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THE RELATIONSHIP OF THE THERMAL REGIME OF THE SOIL TO THE EXTRINSIC ENVIRONMENT; WITH SPECIAL REFERENCE TO THE NORTH CENTRAL UNITED STATES

by

Jack T. Dugan

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Under the Supervision of Professor Merlin P. Lawson

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TITLE

THE RELATIONSHIP OF THE THERMAL REGIME OF THE SOIL TO THE EXTRINSIC ENVIRONMENT; WITH SPECIAL REFERENCE TO THE NORTH CENTRAL UNITED STATES

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CHAPTER I

INTRODUCTION

The Problem

It has long been evident that a strong relationship exists between the thermal regime of the earth's surface and other climatological and meteorological events. Micro as well as macro aspects of the atmosphere are highly dependent upon thermal conditions of the soil. The mechanism by which the atmosphere is indirectly heated by shortwave solar radiation as it is absorbed by the earth, converted to sensible heat (longwave infrared), and transmitted back to the atmosphere and space is conceptually well-understood. The diurnal and seasonal heating and cooling of the atmosphere, which is intensively monitored and documented, is parallel to thermal processes occurring in the soil. There are apparent relationships between soil temperature and such events as: tornado genesis ('hot spot' concept), drought intensification, fog, and frost occurrence (Blanc, 1958; Landsberg and Blanc, 1958; Chang, 1958; Carson, 1961, Namais, 1960). Furthermore, temperature plays a key role in soil formation, soil moisture movement, evapotranspiration demands, and biological activities in the soil (Shaw, 1952, Sutton, 1953; Lettau, 1957, Geiger, 1965).

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° is a thermal pan to roots of most plants. The soil does not really come to life until its temperature exceeds 42°F...(G. D. Smith and others, 1964: 1)

It is, therefore, apparent that soil temperature is important to meteorological processes and biological activities. The earth is analogous to a heat reservoir for the atmosphere; however, a feedback mechanism exists in the relationship that allows the atmosphere to imprint its attributes back upon the earth's surface. This latter aspect has received only cursory treatment because of the difficulty in measuring the direction and magnitude of the interrelationship. Landsberg and Blanc (1958) point out the existence of this mutual relationship; but also emphasize that the two phenomena, soil and atmosphere, have rarely been analyzed simultaneously, but as independent entities. Many studies have provided crude comparisons between the temperature of the soil and various atmospheric conditions. A few have examined this relationship in detail on a microscale, but under very controlled experimental conditions. These studies have usually been limited to single sites for short periods of time. The applicability of their results to other sites and conditions is debatable.

The key problem to be addressed in this study is the strength of the relationship between soil and atmospheric

temperature. Intuitively, a strong positive relationship should exist between their thermal responses. The consistency of this relationship, both temporally and spatially; however, is a significant aspect to be examined. Is the temperature relationship constant over time or do seasonal changes occur? Do relationships change from place to place? Do other factors, both intrinsic and extrinsic to the soil, alter this relationship appreciably? It appears that an examination of the soil-atmospheric relationship over a large number of sites with long-term data can produce a better understanding of this interaction. Anomalies that occasionally occur can be minimized and more stable relationships established.

A second problem is the relative influence other factors, both intrinsic and extrinsic to the soil, have in the thermal relationships between the soil and atmosphere. Soil is a very complex medium, which can vary over a wide continuum. The intrinsic characteristics of the soil (texture, structure, chemical composition, compaction, topographic position, color, organic content, moisture content, cover, etc.) must have an appreciable effect on its thermal properties. Furthermore, other factors external to soil, such as solar radiation and precipitation, must be considered in the heating and cooling of the soil, in addition to air temperature.

The preceding problem creates the question of which variables related to soil temperature are to be initially

considered. Obviously, numerous factors can be considered for inclusion, but many are essentially impossible to quantatively evaluate. Others are so subject to change over time and space that their measurement premised on uniform conditions is tenuous at best. Therefore, only those conceptually significant factors that are suited to a reliable system of quantative measurement can be included. The literature should provide some guidelines to those factors influencing soil temperature. Most intensive research on the subject has been laboratory-type experiments for which detailed information on the physical characteristics of the soil was obtained, data that are not commonly available. Certain variables must, therefore, be excluded for lack of data and surrogate measurements developed for others.

