic regimes should be defined separately, but at present we have only fragmentary data on the dry soils of very high latitudes. Ice wedges and lenses are normal in such soils in the United States.

Cryic. (Gr. *kryos,* coldness; connoting very cold soils).— In this regime soils have a mean annual temperature higher than 0°C (32dF) but lower than 8°C (47°F).

1. In mineral soils, the mean summer temperature for June, July, and August in the northern hemisphere and December, January and February in the southern hemisphere at a depth of 50 cm or at a lithic or paralithic contact, whichever is shallower, is as follows:
   a. If the soil is not saturated with water during some part of the summer and
      (1) There is no O horizon, lower than 15°C (59°F);
      (2) There is an O horizon, lower than 8°C (47°F);
   b. If the soil is saturated with water during some part of the summer and
      (1) There is no O horizon, lower than 13°C (55°F);
      (2) There is an O horizon or a histic epipedon, lower than 6°C (43°F).
2. In organic soils, either
   a. The soil is frozen in some layer within the control section in most years about 2 months after the summer solstice; that is, the soil is very cold in winter but warms up slightly in summer; or
   b. The soil is not frozen in most years below a depth of 5 cm; that is, the soil is cold throughout the year but, because of marine influence, does not freeze in most years.

Cryic soils that have an aquic moisture regime commonly are churned by frost.

Most isofrigid soils with a mean annual soil temperature above 0°C have a cryic temperature regime. A few with organic materials in the upper part are exceptions. Throughout this text all isofrigid soils without permafrost are considered to have a cryic temperature regime.

Frigid.—The frigid regime and some of the others that follow are used chiefly in defining classes of soils in the low categories. In the frigid regime the soil is warmer in summer than one in the cryic regime, but its mean annual temperature is lower than 8°C (47°F), and the difference between mean winter and mean summer soil temperature is more than 5°C (9°F) at a depth of 50 cm or at a lithic or paralithic contact, whichever is shallower.

Mesic.—The mean annual soil temperature is 8°C or higher but lower than 15°C (59°F) and the difference between mean summer and mean winter soil temperature is more than 5°C at a depth of 50 cm or at a lithic or paralithic contact, whichever is shallower.

Thermic.—The mean annual soil temperature is 15°C (59°F) or higher but lower than 22°C (72°F), and the difference between mean summer and mean winter soil temperature is more than 5°C at a depth of 50 cm or at a lithic or paralithic contact, whichever is shallower.

Hyperthermic.—The mean annual soil temperature is 22°C (72°F) or higher, and the difference between mean summer and mean winter soil temperature is more than 5°C at a depth of 50 cm or at a lithic or paralithic contact, whichever is shallower.

If the name of a soil temperature regime has the prefix iso, the mean summer and winter soil temperature for June, July, and August and for December, January, and February differ by less than 5°C at a depth of 50 cm or at a lithic or paralithic contact, whichever is shallower.

Isofrigid.—The mean annual soil temperature is lower than 8°C (47°F).

Isomesic.—The mean annual soil temperature is 8°C or higher but lower than 15°C (59°F).

Isothermic.—The mean annual soil temperature is 15°C or higher but lower than 22°C (72°F).

Isohyperthermic.—The mean annual soil temperature is 22°C or higher.

Key to Tentative Subdivisions of Moisture Regimes

In this key, all climatic requirements are assumed to occur in most years (at least six out of ten).

A. Key to Subdivision of ARIDIC

1) Soils with aridic moisture regimes in which the moisture control section (MCS) is completely dry during the whole year.

EXTREME ARIDIC

2) Other soils with aridic moisture regimes in which the MCS is moist in some or all parts for 45 consecutive days or less during the period that the soil temperature at 50 cm depth is more than 8°C

TYPIC ARIDIC

3) Other soils with aridic moisture regimes

WEAK ARIDIC

B. Key to Subdivision of XERIC

1) Soils with xeric moisture regimes in which the MCS is dry in all parts for more than 90 consecutive days during the four months following the summer solstice

DRY XERIC

2) Other soils with xeric moisture regimes

TYPIC XERIC

C. Key to Subdivision of USTIC

1) Soils with an ustic moisture regime and an iso-temperature regime in which the number of consecutive days that the MCS is completely or partly moist when the soil temperature at 50 cm depth is more than 8°C, is as follows:

- a) less than 180 days

ARIDIC TROPUSTIC

- b) 180 or more but less than 270 days

TYPIC TROPUSTIC

- c) 270 or more days

UDIC TROPUSTIC

2) Other soils with an ustic moisture regime and without an iso-temperature regime:

- a) soils in which the MCS is dry in all parts for more than 45 consecutive days during 4 months following the summer solstice, *and* where the MCS is moist in all parts for more than 45 consecutive days during 4 months following the winter solstice

XERIC TEMPUSTIC

- b) other soils where the MCS is moist in all parts for more than 45 consecutiv days during 4 months following the winter solstice, *and* where the MCS is not completely dry for more than 45 consecutive days during 4 months following the summer solstice.

WET TEMPUSTIC

- c) other soils

TYPIC TEMPUSTIC

D. Key to Subdivision of UDIC

1) Soils with a udic moisture regime in which the MCS is dry in some of all parts for less than 30 cumulative days

TYPIC UDIC

2) Other soils with a udic moisture regime in which the MCS is dry in some or all parts for 30 or more cumulative days

- a) with an iso-temperature regime

DRY TROPUDIC

- b) without an iso-temperature regime

DRY TEMPUDIC

Brief Description of Tentative Moisture Regime Subdivisions

Aridic Tropustic

The aridic tropustic regime is an ustic moisture regime in which there is acute moisture stress lasting several months. For practically all African stations recorded in this study, the interval that the moisture control section is completely dry varies between 3 and 9 months. The season when water is available in the moisture control section lasts from 3 to 6 months. Crops can be grown without irrigation.

According to the calculations, there are strong variations among the stations in Africa in the time that the moisture control section is completely moist in one year. The range is from zero to five months.

The temperature regimes in Africa in this moisture range are isothermic and isohyperthermic.

Stations in the hyperthermic region which belong to this moisture regime are N'djamena (Chad), Accra (Ghana), Kano (Nigeria), Niamey (Niger), Dakar (Senegambia), Lome (Togo), Ouagadougou (Upper Volta).

Dry Tempudic

This is a udic moisture regime with a minimum of nine months in one year during which the moisture control section is completely moist. However, the length of the time that the moisture control section is dry in some parts is at least one month. The soils with this moisture regime registered in Africa never dry out completely during the summertime.

The dry tempudic moisture regimes have a seasonal temperature variation exceeding 5°C in the soil at 50 cm depth. They only occur in the southern part of the continent.

Dry Tropudic

The soils with this soil moisture regime have at least nine months in one year that the moisture control section is completely moist. However at least one month has some dryness; some soils dry out completely in the control section but seldom for more than one month.

In soils with a dry tropudic moisture regime the difference between winter and summer soil temperatures at 50 cm depth is less than 5°C. The stations recorded in Africa are either isohyperthermic or isothermic.

According to the results of the calculations for Africa, the moisture control section almost never dries out completely during the four months following the summer solstice. The wet season may be bimodal and separated into two rainy seasons. In isohyperthermic regimes there is almost always some moisture in the control section for approximately 10 consecutive months.

Stations in the isohyperthermic region which belong to this class are Douala, Dschang, Yaounde (Cameroon), Libreville (Gabon), Abidjan (Ivory Coast), Monrovia (Liberia), Kinshasa (Zaire). For isothermic areas Tananarive (Malagasy) is an example.

Dry Xeric

These are soils with wet winters and dry summers.

The dry xeric moisture regime is a xeric moisture regime in which the moisture control section is dry in all parts for more than 3 months during summer.

All stations included in this study have a thermic moisture regime. The duration of the season when the soil temperature drops below 8°C varies from 0 to 5 months.

Almost all stations are located in the Mediterranean area in North Africa: Oran (Algeria), Casablanca (Morocco), and Tunis (Tunisia) are examples.

Extreme Aridic

The extreme aridic moisture regime is an aridic moisture regime in which the moisture control section is always completely dry.

No cultivation is possible without irrigation.

Soils with this moisture regime occur in the northern and in the southern part of the continent. Examples are Cairo, Luxor, Suez (Egypt), Agadir (Morocco), Berbera (Somalia), Mossel Bay (South Africa).

