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Early Warning and Crop Condition Assessment

July 1981

REVIEW OF LITERATURE RELATING TO THE MODELING OF SOIL TEMPERATURES BASED ON METEOROLOGICAL FACTORS

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16. Abstract

Literature review relating to the modeling of soil temperatures based on meteorological factors. Included in this review are:

1. Brief abstract of paper
2. Facorable aspects of paper
3. Limitations of paper
4. Applicability of this paper to the overall objectives for improvements to the winterkill model
5. Comments, notes and references

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REVIEW OF LITERATURE RELATING TO THE MODELING OF SOIL TEMPERATURES BASED ON METEOROLOGICAL FACTORS

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REVIEW OF LITERATURE RELATING TO THE MODELING OF SOIL TEMPERATURES BASED ON METEOROLOGICAL FACTORS

by

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April 20, 1981

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In connection with the AgRISTARS Program, this review of literature was conducted to fulfill a project objective of Task 8 entitled "Winterkill Model Improvements" in the Early Warning Crop Condition Assessment Project (EW/CCA). The title of this contributing project is "Study to Improve Winterkill Parameters for a Winter Wheat Model" and it has the following objectives:

1. To establish experimental sites at about five Agricultural Research Centers in Montana for monitoring soil and air temperature.
2. To make recordings at each site from about October 15 through April 15 of air temperature at the 2-meter height and of soil temperature at the 3-cm depth (a) on bare ground with snow cover removed, and (b) on bare ground with natural snow cover.
3. To conduct analytical studies directed to the development of a procedure(s) to estimate soil temperature at the 3-cm depth using air temperature data.

Preliminary to conducting analytical studies of the field data, this survey of the literature was undertaken by Kent H. Sandefer, a graduate student at Montana State University who has a Research Assistantship supported by this research program. Dr. Joseph M. Caprio, Principal Investigator, and Dr. Richard E. Lund, M.S.U. Mathematical Sciences Department, supervised the work.

AUTHOR INDEX

AUTHOR INDEX (Continued)

TITLE INDEX

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TITLE INDEX (Continued)

The reviewer's comments are listed in sections according to the following numerical system:

1) A brief abstract of the paper

2) Favorable aspects of the paper

3) Limitations of the paper

4) Applicability of the paper to this project

5) Other comments, notes and references

No. 1 File No. 2529

Title: Seasonal Subsoil Temperature Variations

Pub: Journal of Agricultural Research

Date: March 1, 1932 Vol: 44 No: 5 Pages: 421-428

Author: Smith, A.

1. The paper presents data collected on subsoil temperature for a two-year period between December 1928 and December 1930. The temperatures at depths from one foot to 12 feet were recorded weekly. The data are presented in graphical form and a qualitative agreement with theory is shown.

2.

3. No model was included in the paper, but reference is made to a book by Keen (p. 308 (1)) for a discussion of theory. The relationship of soil temperature and air temperature was not explored, nor was the influence of soil moisture on soil temperature.

4. Since no model was presented and no quantitative relationship discussed, the paper is of little use in the project.

5. (1) Keen, B. A.; The Physical Properties of the Soil: London, New York.

No. 2 File No. 3400

Title: Soil Temperature Modeling Using Air Temperature As A Driving Mechanism

Pub: Transactions of the ASAE

Date: Jan/Feb 1974 Vol: 17 No: 1 Pages: 78-81

Authors: Hasfurther, V. R.; Burman, R. D.

1. A mathematical model is used to predict soil temperature at various depths, given the soil temperature at a depth of one inch. An empirical relationship is found to predict soil temperature at one inch with the air temperature of the same day and two previous days. Then the one dimensional heat equation is used to predict soil temperature at other depths using the predicted temperature at the one inch level. The accuracy of prediction was $\pm$ 3°F. Errors are larger for greater depths.

2. Reasonable accuracy of prediction is demonstrated for soil temperature at various depths, based on knowledge of soil temperature at the one inch level. The data show a near linear relationship of air temperature and soil temperature at the one inch depth.

3. The linear relationship of air temperature and one inch level soil temperature is highly dependent on parameters unique to a particular site. Two sites were used, but comparison between the two sites are not made. No model is given to relate the parameters to soil properties or other influences.

4. Since the prediction is partially based on empirical equations and on a simple model of heat flow in the soil, ignoring moisture, etc., this paper has limited interest in the project.