A secondary problem is what time scale is most optimal in an analysis of soil-atmosphere relationships. Published data usually consists of multiple daily observations or monthly summations. The former would involve an unwieldly number of observations. The latter would be too gross to reveal the sensitivity among the variables. Furthermore, an analysis on a daily basis would probably result in highly unstable relationships, while on a monthly basis seasonal trends would be somewhat obscured. An intermediate time frame that retains some of the sensitivity of daily data and the convenience of monthly data appears to be optimal.

To summarize the three perceived problems in this study,

the first two are substantive and the third technical:

1. How strong and consistent is the relationship between soil and atmospheric temperature?
2. What other factors, both internal and external to the soil, have an effect on soil temperature and how significant are they to the thermal response of the soil?
3. What time scale provides the most sensitive, yet stable relationship between soil temperature and those factors influencing it?

Objectives of the Study

Within the framework of the problems set forth above, the following are the objectives of this study:

1. Determine those variables that influence soil temperature and to gain a perspective on the thermal processes occurring within the soil.
2. Provide a refined and/or more simplified method of predicting soil temperatures from other climatic parameters.
3. To aide materially in the understanding of the mechanism operating with respect to the thermal response of the soil.
4. Establish more firmly the relationship between atmospheric and soil temperatures.
5. Account for deviations in predicted soil temperatures from actual observations.
6. Provide a detailed analysis of temporal patterns of soil temperatures on a spatial basis in a significant agricultural region.

7. Analyze the spatial patterns of soil temperature in the study area.

The above objectives are not all inclusive, but provide a guide to the major emphasis of this study. Secondary objectives are inherent in the achievement of the major goals of this study.

Research in Soil Temperature Estimation

With the relative paucity of direct soil temperature observations, considerable research has been devoted to estimating the temperature of the soil. Two principal approaches have been followed in this prediction process. One technique, the heat transference approach, attempts to project temperatures at various depths and time from a limited number of soil temperature observations. The other method, the extrinsic approach attempts to estimate soil temperatures from meteorological or climatological conditions. The two are fundamentally different in that the former is only concerned with temperature changes in the soil profile, while the latter relates to the interrelationships between the soil and the external environment.

Studies in Soil Heat Transference

Soil temperature estimation for given depths and times from other soil temperature observations are generally based on heat flow equations for homogeneous, isotropic, semi-infinite media, known as the Fourier series (Shaw, 1952: 326; Fluker, 1958: 46). Expressed as:

$$\left(\frac{dt}{dr}\right) = \left(\frac{dt^2}{dx^2}\right) \qquad (1)$$

Where: t = temperature
r = time
x = distance

(Penrod and others, 1960: 275).

The solution to the equation requires several empirically derived parameters, such as thermal conductivity, thermal diffusivity, and specific and volumetric heat capacities.[1] Thus, to estimate soil temperature change through time and with depth, extensive information about a particular soil's thermal properties is required. Studies utilizing Fourier analysis have been generally confined to single sites for a limited time period where the physical properties of the soil can be

---

[1] Thermal conductivity is the quantity of heat flowing per unit of time through a unit area of material of a given thickness, usually expressed in cal./cm./sec./C° (Chang, 1958: 28). Generally, the greater the conductivity of the soil, the smaller the temperature gradient. Soil moisture is the most significant parameter affecting conductivity.

Thermal diffusivity is the change in temperature per unit area per unit of time, expressed as: C°/cm.^{2}/sec.

Specific heat capacity of the soil is the heat required to produce a given change in the temperature of a given mass, expressed as cal./gm./C°. For most soils it ranges from .17 to .26 cal./gm./C° (Bouyoucos, 1913; Kersten, 1949).

Volumetric heat capacity is the heat required to produce a given temperature change per given volume expressed as cal./cm.^{3}/C°. For most soils values usually range from .29 to .70 (W. O. Smith, 1939; Kersten, 1949).

measured and the soil moisture conditions continuously monitored. This research belongs in the realm of laboratory analysis, but are of great value in understanding soil temperature phase-lag and amplitude, moisture movement, and other processes occurring in the soil.