Perudic

The perudic moisture regime is a moisture regime defined by properties of the atmospheric climate. For each month the rainfall exceeds the potential evapotranspiration. When considered on a monthly basis the moisture control section is always completely moist and crops should not suffer at any time from drought. This does not mean, however, that short periods of moisture stress may not occur in the surface layers of the soil. Boende (Zaire) and Greenville (Liberia) are examples of perudic moisture regimes.

Typic Aridic

The typic aridic moisture regime is an aridic moisture regime in which the moisture control section is moist in some or in all parts at some time in one year for 45 consecutive days or less when the soil temperature at 50 cm depth is more than 8°C.

The stations grouped in this class in Africa seldom have moisture for more than one month when the temperature is high enough for crop growth. Cultivation is not possible without irrigation in soils with typic aridic moisture regimes. Tombouctou (Mali), Khartoum (Sudan), Luanda, Lobito (Angola), Mogadishu (Somalia), Nouakchott (Mauritania) are examples of stations with soils having a typic aridic moisture regime.

Typic Tempustic

The typic tempustic moisture regime by definition has marked seasonal variation both in temperature and moisture. There are more than 90 days in one year that the moisture control section is dry in some or all parts.

The typic tempustic moisture regime does not have the characteristics of xeric moisture regimes which require the moisture control section to be completely moist during more than 45 days during the winter time and completely dry for more than 45 days in the summertime. Therefore the typic tempustic moisture regime does not have the characteristics of the Mediterranean climates.

Most stations, but not all classified in this regime, are never completely moist in the control section. Almost all are dry in some or all parts during winter; therefore, leaching in these soils is minimal.

The typic tempustic moisture regimes is found in Africa under hyperthermic, thermic, and mesic temperature regimes. Alexandria (Egypt), Bloemfontein (South Africa) are examples of stations which belong to this moisture regime.

Typic Tropustic

The soils with a typic tropustic moisture regime are dry in some or all parts for more than 3 months during one year. The rainy season, however, is long enough to grow a crop without supplemental irrigation. In soils with a typic tropustic moisture regime the time that the moisture control section is completely or partly moist without interruption, and the soil temperature is more than 8°C, varies between 6 and 9 months.

The seasonal variation in soil temperature at 50 cm depth does not exceed 5°C.

Stations which have soils with a typic tropustic moisture regime are Cotonou (Benin), Bujumbura (Burundi), Bambari (Central African Republic), Conakry (Guinea), Bouake (Ivory Coast), Mombasa (Kenya), Ibadan (Nigeria), Bissau (Guinea Bissau), Njala, Rokupr (Sierra Leone), Dar es Salaam (Tanzania), Livingstone (Zambia), Bulawayo (Zimbabwe), Port Elizabeth (South Africa).

Typic Udic

The moisture control section in soils with a typic udic moisture regime is moist in all parts for at least eleven months in one year. The moisture control section seldom dries out completely. There is at least one month where the evapotranspiration is higher than the actual precipitation.

Typic udic moisture regimes may have both iso- and non-iso-temperature regimes. The following stations may be mentioned: Entebbe (Uganda), Yangambi (Zaire), Addis-Ababa (Ethiopia), Nairobi (Kenya), Johannesburg, Pretoria (South Africa).

Typic Xeric

Soils with a typic xeric moisture regime are those soils in which the moisture control section is completely moist during more than 45 consecutive days during the four months following the winter solstice. The moisture control section dries out completely between 45 and 90 days in the summer.

Typical stations are Alger (Algeria), Rabat (Morocco), Capetown (South Africa) and Bizerte (Tunis).

Udic Tropustic

In this regime, the moisture control section is dry in some or all parts for more than 90 cumulative days. The number of consecutive days that there is some available water in the moisture control section is 270 or more.

The difference between the summer and winter soil temperatures at 50 cm depth is less than 5°C.

Stations which belong to this regime are Ekona (Cameroon), Bangui (Central African Republic), Lambarene (Gabon), Kumasi (Ghana), Lilongwe (Malawi), Lubumbashi (Zaire), Lusaka (Zambia), Salisbury (Zimbabwe), Arusha (Tanzania).

Weak Aridic

The soils with weak aridic moisture regimes are moist in some or all parts of the moisture control section for more than 45 consecutive days during the time that the soil temperature at 50 cm depth is more than 8°C. By the definition of aridic, however, the maximum length of time that some water is available in the moisture control section is less than 3 months.

In some years some crops may be grown without supplemental irrigation primarily in areas of temperature regimes cooler than hyperthermic and isohyperthermic. However, rainfall is very erratic and irrigation is usually required.

Tobruk (Libya), Windhoek (Namibia) are stations where soils with weak aridic regimes occur.

Wet Tempustic

The wet tempustic moisture regime is found in Africa in soils with a thermic temperature regime with seasonal variation of temperature between winter and summer. Soils with wet tempustic moisture regimes suffer from moisture stress in the moisture control section for more than 3 months, but they do not dry out completecy during the four months after the summer solstice for more than 45 days. They are completely moist in winter for more than 45 days in the period of four months following the winter solstice.

Only a few stations of Africa were classified in this regime with examples in Algeria, Tunisia and South Africa. They are usually completely moist for more than 2 months in winter and seldom dry out completely during the summertime. These conditions are such that leaching of salts should occur at least during the wintertime.

Xeric Tempustic

The xeric tempustic moisture regime is a moisture regime that has all the characteristics of a xeric moisture regime except the temperature requirement implied in the definition of xeric.

The stations identified in this study with xeric tempustic moisture regime are located in Libya and Morocco. The moisture conditions are very similar to the dry xeric conditions.

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Van Wambeke, A. R. 2000. ***The Newhall Simulation Model for estimating soil moisture & temperature regimes.*** Department of Crop and Soil Sciences. Cornell University, Ithaca, NY.

The Newhall Simulation Model for estimating soil moisture & temperature regimes

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Contents

1 Introduction

This paper describes the rationale of two software programs that use the Newhall model for the determination of soil moisture regimes: one is written in BASIC, the other one is written in and compiled in FORTRAN 77.

This text is an excerpt of a mimeographed article by Frank Newhall [2], which explained the rationale of his soil moisture regime model that he developed in the Soil Conservation Service of USDA as a climatologist working with Guy D. Smith. The sections which follow are only a part of Newhall's paper and are limited to the description of the mechanisms that his model uses to follow soil moisture changes and identify soil moisture regimes on the basis of monthly rainfall and temperature data.

The BASIC software works with monthly input data of only one year (either one indiviual year, monthly averages of a number of years, or normal years), longitude and latitude information, and computes potential evapotranspiration according to Thornthwaite [4]. It calculates the criteria that Soil Taxonomy [3] uses to define soil moisture and soil temperature regimes and classifies the regimes according to these criteria. The original Newhall model that he wrote in COBOL used inputs of several years, calculated the criteria of each year, and computed the frequency of occurrence of each of them durimg the years that data were available. It identified the soil regimes on the basis of these frequencies. The BASIC software discussed in this paper therefore differs in its approach from the original Newhall model by using average years. Newhall actually was opposed to the use of average input data. The BASIC model however strictly follows the mechanisms that Newhall used for moisture changes in the soil profile, as well as the Soil Taxonomy definitions of the moisture and temperature regimes.

Other additions were introduced in the BASIC model. The subdivisions of the soil moisture regimes were set up by A. Van Wambeke in 1976 in a research perspective and not modified since. They do not correspond to certain subdivisions that Soil Taxonomy uses in some taxa. The BASIC model also allows changes in the water holding capacity of the soil moisture profile that can be increased to 400 mm water. Finally, a year in the BASIC software is only 360 days long and all months last 30 days.

The FORTRAN model follows Newhall's rationale entirely and works with input data of several years that are processed separately. It allows changes in the water holding capacity of the moisture profile, and changes in the factors that relate air temperatures with soil temperatures.

2 Preliminary Assumptions of the Newhall Model

2.1 The Soil Moisture Profile

The soil moisture profile considered by the model extends from the surface down to the depth of an available water holding capacity (AWC) of 200 mm (≈8"). The soil depth needed to achieve this AWC depends on the pore geometry of the soil, and ranges from 80 cm in a well-structured clay to 200 cm in a light sandy loam; in a wide range of medium-textured soils, the depth required is 100 to 135 cm[1].