5. Additional References:

Van Wizh, W. R., 1963
Physics of Plant Environment
North-Holland Publishing Co., Amsterdam 382 p.

Location of site for data collection was Archer, Wyoming

No. 3 File No. 1446

Title: A Statistical Procedure for Determining the Association Between Weather and Non-Measurement Biological Data

Pub: Agricultural Meteorology

Date: 1966 Vol: 3 No: 1-2 Pages: 55-72

Author: Caprio, J. M.

1. The paper gives a method of relating the general nature of environment input such as temperature and moisture to crop yield. For three week periods of a year, a frequency table is constructed as follows. The years are classified as good yield years, average yield years, or poor yield years. Then for each class of year the number of times a temperature, for example, was in excess of a preassigned value is found and tabled. A Chi-Squared statistic is caluclated to compare years to each other.

2. This approach has good flexibility and generality. It explicitly relates when and how long a high temperature condition can be related to a poor yield or good yield, rather than an average temperature for the month. How the temperature varies is as important or more important than the average temperature.

3. The information given by this approach would be hard to use to predict quantitatively. What are the effects of a 3-week cold period, for example, on winterkill or crop yield?

4. How the temperature varies with time would surely affect the winterkill, since the duration of a cold spell is as important as the average temperature.

5.

No. 4 File No. 1220

Title: Soil-Temperature Regimes, Their Characteristics and Predictability

Pub: U. S. Department of Agriculture

Date: April, 1964 Pages: 1-14

Authors: Smith, G. D.; Nowhall, F.; Robinson, L.; and Swanson, D.

1. The paper presents an extensive amount of data, in tables and in graphical form, about monthly average temperatures in the air and at various depths in soil.

It discusses the effects of ground cover on soil temperatures and moisture. It is concerned mainly with yearly and some monthly averages.

2. A source of data to compare with future models about long term predictions. Also some data on the effects of snow cover.

3. No quantitative model is given on heat flow changes caused by ground cover, snow, etc.

4. Useful for some data to test the validity of future models. Data are available on monthly averages of air and soil temperatures.

5. Data presented have been collected from around the world.

No. 5 File No. 1760

Title: Temperature of the Active Surface and its Bioclimatic Significance.

Pub: Gidromesoezdat, (Translated by Weather Bureau)

Date: 1960 Pages: 201-211

Author: Budyko, M. I.

1. The paper is concerned mainly with the effects of temperature, humidity, etc., on the comfort of plants and animal. Data are presented to show the difference in temperature between the air and the active surface of the ground and possible plant leaves, etc. It discusses the use of the heat balance equation.

2. It presents a fundamental equation of heat balance, for a land area and gives approximate values of some of the constants involved.

3. No reference is made to soil temperatures. Only basic equations are used in the discussion.

4. A discussion of the basic heat balance equation is presented. This is of little additional use in the project.

No. 6 File No. 486

Title: On the Thermal Conditions of Cultivated Peat Soil in Pelsonsuo in the years 1952-1955.

Pub: Finnish State Agricultural Research Board. No. 154

Date: 1957 No: 154 Pages: 1-47

Author: Pessi, Yrjo

1. Presents data collected on a plot in Pelsonsuo between 1952 and 1955 and a fairly complete history of snowfall on the plot as well as soil temperature at depth 5 cm, 10 cm, 20 cm, 50 cm, 100 cm is given. The temperature is presented in tabular form. The snow depth is provided in graphical form only.

2. A good source of data on soil temperature and snowfall.

3.

4. This paper demonstrates the importance of considering ground moisture on temperature, since one year was particularly wetter than normal and this shows up later in the temperature record. Also note evidence that the thermal conductivity increases with increasing depth in approximately a linear manner.

5. Thermal Conductivity in dry soil .00022 cal/cm sec C^o
Thermal Conductivity in wet soil .00107 cal/cm sec C^o

Additional References

Bouyoucas, Q. J., 1913
"An investigation of soil temperature and some of the most important factors influencing it."
Michigan Agr. Coll. Exp. Sta. Techn. Bul. 17: 1-196

Smith, W. O., 1939
"Soil temperature, thermal conductivities in moist soils."
Proc. Soil Sci. Soc. Amer. 4: 32-40.