The early work done with heat transference in the soil was by Patten (1909). His methodology, while simplistic, emphasized the importance of thermal diffusivity in temperature changes of the soil. Langbein (1949) attempted to compute soil temperatures at depths in soil from surface temperatures by expressing the variations in soil temperature as a weighted mean of the antecedent surface temperature. Fourier analysis was used to compute the amplitudes of simple periodic curves (sine curves) for changing depths. Fluker (1958) compared actual soil temperature observations with sinusoidal curves for a series of depths and derived a general equation to describe the annual temperature variations observed at various depths at College Station, Texas. Penrod and others (1960), using techniques similar to Fluker, compared solar radiation observations to temperature gradients of the soil in Kentucky. It was concluded that the soil absorbs more energy than it transmits to the atmosphere and space from March to September when temperature gradients are negative (temperatures decrease with depth). During the remainder of the year when the gradients are positive (temperatures increase with depth), more heat is transmitted than absorbed.

Carson (1961) applied harmonic Fourier analysis to the ten day mean of temperature to determine average relationships at Argonne, Illinois. His analysis found that the logrithmic values of temperature amplitudes decrease linearly with depth; and the time lag of extreme temperatures increased linearly with depths below 10 cm. (4 inches) (Carson, 1961: 91). Analyzing the heat exchange process in the soil and changes in monthly soil temperature, Carson and Moses (1963) derived monthly values for the gain or loss of heat energy from the soil. They confirmed the findings by Penrod and others (1960) that energy was gained by the soil from March through September and lost from October through February. Values for this monthly gain or loss of heat in calories per square centimeter per day were provided. The greatest heat exchanges occurred in June (positive) and November (negative). These findings of daily heat exchange between the earth and atmosphere compare favorably with those reported by Lettau (1957) in experiments conducted near O'Neill, Nebraska. On a diurnal basis, the heat flux patterns between the soil and atmosphere are quite similar to those for net radiation (Carson and Moses, 1963: 404)

Wierenga and Wit (1970) and Hanks and others (1971) applied numerical methods to estimate subsoil temperatures from surface temperatures. Again, information on the physical and thermal properties of the particular soils were necessary to the studies. Wierenga and Wit (1970) found that soil

temperature gradients could be closely simulated in wet soils, but poorly represented in soils that were drying out. They concluded that the difference between computed and measured values were greater in dry soils because of more variable temperatures at the surface, resulting from lower specific and volumetric heat capacities. Hanks and others (1971) recommend that soil temperature observations be made at depths where evaporation is essentially zero and heat capacities rather constant.

Van Wijk and de Vries (Van Wijk, 1963) provide a very comprehensive review of the techniques utilized in several of the above reported studies. The principles and factors in the application of the theories of heat flow to soil temperatures are given good treatment. Richards and others (Shaw, 1952) and Chang (1958) provide more concise reviews of earlier studies on thermal processes in soil.

Several studies question the applicability of these heat flow theories to soil. Alfred Smith (1939) concludes that soil is not a homogeneous medium and that the fundamental differential equation for heat flow does not hold for soils under actual field conditions. Landsberg and Blanc (1958) maintain that the thermal properties of soil constantly change through time and with depth as moisture conditions and other meteorological elements vary.

Research in Climatological Relationships with Soil Temperature

Substantial literature exists concerning the relationship between climatological or meteorological conditions and soil temperatures. Only some of the more significant research will be related at this point. Many of these studies are basically descriptive and provide few analyses of these interrelationships. A few attempt some type of quantative analysis to measure the direction and strength of these relationships.

Bouyoucos (1913, 1916) performed some of the first extensive research into the factors influencing soil temperature. He concluded that the external factors or meteorological elements are the most significant factors to long term soil temperature regimes.

> "...the degree of soil temperature is almost wholly controlled by the external factors and especially the air temperature, but modified by the intrinsic factors. Inequality in temperature, therefore, in different kinds of soil during the same day will depend upon the intrinsic factors, but variations in temperature in any soil in succeeding days or seasons will depend upon the external factors.... In other words each type of soil possesses the various intrinsic factors in a compensating or neutralizing degree and consequently they all tend to have the same average temperature under the same meteorological elements." (Bouyoucos, 1916: 127-28).

The temperature of the soil is interrelated with many climatological or meteorological variables. Solar radiation, clarity of the atmosphere, precipitation, wind humidity, and air mass conditions all play significant roles in the thermal regime of the soil. Blanc (1958) and Landsberg and Blanc