Moisture Control Section

The profile is divided into 8 layers each of which retains 25 mm of available water; the second and the third layer form the **moisture control section** (MCS). This is defined by Soil Taxonomy as the layer having an upper boundary at the depth to which a dry (tension of more than 1500 kPA) but not air dry soil will be moistened by 25 mm

---

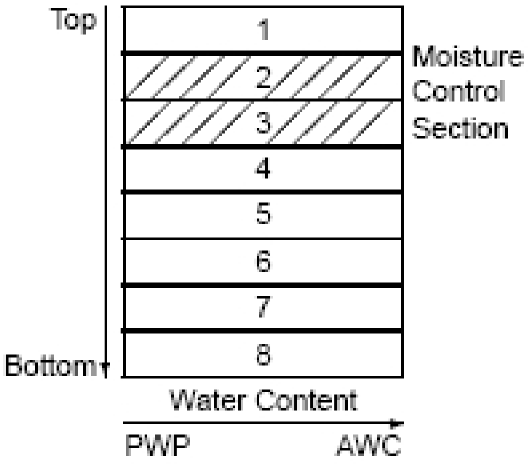
[1] [1], Table 2.3/7

of water moving downward from the surface within 24 hours. The lower boundary is the depth to which a dry soil will be moistened by 75 mm of water moving downward from the surface within 48 hours.

Figure 1 represents Newhall's soil moisture profile. The vertical axis indicates the depth of the eight layers, and the horizontal axis scales the amounts of available water present in each of them. The tension at which water is held in the profile decreases from left (**permanent wilting point**, PWP) to right (**field capacity**, FC). Each layer is divided into eight slots to form an eight by eight square matrix of 64 slots, which is designated as the *soil moisture diagram* as shown in Table 1. Each slot can be filled with a value corresponding to an amount of water which can vary between 0 and 1/64th part of the total available water holding capacity, or 3.125 mm in the case of water holding capacity of 200 mm.

Soil Moisture Diagram

Figure 1: Newhall's Soil Moisture Profile



2.2 Water Uptake and Water Removal

The model simulates the **downward movement of moisture** into the soil as the progression of a wetting front; it is further referred to as *accretion*. The distance that the wetting front moves downward depends on the amount of water needed to bring all the soil above it to field capacity.

When the wetting front reaches the bottom of the profile and the complete soil moisture profile is at field capacity, the **excess water** is lost either by *percolation* or by *runoff*.

The rate of **removal of water out of the soil**, or *depletion*, depends on the energy available for moisture extraction, expressed in terms of *potential evapotranspiration* (PE) which acts on the soil and the plants growing in the soil. The energy required to remove moisture from the soil depends on the amount of water (AW) present and the forces exerted by the soil to retain it. Water is removed more readily when the soil water is at low tensions than when the water content in the profile is at a minimum.

Less energy is used by the model to remove water from the upper layers of a soil than from the lower layers. The time needed to extract water from the soil depends on the depth at which it is located; this is in line with the fact that roots are more abundant near the surface than in deeper layers.

Depletion continues until the soil is at wilting point, e.g. when the soil moisture tension is 1500 kPA. The amount of water held in the soil is assumed not to be reduced below the amount held at 1500 kPA.

2.3 Distribution of Climatic Factors in the month

Precipitation

The monthly precipitation (MP) is distributed in each month according to the following sequence:

1. One half of the monthly precipitation (HP for *heavy precipitation*) falls during one storm in the middle of the month; this moisture enters the soil immediately without losses, except when the available water capacity of the soil moisture profiles is exceeded.
2. One half of the monthly precipitation (LP for *light precipitation*) occurs in several light falls, and is partly lost by evapotranspiration before it enters the soil; it can only infiltrate into the soil when LP exceeds the potential evapotranspiration.

Potential Evapotranspiration

The potential evapotranspiration (PE) is assumed to be uniformly distributed during each month. Not all its energy is used to extract water from the soil. A part is used to dissipate as much light precipitation as possible before it reaches the soil. If there is surplus energy, it is used for water extraction from the profile. PE is calculated according to Thornthwaite.

3 The Time-Step Progression of the Model

Each month, all of which are assumed to have 30 days, is divided into three parts. The first is a 15-day period of light precipitation (LP), the second is the heavy rainfall (HP) which occurs at midnight between the 15th and 16th of the month, and the third corresponds to another fortnight of light precipitation.

For each of these events water is either added to the soil or extracted from it. At the completion of each step, the **moisture condition** of the soil is determined, and if it changed, the model computes the number of days that each condition prevailed in the moisture control section.

The **starting** soil moisture condition of the profile is determined by running the simulation program for a number of consecutive iterations using each time the same yearly input until the moisture content of December 30th does not differ by more than one hundredth of the content found at the same date in the immediately preceding iteration. The program then starts the diagnostic processing of monthly data with an initial amount of water in each slot equal to the one found on December 30th.

When all months are processed the soil moisture conditions for each day are combined in the **moisture condition calendar** which forms the data base for the determination of the soil moisture regime criteria according to the definitions of Soil Taxonomy.

3.1 Processing sequence during one month

Each **half-month interval** is processed using the following inputs: monthly precipitation (MP) and monthly potential evapotranspiration (PE). The steps are as follows:

1. compute light precipitation, where $LP = MP/2$
2. compute the net potential evapotranspiration (NPE), where $NPE = (LP - PE)/2$

If $NPE > 0$, accretion will take place during this period; otherwise, water will be extracted from the profile.

All heavy precipitations in the middle of each month are processed by computing the heavy precipitations $HP = MP/2$ and entering this amount in the profile as accretion.

3.2 Changes in Water Content during each Period

Accretion

To simulate the additions of moisture to the profile, water is entered in the soil in,each non-full slot following a specific order shown in the soil moisture diagram of Table 1.

Table 1: Slot Sequence during Accretion

O1	02	03	04	05	06	07	08
09	10	11	12	13	14	15	16
17	18	19	20	21	22	23	24
25	26	27	28	29	30	31	32
33	34	35	36	37	38	39	40
41	42	43	44	45	46	47	48
49	50	51	52	53	54	55	56
57	58	59	60	61	62	63	64

The sequence starts with the left slot in the top row. Water is added to each successive slot in a row until the row is filled, or until the water supply is exhausted. When a row is completely full the program proceeds with the immediately underlying row, starting again on the left side of the moisture diagram. The accretion procedures in this way simulate the downward movement of a wetting front.

Depletion

The sequence for the extraction of water from the profile starts with the top right-hand slot and scans the slots in successive right-downward diagonals, as shown in Table 2

During the sequence each slot is examined, and if water is present, it is removed from it. The depletion stops when the potential evapotranspiration, or the energy it represents for the period being processed, is exhausted.

The rate of depletion is inversely proportional to the tension under which the water is held. It also varies with the depth of the layer. Both factors are taken into account in the calculations by means of the **depletion requirement diagram** which indicates the

Table 2: Slot Sequence during Depletion

29	22	16	11	07	04	02	01
37	30	23	17	12	08	05	03
44	38	31	24	18	13	09	06
50	45	39	32	25	19	14	10
55	51	46	40	33	26	20	15
59	56	52	47	41	34	27	21
64	63	61	58	54	49	43	36

value by which a unit of energy (expressed as evapotranspiration) has to be multiplied to extract one unit of water from the soil. This matrix of values is given in Table 3.

Table 3: Depletion Requirements

1.65	1.40	1.23	1.13	1.05	1.00	1.00	1.00
2.07	1.69	1.46	1.26	1.15	1.07	1.02	1.00
2.68	2.14	1.74	1.46	1.28	1.17	1.09	1.00
3.58	2.80	2.22	1.78	1.49	1.31	1.19	1.11
4.98	3.80	2.93	2.30	1.84	1.53	1.34	1.21
5.00	5.00	4.03	3.07	2.38	1.89	1.57	1.37
5.00	5.00	5.00	4.31	3.22	2.47	1.95	1.61
5.00	5.00	5.00	5.00	4.62	3.39	2.57	2.01

The processing continues until the entire evapotranspiration potential has been used, or until all slots have been set to zero. In the latter case any remaining depletion amount is not carried forward but is discarded.

3.2.1 Definitions of Soil Moisture Conditions

Soil Taxonomy recognizes three **soil moisture conditions**. They are diagnostic for determining the moisture regime of a pedon, and are evaluated in the moisture control section.

1. The moisture control section is *dry in all parts*. It is also called *completely dry*. The Newhall model accepts this condition when the leftmost slots numbered 09, 17, and 25 in Table 1 are all empty.

   soil completely dry

2. The moisture control section is *moist in all parts*, or *completely moist*. The Newhall model defines this condition when none of the leftmost slots numbered 09, 17, 25 in Table 1 is empty.

   soil completely moist

3. The moisture control section is *dry in some parts* or *moist in some parts*. It is also called *partly dry* or *partly moist*. The Newhall model considers this condition only when the moisture control section does not fulfill the requirements for (a) nor (b), e.g. when it is neither completely dry nor completely moist.

   soil partly moist, partly dry

The Newhall model includes slot 25 which is located outside the moisture control section (MCS) to determine the soil moisture condition. In an accretion step this slot signals that the MCS is completely full. In a depletion sequence it increases the amount of water which has to be extracted from the soil before a change to the completely dry condition is recorded. The inclusion of slot 25, and the diagonal extraction pattern, compensate in part for the fact that the model ignores all upward movements of water in the soil which in reality participates in the moisture supply to the MCS.