_____, et. al., 1938
"The thermal conductivity of dry soils of certain of the great soil groups."
Proc. Soil Sci. Soc. Amer. 3: 13-19

No. 7 File No. 1348

Title: Climatological and Solar Radiation Relationships

Pub: Agr. Exp. Station, State College, Mississippi

Date: August 1965 No: 715 Pages: 1-35

Authors: McWhorter, J.P.; Brook, B. P.

1. Uses empirical relationships of solar radiation, evaporation rate, air temperature and soil temperature to predict solar radiation. A large amount of data is presented.

2. The data are given mainly in weekly averages of the above variables, but some daily averages, collected every six days, are also available for soil depths at four and eight inch intervals.

3.

4. Useful as a source of data to test models.

5. Most of the relationships are closely linear between the variables in this paper.

No. 8 File No. 3486

Title: Climate and Permafrost in Canada

Pub: Weather

Date: August 1974 Vol: 29 No: 8 Pages: 298-305

Author: Thompson, R. D.

1. The paper presents a qualitative discussion of permafrost and the factors influencing permafrost. Microclimate is shown to be very important in the formation, etc., of permafrost.

2. A good qualitative discussion of the various factors influencing permafrost.

3. No models, no data.

4. Of little use in the project.

No. 9

Title: Ground Temperature Vol. I

Pub: Blue Hill Meteorological Observatory, Harvard University

Date: June 21, 1958 Vol: I Pages: 1-11 (Chapter 1)

Author: Jen-Hu-Chang

1. Chapter One is an introduction to the problems and needs of accurate quantitative information. It shows the importance of understanding ground temperature and related areas.

2. Good introduction to the need for understanding ground temperature.

3.

4.

No. 10

Title: Ground Temperature Vol. I

Pub: Blue Hill Meteorological Observatory, Harvard University

Date: 1958 Vol: I Pages: 12-20 (Chapter 2)

Author: Jen-Hu-Chang

1. The title of this chapter is "Measurement of Ground Temperature". It discusses the errors of measurement involved in the collection of data. Also it discusses the different types of thermometers in use, and gives advantages and disadvantages of each. Also discusses measurement errors due to the time of observation.

2. Gives a numerical example of the differences in the way the daily average is estimated. This is Table One in the text. It shows differences of $\pm \frac{1}{2}$°C in the different methods commonly used to estimate daily averages.

3.

4. Useful in designing the data collecting phase of this project.

5. Of the three thermometers in use; mercury, resistance and thermocouple, the easiest and most rugged one is the resistance thermometer which has fairly small measurement errors.

No. 11

Title: Ground Temperature

Pub: Blue Hill Meteo. Obser.

Date: 1958. Vol: I Pages: 21-42 (Chapter 3)

Author: Jen-Hu-Chang

1. This chapter discusses the various thermal properties of soil and soil cover, giving a fair amount of information about conductivity, reflectivity, transmissivity, etc. It also discusses the influence of moisture and temperature on these properties.

For example, thermal diffusivity depends on soil moisture in a very important way, as moisture varies from 10% to 30% water by weight the diffusivity varies from .0015 to .0030. Also, at freezing, the diffusivity is also dependent on temperature.

2. A good discussion of the thermal properties of soil and what factors influence these properties and by how much.

3.

4. Will be of use to determine what factors should be included in a model, giving information about how the properties depend on the factors, etc. Clearly any model is an oversimplification of the problem. This chapter shows the need to try many different models, each being progressively more complex, until a reasonable agreement with data is found.

5. A list of factors that influence various properties.

A. Reflectivity.
   (a) Wavelength (important)
   (b) Angle of incident (important)
   (c) Soil color (albedo) (important)
   (d) Type of minerals in soil (less important)
   (e) Organic material, influence color (important)
   (f) Moisture influence on color (important for a short time after rain)
   (g) Snow cover (important)

B. Transmissivity.
(a) Snow cover, age, compactness, presence of layer or not, all influence transmissivity. (important)

C. Emissivity.
(a) Wavelength (important)
(b) Absolute temperature (important)
(c) Character of surface (smooth or rough, etc.)
(d) Kirchoff's Law (good absorber = good emitter)
(e) Stefan-Boltzman Law (rate of radiation = $(T_1^4 - T_2^4)$, $= 8.13 \times 10^{-11}$ cal cm^{-2} min^{-1} deg^{-4}

D. Specific Heat and Heat Capacity.
(a) Moisture (important)
(b) Soil Composition (less important)

E. Thermal Conductivity.
(a) Porosity (important)
(b) Moisture (important)
(c) Organic content (less important)
(d) Temperature (minor)
(e) Soil minerals (minor)

F. Thermal Diffusivity
(same as Thermal Conductivity)

No. 12

Title: Ground Temperature Vol. I

Pub: Blue Hill Meteo. Obser.