3.3 Moisture conditions in each two-week period

If the moisture condition changes during a period of light precipitation, the relative durations of each moisture condition is computed using the following equations:

$$DX = 15 \cdot RPEX / NPE$$

where DX is the duration in days of condition X, and $RPEX$ is either the amount of potential evapotranspiration needed to change this condition into the next one during a depletion phase (for example from completely moist to partly moist) or rainfall during an accretion phase. NPE is the potential evapotranspiration (or rain) which was available during the half-month being processed.

The duration of the moisture condition which ends a half month is calculated by difference, or

$$DE = 15 - DX - DX2$$

where DE is the duration of the soil moisture condition which ends the half month, and where DX and $DX2$ are the durations of the preceding conditions.

3.4 Changes in Soil Temperature

The definitions of both soil moisture and temperature regimes require the calculation of the periods when soil temperature is above or below certain critical values, e.g. 6°C or 8°C, as given in the definitions.

The beginning and ending dates of the period when the soil temperature is above or below a given critical value are approximated from the sequence of mean monthly temperatures.

The onset of a period when the soil temperature *rises above* a critical level is obtained by linear interpolation between the 15th day of each month; 21 days are then added to this date to compensate for the time lag between air and soil temperature at 50cm.

The onset of a period when the soil temperature *falls below* a critical level is obtained by linear interpolation between the 15th day of each month; 10 days are then added to this date to compensate for the time lag between air and soil temperature at 50cm; this lag is about half of the lag when the soil is warming up. This is because the soil is usually wetter when warming up than when cooling down, and so has a higher thermal capacity.

4 Determination of Moisture and Temperature Regimes

The model in the BASIC software processes the monthly data of one year and computes a calendar in which the moisture condition of each day is recorded. For the calculations of lengths of periods of soil conditions that extend across calendar years, the model attaches an identical second year to the input.

The two-year calendars are then scanned and the number of consecutive or cumulative days during which given soil climatic conditions prevail are calculated. These are included in the output, and listed in the tables.

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Newhall Simulation Model

a BASIC program for the IBM PC
(DOS 2.0 or later)

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IMPORTANT

Some setup is required before this disk can be used. See section 1.1 for details.

Preface

The Newhall Simulation Model is useful in determining the soil moisture regimes used in *Soil Taxonomy*. Given a limited amount of monthly information that is often available from local weather reporting stations, the soil scientist is able to approximate daily moisture conditions in a soil.

The model lends itself to use on computers. Much of the processing involves repetitive use of arithmetic equations. The equations are not complicated or difficult, but are prone to error just due to the repetition involved. The computer is faster and more accurate than manual calculating, and its use frees the user so s/he can spend time interpreting the results of the model.

This program has a number of supplementary features. Graphics are used extensively so the user can watch the processing as it is being done. Patterns and trends are more evident when displayed this way. Furthermore, additional routines help the user to run the program and to create and modify input data.

The program is written in BASICA and runs on IBM PCs, XTs and ATs using DOS 2.0 or later. A color graphics adapter is required for most of the programs, and a printer is optional.

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[3] taken from A.Van Wambeke, Asia Soil Moisture Regimes SMSS Technical Monograph #9, 1985.

Chapter 1

NSM Tutorial

For those who prefer to learn at the keyboard, the following will help you get through the NSM program and see most of its features. Explanations, which are kept to a minimum here, can be found in the next chapter.

As a convention throughout this manual, `typewriter-like` type signifies what you should type or what you should see on the computer monitor.

Do not use the keypad to enter numbers as this produces unreliable results.

1.1 Setup the NSM disk

IMPORTANT: Some set-up is needed before the NSM program can be used. This is a one-time step; it never needs to be repeated.

NSM is written in BASICA. Whenever the program is run, the computer needs to find this version of the BASIC language. The easiest way to ensure that this happens is to copy BASICA to the NSM disk. (BASICA is distributed by IBM on your DOS disk as BASICA.COM). Once a copy of BASICA.COM is on the NSM disk, the disk is ready to use.

BASICA.COM isn't included on the NSM disk because

- there are different versions; a newer version will not always run on an older computer

and

- it is a copyright infringement to distribute BASICA.COM without an agreement with IBM.

So while it may seem round-about to make you do the copying, in the end it avoids some compatibility problems and gets around the copyright issue.

The SETUP program on the NSM disk will help you copy BASICA to the NSM disk if you don't know how to do this. To use it

1. Place the NSM disk in the default drive.
2. Place the DOS disk in the other drive.
3. Type **SETUP** followed by the letter of the disk drive that holds the DOS disk (and therefore the BASICA.COM file).
4. Hit ENTER.

If everything went right, you will see:

```
              1 File(s) copied
Installation completed
```

and the NSM disk is ready to use.

If BASICA.COM is not found however, you will be told to restart the installation procedure.

As an example, if the DOS disk is in drive A: and NSM is in the default drive B:, type:

```
SETUP A:
```

If BASICA.COM was on a hard disk in a subdirectory called \DOSFILES and NSM was in the default drive B:, you'd type

```
SETUP C:\DOSFILES\
```

Notice that you must end a directory name with a backward slash.

For those of you with a hard disk and one floppy disk drive, the situation is more complicated. If your hard disk has a copy of BASICA.COM on it, you can follow the above procedure, but if it doesn't, try the following.

Assuming that the floppy disk drive is called A: and the hard disk C:,
1. Place the DOS disk in A:
2. Type `A:` to make the floppy disk drive the default. You should now see a A> prompt.
3. Type

```
COPY BASICA.COM C:
```

This will copy BASICA.COM from the DOS disk in the A: drive to the hard disk C:.
4. Now remove the DOS disk and insert the NSM disk.
5. Type

```
SETUP C:
```

This should copy BASICA.COM from the hard disk to the NSM disk.

Once BASICA.COM is on the NSM disk, the NSM disk can be backed up to another floppy disk or transferred to a hard disk. You don't need to run the SETUP for these copies.

1.2 Make backups

1. Start up your computer using DOS version 2.0 or later.

2. Format a blank disk if necessary.

3. Place the NSM program disk in the default drive.

4. Type: `COPY *.* X:` and substitute the target drive for X. The target drive may be a hard disk or a floppy disk.

1.3 Start program

1. Place your copy of the NSM program disk in the default drive (store the original somewhere). If you copied the NSM disk to your hard disk, make the hard disk the default.

2. Type `NSM`

You will be presented with a menu that looks like this:

```
Type the NUMBER of the desired
action

1  Create a new data file or edit
an existing file
2  Start processing data (compute
PET and check data)
3  Run Newhall Simulation
4  Print results of Newhall
Simulation on screen or printer
5  See a directory of a disk
6  Quit
```

Because no data is available, the first step is to create a file using option 1. Type `1` followed by ENTER. This will put you in the editor.

1.4 Data editor

You should now see the following:

```
TYPE THE NUMBER THAT CORRESPONDS TO
YOUR CHOICE

1-Create a new file
2-Edit a file
3-See a directory of a disk
4-Start processing a file

YOUR CHOICE ==>
```

To create a file, choose option 1. You will be asked a number of questions about temperature, precipitation, and location of a weather reporting station. Answer these with reasonable replies, but for the sake of this tutorial, don't spend the time with actual data until you know what to expect.

A few notes:

1. The first request is for a file name. Use a name that doesn't exist on the disk.

2. After providing 12 months of temperature readings, you will be asked to supply a record length. This might be confusing at first. This information is not used in processing the data, so just supply a year number (i.e. 1958). The next question is similar, so supply it with a year (i.e. 1978). An explanation is provided in the next chapter.

3. You can't correct data that has been already entered in this option. Don't worry about it now; that's the next step.

After answering all the questions, you will be returned to the editor's menu. Once a file exists on the disk, it can be edited using option 2. This is useful for changing typos. Type 2

You'll be asked if you would like to edit the file that was just created. Reply Y

The screen will change to display the station's location and precipitation data. To change an entry, use the arrow keys to place the cursor on a specific entry, and hit ENTER. The screen will go blank, and be replaced with a prompt in the upper left. Type the correct entry and hit ENTER. The old screen will be restored with the updated entry.

To see the rest of the data, press function key F2, and edit using the above procedure. At any time you can return to page 1 by pressing F1, and from there back to page 2 with F2.

When you have finished editing, press F3. You will be asked if you would like to erase the old version of the file. If you reply Y the data you just edited will be placed in the file; if you reply N, the old data will be left in the file and you will have to supply a new file name for the edited data. For simplicity, reply Y

You should now be back at the menu for the editor.

The next step is to start processing the file.

1.5 Start processing file

Chose option 4.

You will be asked if you wish to process the last file that you worked on. Reply Y

If you have a graphics adapter, the screen will turn blue, and in a short while, a title will appear. If the graphics adapter is not present, the program will end at this point.

Assuming that the title has appeared, hit ENTER.

The screen will display a few messages, and eventually display a histogram of the monthly potential evapotranspiration and monthly precipitation of the site. At the bottom of the screen, a prompt will ask you if you would like a printout of the graph. Reply N this time. You will then be asked if you would like to continue on. Reply Y

1.6 Newhall simulation model

A tutorial of the Newhall simulation model is available as an option. When asked, reply Y if you would like to see it.

The tutorial and processing routines use sound effects. To turn the sound effects off, press F2. (They can be turned on again by pressing F2).

If you choose to see the tutorial, you will be prompted at the end of it to press ENTER in order to continue. This will not happen if the tutorial isn't seen.

When the program is processing a file, the screen displays a large moisture calendar and a smaller soil profile. These show the wetting and drying of the soil as the program computes them from the Newhall model. This section of the program will take about 4 minutes to run. If at any time you would like to pause the execution, press F1. Pressing any key thereafter will cause execution to resume.

When this section has been completed , there will be a short delay, and then you will be asked if you wish to continue on. Reply Y

1.7 Displaying results

You will be asked if you would like to display the results on a printer. For speed and simplicity in this tutorial, reply **N**

Three screens of information will then follow. Everything that was calculated will be displayed. The graphic moisture calendar will use numbers where the display used color, but it will be the same information.

At the end of this display you will be returned to the main menu.

1.8 Re-running a data file

Once an input data-file has been processed as in the above, it is no longer necessary to proceed through the steps in order. The main menu will let you jump into the initial histogram, the Newhall processing, or the display routines. However, when a file is not processed sequentially, you are responsible for supplying the data file name. For the histogram section, the correct file name is the name you chose when creating the input data-file; for the Newhall processing it is the first part of the input data-file name, but with an extension of .INT or .PRT. For the printing routines the correct filename is the first part of the input data-file name with and extension of .PRT. The purpose of these files will be explained in the next section.

Not every feature was covered in this tutorial, but you should now have a basic understanding of what is going on. Additional information is provided in the next section.

1.9 Problems

If an error occurs, the following steps may help you correct it.

First, find out if the program is still running or if it has crashed. If there is an error message on the screen followed by an **Ok** on the next line, the program has crashed and you are now in BASICA. To restart the program from the beginning, type RUN and press ENTER.

If the program didn't crash, or you re-started it by using the above, there are now two ways out. Function key F9 will return you to the main menu; F10 will return you to DOS. (You may need to press ENTER after pressing these function keys.) These should help you get to a point where you know what's happening.

Chapter 2

How NSM works

2.1 Overview of structure

The NSM "program" is actually a series of five BASICA programs designed to make use of the Newhall Simulation Model easier and more instructive. This five-part structure is not inherently obvious because one of the programs acts as a menu-driven selector switch, running the program appropriate to the operator's choice. Additionally, the name of the file currently being processed is passed between the programs, further obscuring the five-part structure.

The original intent of using this structure was to make sure there was enough available memory for the program to run on older computers. BASICA can only occupy a maximum of 64K, and the concern was that the combined set of programs would not all fit. As it turned out, this was not the case, but the structure was maintained as one method of allowing the user to start processing a file at different points. Because BASICA is relatively slow and some of the computations take some time, this option is useful in reducing waiting by allowing the operator to get close to the procedure s/he is interested in.

Figure 2.1 shows how the programs link together. In addition, the files produced and used by the different programs are shown.

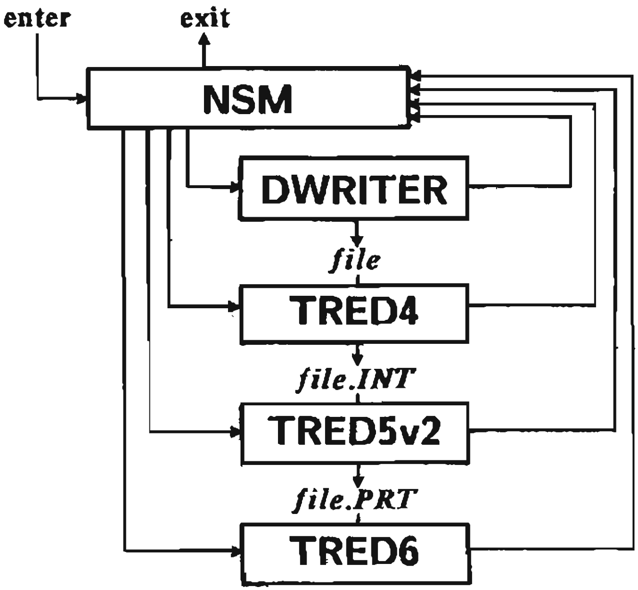

Figure 2.1: Structure of NSM

2.1.1 Data files

The names of data files are subject to the same constraints as any other file in the IBM DOS. Names must be eight letters or less and may include a suffix (or extension) of up to three letters. This suffix is separated from the file name by a period (.). The characters that can be used in these file names are listed in the IBM manuals.

The name chosen for the input data-file is completely under the user's choice.

The first program, DWRITER, is an editor that produces an input data-file with a name chosen by the user. The TRED4 program reads this data, does some computations, and writes data to an intermediate file. No choice is available for this file name. This name consists of the root of the input data-file (file name minus the suffix) with a suffix of .INT added to it. Similarly, the .INT file is read by TRED5v2 and processed. The .INT file is then renamed so it has a suffix of .PRT, and new data is added to it.

2.1.2 Names of files

Because these programs and the IBM DOS overwrite files with the same name without warning the user, some precautions are necessary.

First, names longer than eight letters are truncated at the eighth letter. Therefore, if a file named PARAGUAY.DAT exists on a disk and a new file with the name PARAGUAY2.DAT is written to the disk, the original file will be overwritten and lost. (The ninth character of PARAGUAY2, (2), is lost, making the file name PARAGUAY.DAT) It's up to the user to select names of eight letters or less.

Second, the intermediate files created by the different programs may inadvertently overwrite another file. If an input data-file named CHILE is created by the user and processed by TRED4, a file named CHILE.INT is created. Now if another input data-file named CHILE.DAT is created by the user and processed by TRED4, its intermediate file will also be named CHILE.INT, and will overwrite the original file.

Third, if an input data-file is edited and it is not run through the simulation programs, it is possible to have results in a .PRT file that don't correspond to the input data. It will not be obvious by looking at the filenames that this has occurred. If an input data-file is changed, erase the .INT or .PRT file associated with it.

2.1.3 Using routines out of order

In most cases, the programs will be used from top to bottom as shown in figure 2.1. If for any reason you want to get out of one section and go to another one, press the F9 function key (if the program is waiting for some input from you, you may have to also hit ENTER). This will return you to the main menu.

2.1.4 Ending the program

For simplicity, entry into and exit from the programs is always through NSM under normal program use. It is recommended that you always exit through NSM, because this ensures that any files that have been opened will be closed. Switching off the main power when a file is open may result in a lost cluster disk error which generally makes a data file unusable.

At times, the user may wish to bail out of the program. The bail-out is accomplished by pressing the F10 key. If the program is waiting for input from the user, F10 needs to be followed by ENTER, but if the program is running, F10 alone is enough. This bail-out closes any open files and returns the user to DOS.

Because the programs are in BASICA, the CTRL BREAK sequence of keys will stop execution. This will leave opened files open. If the power is switched off, data files may be made unusable. Open files may be closed by typing END, which leaves the user in BASICA, or SYSTEM, which returns the user to DOS.

2.1.5 Finding filenames

At times the program requires that you supply a filename. Whenever you are prompted for a filename you have the option of typing a ? This will list the directory of any disk you specify, and is helpful to check spellings or to see what is available.