Date: 1958 Vol: I Pages: 43-57 (Chapter 4)

Author: Jen-Hu-Chang

1. This chapter is about heat flux in the ground. It discusses the sources of energy and the disposition of energy as well as the factors influencing the flow of heat in the soil. It also shows the importance of considering soil moisture and other modes of transfer of heat in the soil.

2. Good overview of the factors and the importance of each factor that influence heat transfer in the soil and to the soil.

3. Most all of the equations used in this chapter are based on the assumption that the soil is homogenous throughout. It is not completely an accurate model since data are presented that show that near the surface, within 30 cm, this model does not agree well with the observations.

4. This serves as a starting point to select the major sources of energy and major disposition factors for a model.

5. I. Sources of Energy.
   - A. Earths interior heat (minor)
   - B. Radioactivity of rock (minor)
   - C. Decomposition of organic matter (minor)
   - D. Chemical Reactions (generally minor)
   - E. Radiation from moon, stars, etc. (very minor)
   - F. Direct solar radiation, not reflected from moon, etc. (major)

   II. Disposition of Energy received at the ground surface.
   - A. Evaporation of soil moisture (important)
   - B. Transfer to atmosphere (important)
   - C. Transfer into ground
     1. By conduction (major mode at lower depths)
     2. Heat transfer to water in soil.
     3. Convection of air in the soil (negligible if soil particles are smaller than .1 cm and pores are small)

4. Diffusion of water vapor in soil.
   (may account for as much as 45% of total transfer, generally x 1% or 2%)
5. Movement of water in soil.

No. 13

Title: Ground Temperature Vol. I

Pub: Blue Hill Meteo. Obser.

Date: 1958 Vol: I Pages: 58-127 (Chapter 5)

Author: Jen-Hu-Chang

1. This chapter presents, in graphical form, the annual trends of soil temperature at various depths over the world, if data are available. The discussion is generally qualitative and summarizes the data collected.

2. It combines the data and knowledge of the field about soil temperatures.

3. Very little is said about a detailed model of the soil temperature problem, but the information presented will be very useful in forming the model.

4. This is useful because the chapter discusses practically all of the factors involved with soil temperatures and gives information about the relative importance of each factor. This chapter should help in choosing the variables to include in the model.

5. This shows that the conduction process in the ground is dominant at lower depths, but not near the surface.

No. 14

Title: Ground Temperature Vol. I

Pub: Blue Hill Meteo. Obser.

Date: 1958 Vol: I Pages: 128-193 (Chapter 6)

Author: Jen-Hu-Chang

1. This chapter summarizes the factors that influence ground temperatures and presents literature to support the claims and also to estimate the relative importance of the various factors. The main conclusion is that microclimatic properties have a sizable effect on soil temperature. Most important are ground cover, moisture in the ground and on or near the surface, color of ground, whether the ground is cultivated or not, latitude, slope and altitude.

2. This chapter shows the importance of the various factors influencing soil temperature.

3.

4. This chapter should be useful to help select variables, factors, etc., to include in a model, but gives little help in determining quantitative relationships of the various effects. A large supply of graphs. No equations.

5. A. Meteorological Elements.
   1. Solar Radiation
   2. Radiation, related to clouds
      (a) keep heat in at night
      (b) keep heat out by day
   3. Rain
      (a) source of heat energy, due to temperature difference, generally cooling the soil
      (b) changes the thermal properties
      (c) temporarily increases at lower depth due to forcing soil air down (very minor)
      (d) changes reflectivity as well
   4. Snow cover.
      (a) low thermal conductivity
      (b) high reflectivity
      (c) excellent long wave radiator

(d) large heat of fusion
(e) density changes, depending on age of snow, degree of melting, etc.
(f) the insulating effect is not proportional to depth of snow
(g) affects the temperature of soil depending on the initial condition of soil
(h) shows heat exchange between soil and air. Shows lag and amplitude reduction