2.1.6 Untrapped errors

While error trapping is used in these programs, it is not extensive enough to catch every possible mistake. If a program prints an error message and stops, you will be left in BASICA. You can restart the program by typing **RUN**, or exit to DOS by typing **SYSTEM**

2.2 Program Specifics

2.2.1 SETUP.BAT

If you understand the use of the DOS COPY command, this batch file is unnecessary. Its purpose is to copy BASICA.COM to the NSM program disk. As long as BASICA.COM ends up on the NSM program disk, it makes no difference how it gets there. See section 1.1 for information on how to use this file.

2.2.2 NSM.BAT

This is a one line batch file that loads BASICA and runs the NSM.BAS program. It was included rather than explaining how to load BASICA and run a program from there. Typing:

```
NSM
```

from DOS executes this file.

2.2.3 NSM.BAS

This program serves as the main menu, and runs the program appropriate to the user's request. The programs which it runs are explained in more detail below.

In addition to running programs, it can also provide a directory of a disk. On disks that have subdirectories, it is necessary to follow the name of the subdirectory with a slash (\) in order to see the files contained within. Otherwise, the command will just ascertain whether that subdirectory exists. For example, typing in:

```
A:\TEST\
```

will list all files and sub-subdirectories in the TEST directory of the A: drive, while

```
A:\TEST
```

will just check to see if there is a TEST subdirectory on the A: drive.

2.2.4 DWRITER.BAS

DWRITER is an input data-file editor. The advantage of using DWRITER to create files is that their format will always be correct. For those who wish to use another editor, or to link the output of another program into NSM, Appendix A provides the file format.

DWRITER does not require a graphics adapter. This allows input data-files to be created on all IBM PC's with a disk drive. Subsequent programs that do require the graphics adapter can then be run at a later time.

A title will appear when this program is run, and after a short delay, a four choice menu will appear. Chose the **number** of the option you would like to use, as explained below.

2.2.4.1 1. Create a file

As it says, this is used to start an input data-file. By answering the questions, a data file with the correct format will be produced.

The first request is for the name of the file to be created. DWRITER checks to see if this file exists, and warns you if it does. You then have the option of over-writing it or supplying another name.

Some of the prompts that follow are straightforward, while the others listed below need a bit of explanation.

elevation: if not known, hit ENTER. This enters a -100 in this data field which is ignored by the programs. Units need not be specified here.

units: the system of units used (either Inches or Millimeters) for precipitation. This sets the prompt for temperature to the appropriate unit (Fahrenheit or Celsius). While you can enter site data in either system of units, TRED4 is going to convert English to metric before it begins processing.

monthly precipitation and temperatures can be in either English (inches) or metric (mm) units. The prompt is set by the entry for *units* (above). Don't mix the two systems.

record length can be filled out in one of two ways. Either enter the starting year and ending year of the record of temperature and precipitation, one per data field or enter the record length two times (repeat it in each field).

2.2.4.2 2. Edit a file

In order to use this option, a file must exist; it is not possible to create a file using Edit. If there is a file, it is possible to change any, all, or none of its contents. Additionally, you have the option of saving the old version or writing over and erasing it.

In creating a file, your responses cannot be changed once they have been entered. Correcting these typos is the main purpose of option 2. If option 2 is chosen immediately after creating a file, you will be asked if you would like to edit the newly created file. Otherwise, if no file was created, or you reply N, you will be asked for the name of the file to be edited.

Because this editor only accepts and produces a data file of one format, it is not useful to edit the .INT or .PRT data files. Editing these files is really not necessary because they're filled with calculated information based on the input file. To update them, re-run the program.

In the Edit mode, data files take up two display screens. When the editor starts, it will display page 1. To go to page 2 at any time, press function key F2. Viewing page 1 is done by pressing F1. The screens can be accessed as many times as you desire.

It is important to realize that this is not a screen-type editor; don't try to change the information on the screen. To change an entry, use the arrow keys to locate the cursor on the entry to be changed (not its heading). Press ENTER. The screen will be replaced by a prompt at the upper left asking for the new information. This serves as a check to make sure you are changing the correct entry. Type the correction and hit ENTER. You must type an entry. Otherwise, just hitting ENTER will place a zero or an empty string in this data field. Upon hitting ENTER, the updated screen will appear.

To stop editing and write the file, press F3.

If a file on the disk shares the same name as the one you're working on, you'll be asked if you'd like to overwrite it. Usually the reply to this question will be Y because you are correcting mistakes and want to get rid of them. Sometimes however, it's instructive to vary the input file slightly to see how the results change. In this case you would want to keep the original as well as the edited file.

The actions of function keys F1 through F3 are displayed at the bottom of the screen to help the user recall their purpose. (F9 and F10, which are active in the programs, are also displayed.) When using any of the function keys, cursor location is unimportant.

2.2.4.3 3. See a directory of a disk

This option is the same as that explained in the NSM.BAS section.

2.2.4.4 4. Start processing a file

Selecting this will link to the next program. You are asked if you would like to run TRED4 with the last data file created or edited. If you reply "Y", TRED4 will execute without asking for a file name; "N" means TRED4 will prompt you for an input data-file name.

2.2.5 TRED4

When run, the first thing the TRED4 program does is check for the presence of the graphics adapter card. If it is not found, an error message is printed and the program ends. Therefore, if you are uncertain about whether a graphics adapter is present in your computer, the easiest way to check might be to run this program.

The first visible thing that should appear is a title screen. This graphic is stored as a file called TITLE.BAS. TRED4 expects to find this file in the default drive. If the file isn't found, you are reminded to place the NSM disk in the default drive, and the program ends.

TRED4 calculates potential evapotranspiration (PET) and displays a graph of monthly PET and monthly precipitation. After the information has been graphically displayed, you are asked if you would like a printout of the graph. This printout will always use metric units, because this is what the programs all use. It uses text characters to optimize compatibility with printers, and adjusts the scale so that the whole graph is always used (unlike the screen display). Therefore at first glance, it may appear to be different than your input file and/or the screen display. However it's accurate to 2%. (Note: on PCs there will be a 1-1/2 minute delay while the graph is prepared for printing.) After you have answered "Y" or "N" to the prompt for the graph, the .INT file will be written and you'll be asked if you want to proceed on to TRED5v2. Replying Y to this will link to the next program, TRED5v2; N returns you to the main menu.

2.2.6 TRED5v2

This is the workhorse of this series of programs. Because it is doing so much, delays will occur--be patient until you are familiar with the length of these. Actual running speed is dependent on computer hardware--an AT will run faster than a PC (a PC requires about 10 minutes).

If the programs are used in order, you will not be asked for a file name at the outset. A file name will need to be supplied if you use a pre-processed file and jump into this section. The file name you supply at this point must have a suffix or .INT or .PRT and be of the correct format.

You have the option to see an explanation of the Newhall Simulation Model. This is useful the first few times the program is used, or as a refresher. It is a brief explanation of the model and is optional. Appendix B provides a detailed explanation.

If you don't chose to see the explanation, there will be a delay as the program runs the data until equilibrium is reached. As this is happening, dots will appear on the screen. Each dot represents a month. A steady state is usually reached within two years.

Two function keys (F1 and F2) are enabled during this program. F1 causes the program to pause until a key is pressed. Although you are only told of its function when the graphics are running, it actually works at any time. Sound effects are used as the soil profile fills and depletes. As these can become annoying, they can be toggled on or off using F2. When using sound effects on PC's, it is normal for the sound to lag behind the action.

Three colors are used in the large moisture calendar: violet for a moist period, aqua for a moist/dry period and the orange background color (which appears as no color) for dry periods. The smaller profile uses violet for sections that contain water and the orange background for dry areas.

The program will beep when certain squares in the profile are either filled or emptied (leftmost column, rows 2, 3, and 4). This occurs whether the sound is on or off. The Newhall model uses these squares to determine the state of the moisture control section (see appendix B.) and the beeps signal a possible change.

When the graphics have finished, one of two things will happen depending on the kind of file used for input. If an .INT file is used (as when the programs automatically link together), the program checks the disk to see if an associated .PRT file exists and, if found, erases it. The data file's .INT suffix is then changed to .PRT and new data is written to the end of the file. In other words, if TRED5v2 uses an .INT file for input, it will replace the .PRT file.

If, however, you re-run TRED5v2 using a .PRT file for input, nothing is written to the disk at TRED5v2's conclusion. The .PRT file used for input is left unchanged.

In either case, at the conclusion of TRED5v2 you have the option of returning to the main menu or continuing on to display the results.

2.2.7 TRED6

All of the information calculated by or given to NSM is displayed by TRED6. The completed file produced by TRED5v2 (*filename*.PRT) is not formatted for easy reading, hence the reason for a display program.

TRED6 can only use a .PRT file. This is a data file that has been run through TRED5v2 and contains all the information calculated by these programs.

Information can be displayed on the monitor or on a printer. A summary of the input file data, monthly evapotranspiration, moisture and/or temperature calendars, tentative subdivision, and moisture and temperature regimes are displayed.

One of two printout styles will be used. Depending on the input data, the printout will either contain both a moisture and temperature calendar or the printout will just contain a moisture calendar. The other types of information are the same type on both styles of printouts.

2.3 Other notes

Error checking is used throughout all the programs to catch the more likely errors. When an error is caught, the user is notified about the problem and a correction is suggested. However, when an error occurs that was not anticipated, error checking is turned back over to the IBM system so it will print out the error message, and then the program ends. Errors might be as simple as the disk being full or the disk drive door being left open. When this occurs, the user will be left in the BASICA language, as shown by the OK prompt that will appear on the screen. To return to DOS, type **SYSTEM**.

Files may be left open if error checking fails, so make sure that you type **END** or **SYSTEM** before turning off the power. Either of these commands will close any opened files and protect your data.

Because the error checking routines were not checked for every possible error that could occur, erroneous messages might be printed. Only as a last resort should this be suspected as the problem. A person with some familiarity with BASICA should then be able to interrupt the program and print out the code of the error that is occurring. If an untrapped error occurs, you will be left in BASICA. Type **RUN** to restart the program or **SYSTEM** to return to DOS.

We hope that problems of this nature have been weeded out, and would appreciate your comments for improvement.

Appendix A

Format for input data-file

```
"PONCE","PR",18,1,"N",66,36,"W",-100
 .67 , .73 , .31 , 2.43 , 1.99 ,
9.76 , .76 , 2.65 , 2.05 , 7.04 ,
3.52 , 1.76 , 74.32 , 74.89 , 75.94
, 77.65 , 79.4 , 80.18 , 80.39 ,
79.97 , 80.33 , 79.26 , 77.9 , 76.4
,22,18,"E"
```

The format of an input data file is reproduced above. All entries are separated with commas except for one (which is followed by a return) and text is enclosed in quotation marks. Due to the size limitation of this paper, it is not possible to represent the file exactly as it is on the disk, the difference being that all the numbers following the -100 entry are on one continuous line on the disk. The -100 is the only entry to be followed by a return.

On the next page is another input data file, but this one has superscripts added to identify the data. These superscripts do not appear on the disk and are only for the purpose of identification here.

```
"SANDPOINT"[1], "USA"[2], 48[3], 17[4], "N"[5],
116[6], 34[7], "W"[8], 640[9]
114[10] , 84 , 75 , 50 , 52 , 59 , 16
, 21 , 43 , 86 , 107 , 124 ,-3.6[11]
,-1.6 , 2.2 , 7.7 , 12.1 , 15.2 ,
18.5 , 17.4 , 13.4 , 7.8 , 1.6
,-1.3 ,0[12],0[13],"M"[14]
```

1. Station name

2. Country

3. Degrees latitude

4. Minutes latitude

5. Latitude hemisphere

6. Degrees longitude

7. Minutes longitude

8. Longitude hemisphere

9. Elevation

10. The next 12 entries are monthly average precipitations.

11. The next 12 entries are monthly average temperatures.

12. Starting year of climatic data (or length of data in years)

13. Last year of climatic data (or repeat data in field 12)

14. Units used for climatic data.

Appendix B

The Newhall Simulation Model[1]

B.1 Preliminary Assumptions

B.1.1 The Soil Moisture Profile

The soil moisture profile considered by the model extends from the surface down to a depth of an available water holding capacity (AWC) of 200 mm (8 inches).

The profile is divided into 8 layers which each retain 25 mm of available water; the second and third layer form the **moisture control section** (fig. B.1). It is defined as the layer having an upper boundary at the depth to which a dry (tension of more than 1500 kPa) but not air dry soil will be moistened by 25 mm of water moving downward from the surface within 24 hours. The lower boundary is the depth to which a dry soil will be moistened by 75 mm of water moving downward from the surface within 48 hours.

---

[1] taken from A.Van Wambeke, Asia Soil Moisture Regimes SMSS Technical Monograph #9, 1985.

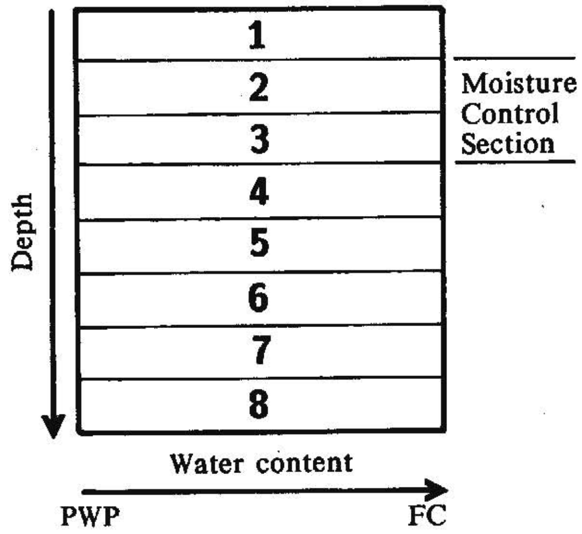

Figure B.1: The soil moisture profile

Figure B.1 represents a soil. The vertical axis indicates the depth of the 8 layers, and the horizontal axis scales the percentages of available water present in each of them. The tension at which the water is held in the profile decreases from left (permanent wilting point ,PWP) to right (field capacity, FC). Each layer can be divided into 8 slots to form an 8 by 8 square matrix of 64 slots. This is termed the *soil moisture diagram*, and is shown in table B.1. Each slot can be filled with a value corresponding to an amount of water which can vary between 0 and 1/64th of the total available water holding capacity, or 3.125 mm.

B.1.2 Water Uptake and Water Removal

The model simulates the **downward movement of moisture** into the soil as the progression of a wetting front; it is further referred to as **accretion**. The distance that the wetting front moves downward depends on the amount of water needed to bring all the soil above it to field capacity.

When the wetting front reaches the bottom of the profile and all the soil above it is at field capacity, the **excess water** is lost either by **percolation** or by **runoff**.

The rate of removal of water out of the soil, or **depletion**, depends on the energy available for moisture extraction, expressed in terms of **potential evapotranspiration**, and the plants growing in the soil. The energy required to remove moisture from the soil depends on the amount of water (AW) present and the force exerted by the soil to retain it. Water is removed more readily at low tensions than when the water content is at a minimum.

Less energy is used by the model to remove water from the upper layers of a soil than from the lower layers. The **depth** at which moisture is located in the profile influences the time needed to extract it from the soil; this is also in line with the fact that roots are more abundant near the surface than in deep layers.

Depletion continues until the soil is at wilting point, that is, when the soil moisture tension is 1500 kPa. The amount of water held in the soil is assumed not to be reduced below the amount held at 1500 kPa.

B.1.3 The Climatic Factors

The distribution of rainfall--The monthly precipitation (MP) is assumed to be distributed within each month according to the following sequence:

(a) One half of the monthly precipitation (HP for **heavy precipitation**) falls during one storm in the middle of the month; this moisture enters the soil immediately without losses, except when the available water capacity is exceeded.

(b) One half of the monthly precipitation (LP for **light precipitation**) occurs as several light falls, and is partly lost by evapotranspiration before it can enter the soil; it can only infiltrate into the soil when LP exceeds the potential evapotranspiration.

The potential evapotranspiration is assumed to be uniformly distributed during each month. Not all its energy is used to extract water from the soil. A part is used to dissipate as much light precipitation as possible before it reaches the soil. If there is surplus energy, it is used for water extraction from the profile.

B.2 The Time-Step Progression of the Model

Each month has 30 days and is divided onto 3 parts. The first is a 15-day period of light precipitation (LP), the second is the heavy rainfall (HP) which occurs at midnight between the 15th and 16th of the month, and the third corresponds to another fortnight of light precipitation.

For each of these events, water is either added to the soil or extracted from it. At the completion of the step, the *moisture condition* of the soil is determined, and if it changed, the model computes the number of days that each condition prevailed in the moisture control section.

The **starting** soil moisture condition of the profile is determined by running the simulation program for a number of consecutive iterations using the same input each year. When the moisture content for December 30th does not differ by more than 1 percent from that of the preceding December 30th, the program then starts the diagnostic processing of monthly data. The initial amount of water is the amount present on December 30th.

When all the months are processed, the soil moisture conditions for each day are combined into the **moisture condition calendar** which forms the data base for the determination of the soil moisture regime according to *Soil Taxonomy*.

B.2.1 Processing Sequence During One Year

Each half-month interval is processed using monthly precipitation (MP) and monthly potential evapotranspiration (PE). The steps are as follows.

(a) compute light precipitation (LP), where

$$LP = MP/2$$

(b) Compute the net potential evapotranspiration (NPE):

$$NPE = (LP - PE)/2$$

if $NPE > 0$, accretion will take place during the period being processed; if $NPE < 0$, the profile will be depleted.

All heavy precipitations in the middle of the month are processed using the following inputs.

(a) compute heavy precipitation (HP), where

$$HP = MP/2$$

(b) enter this amount in the profile as accretion.

B.2.2 Changes in Water Content During Each Period

B.2.2.1 Accretion

To simulate the additions of moisture to the profile, water enters the soil in each empty slot following the specific order shown in table B.1.

Table B.1. Soil moisture diagram and slot sequence during accretion

01	02	03	04	05	06	07	08
09	10	11	12	13	14	15	16
17	18	19	20	21	22	23	24
25	26	27	28	29	30	31	32
33	34	35	36	37	38	39	40
41	42	43	44	45	46	47	48
49	50	51	52	53	54	55	56
57	58	59	60	61	62	63	64

The sequence starts with the left slot in the top row. Water is added to each successive slot in a row until the row is filled or until the water supply is exhausted. When a layer of slots has been filled, the program proceeds with the immediately underlying layer, starting again with the left side of the moisture diagram.

By following the specified order and preventing the accretion of moisture into one layer until the layer above is completely filled, the arithmetic model approximates a downward advancing wetting front.

B.2.2.2 Depletion

In simulating the extraction of water from the profile, the slots are processed in a different order. The sequence starts with the top right-hand slot and scans the slots in successive right-downward diagonals (table B.2).

Table B.2. Sequence of slots during depletion

29	22	16	11	07	04	02	01
37	30	23	17	12	08	05	03
44	38	31	24	18	13	09	06
50	45	39	32	25	19	14	10
55	51	46	40	33	26	20	15
59	56	52	47	41	34	27	21
62	60	57	53	48	42	35	28
64	63	61	58	54	49	43	36

During the sequence each slot is examined, and if water is present, it is removed from the slot. The depletion stops when the potential evapotranspiration, or the energy it represents for the period being processed, is exhausted.

The rate of depletion is inversely proportional to the tension under which the water is held. It also varies with the depth of the layer. Both factors are taken into account in the calculations by means of the *depletion requirement diagram* which indicates the value by which a unit of energy (expressed as evapotranspiration) has to be multiplied to extract 1 unit of water from the soil. This matrix of values is given in table B.3.

Table B.3. Depletion requirement diagram

1.65	1.40	1.23	1.13	1.05	1.00	1.00	1.00
2.07	1.69	1.43	1.26	1.15	1.07	1.02	1.00
2.68	2.14	1.74	1.46	1.28	1.17	1.09	1.00
3.58	2.80	2.22	1.78	1.49	1.31	1.19	1.11
4.98	3.80	2.93	2.30	1.84	1.53	1.34	1.21
5.00	5.00	4.03	3.07	2.38	1.89	1.57	1.37
5.00	5.00	5.00	4.31	3.22	2.47	1.95	1.61
5.00	5.00	5.00	5.00	4.62	3.39	2.57	2.01

The processing continues until the entire evapotranspiration potential has been used, or until all the slots have been set to 0. In the latter case, any remaining depletion amount is not carried forward but is discarded.

B.2.2.3 Definitions of Soil Moisture Conditions

Soil Taxonomy recognizes 3 soil moisture conditions. They are diagnostic for compiling the moisture regime of a pedon, and are evaluated in the moisture control section.

(a) The moisture control section is *dry in all parts.* It is also called **completely dry.**

This occurs when the leftmost slots, numbered 9, 17, and 25 in table B.1, are all empty.

(b) The moisture control section is *moist in all parts*, or **completely moist.**

This occurs when none of the leftmost slots, numbered 9,17, and 25 in table B.1, are empty.

(c) The moisture control section is *dry in some parts* or *moist in some parts.* It is also called **partly dry** or **partly moist.**

The Newhall model considers this condition only when the moisture control section does not fulfill the requirements for either (a) or (b).

The Newhall model uses slot 25, which is located outside the moisture control section (MCS), to determine the soil moisture condition. In an accretion step, this slot signals that the MCS is completely filled. In a depletion sequence, it increases the amount of water to be extracted from the soil before a change to a completely dry condition is recorded. The inclusion of slot 25 and the diagonal extraction pattern compensate in part for the fact that the model ignores all upward movements of water in the soil. In reality, upward water movement does participate in the moisture supply to the MCS.

B.2.3 Number of Days of Moisture Conditions in each Period

If the moisture condition changes during a period of light precipitation, the relative durations of each moisture condition are computed. The following equations are used:

$$DX = 15 * RPEX/NPE$$

where DX is the duration in days of condition X, and RPEX is the amount of potential evapotranspiration needed to change this condition into the next one (for example, from completely moist to partly moist). NPE is the potential evapotranspiration which was available during the half-month being processed.

The duration of the moisture condition which ends a half-month is calculated by the difference, or:

$$DE = 15 - DX - DX2$$

where DE is the duration of the soil moisture condition which ends the half-month and where DX and DX2 are the durations of the preceding conditions.

The same equations are used when the conditions change from dry conditions into more humid ones. In this case, rainfall instead of evapotranspiration is used to compute the number of days.

B.2.4 Changes in Soil Temperature

The beginning and ending dates of the time when the soil temperature is above or below a critical value, i.e. 5 or 8 degrees C, is approximated from the sequence of mean monthly temperatures.

The onset of a period when the soil temperature rises above a critical level is obtained by linear interpolation between it and the 15th of each month. 21 days are then added to this date to compensate for the time lag between air and soil temperature.

The date at which a soil temperature falls below a critical level is calculated following a similar process, except that 10 days are added to the result.

Appendix C

Key to Soil Moisture Regimes

Soil Taxonomy has a terminology which is based on the length of the time that the soil moisture control section is completely dry, partly moist, or completely moist. A simplified key, valid for well drained soils, leads to the identification of soil moisture regimes on the basis of these criteria.

Key to Soil Moisture Regimes, except Aquic.

All moisture conditions are assumed to occur in more than five years out of ten.

1. *The moisture control section is completely dry more than half of the time (cumulative) that the soil temperature is over 5 degrees C*
if true, go to ...2 if false, go to...3

2. *When the soil temperature is over 8 degrees C, the moisture control section is partly or completely moist for 90 consecutive days or more*
if true, go to....3 if false: ARIDIC

3. *The mean annual soil temperature is less than 22 degrees C*
if true, go to....4 if false, go to...7

4. *The difference between winter and summer*[1] *soil temperatures at 50 cm depth is equal or higher than 5 degrees C*
   if true, go to....5 if false, go to...7

5. *Within the four months that follow the summer solstice*[2] *the moisture control section is completely dry for at least 45 consecutive days*
   if true, go to....6 if false, go to...7

6. *Within the four months that follow the winter solstice the moisture control section is completely moist for at least 45 consecutive days*
   if true: XERIC if false, go to...7

7. *The moisture control section is completely dry or partly dry for 90 cumulative days or more*
   if true, go to....8 if false, go to...9

8. *The soil temperature regime is warmer than cryic*
   if true: USTIC if false:UNDEFINED

9. *The precipitation exceeds evapotranspiration in all months*
   if true: PERUDIC if false: UDIC

All soil moisture regimes, except Xeric, occur in the tropics. The sequence from most humid to the driest is Perudic, Udic, Ustic and Aridic. The limit between Ustic and Udic sometimes, but not always, coincides with the boundary between rainforests and savannahs. A udic moisture regime is assumed to provide enough water for a rainforest to return after being cleared and the soils cropped

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[1] Winter or summer temperatures refer to averages of December, January, February or June, July, August

[2] The four month period begins the first of the month after the solstice occurs

for a short period. Soils with an aridic moisture regime theoretically cannot produce crops without supplemental irrigation.

B. The Aquic Moisture Regime

The aquic moisture regime implies a reducing regime that is virtually free of dissolved oxygen because the soil is saturated by groundwater or by water of the capillary fringe. The aquic moisture regime is a reducing one, by the presence of electron donors provided by organic matter.