5. Air temperature
6. Humidity (latent heat)
7. Heat transfer by wind
   (a) more important in daylight

B. Properties of Soil
1. Soil texture
   (a) sand
   (b) loams
   (c) clays
2. Moisture content
   (a) varies heat capacity
   (b) surface evaporation
   (c) increases conductivity
   (d) percolation
3. Organic matter
   (a) reduce heat capacity
   (b) reduces thermal conductivity
   (c) increases water holding capacity
   (d) increase absorptivity due to a darker color
4. Color (changes absorptivity)
5. Structure, cultivation and compaction
   (a) cultivation loosens soil and acts as a mulch to reduce heat exchange with lower depths, acts as a protective layer to keep moisture in the lower depths
   (b) diurnal wave at surface of cultivated soil is larger than uncultivated soil
   (c) compaction increases thermal conductivity

C. Topography
1. Aspect
   (a) direct insolation is influence by aspect and slope
   (b) diffuse sky radiation is influenced by slope only

2. Slope
   (a) southward slopes are warmer than northward slopes, in the Northern Hemisphere
3. Altitude
   (a) less air, more radiation
   (b) greater loss at night also, but gain is generally greater than loss
   (c) higher altitudes have larger variations in temperature
4. Concavity and convexity
   (a) at night the ground cools faster than the air, therefore the cool air near the surface flows downslope in the valleys thus transporting energy from the high slope into the air in the valleys

D. Vegetation Cover
1. Forest
   (a) low albedo
   (b) most insolation is used by plants
   (c) slows the losses by radiation at night
   (d) trees, etc., impede air flow near the ground
   (e) very little runoff of rain in forest
   (f) evaporation is less, due to ground cover of leaves, etc.
   (g) changes the nature of the snow fall
2. Grass
   (a) increases evaporation losses
   (b) interferes with heat exchange between ground and atmosphere, depends on height and density of grass
3. Crops
   (much the same as grasses)

E. Urban Environment
   (a) generally warmer air and probably warmer soil temperature
   (b) less wind
   (c) shading, etc.

F. Fires

No. 15

Title: Ground Temperature Vol. I

Pub: Blue Hill Meteo. Obser.

Date: 1958 Vol: I Pages: 194-229 (Chapter 7)

Author: Jen-Hu-Chang

1. The subject of this chapter is formation of frost and thawing properties. Some equations for predicting frost depth are discussed. Each requires a knowledge of detailed measurements of soil properties. There is also a purely empirical equation given. During the formation stage, the temperature of subsoil is constant at 0°C, due to the release of the latent heat of fusion of ice.

2. A fairly complete discussion of the factors influencing the formation of frost, with mathematical models and empirical equations. It also briefly discusses thawing processes.

3.

4. Since we are to predict temperatures in the soil during the winter, the freezing process will be very much a part of the whole model.

5. A. Freezing Point, Latent Heat, and Zero Curtain.
   (a) freezes at x - 1.0°C, due to salts in the soil, etc.
   (b) the release of latent heat during freezing warms the layer below and maintains a fairly constant 0°C
   (c) once frozen the thermal conductivity is increased and normal temperature variation continues

   B. Factors Determining Frost Penetration
   (a) air temperature
   (b) snow cover
   (c) vegetation cover (minor)

   C. Thawing
   (a) influenced mainly by rain and conduction of heat from above, represents about 70% of the heat to thaw

   D. Permafrost
   (a) near and under flowing rivers there is no permafrost

E. Map of Frost Distribution

F. Prediction of Frost Penetration into the ground.

(1) Use the freezing index

(a) cumulative total of degree - days below freezing point

(2) Mathematical Approach

(a) assumes homogeneous material in models

(b) Bergeron's equation

$$z = 2B\sqrt{tK_h}$$

where z=thickness of frozen layer
B = growth coeff. of frozen layer (need table)
t = duration of subfreezing surface temperature in hours
K_h = thermal diffusivity of the soil (relative error reports as 50%)

(c) Franklin's equation

$$z^2 = \frac{K_h T_o t}{40W}$$

W = volume percentage of water
T_o = temperature of the surface

(3) Analog Computer

(a) used to solve the differential equations of the heat problem

(b) direct physical analog is used like hydraulics

(4) Heat Balance (little use)

No. 16

Title: Ground Temperature Vol I

Pub: Blue Hill Meteo. Obser.

Date: 1958 Vol: I Pages: 230-255 (Chapter 8)

Author: Jen-Hu-Chang

1. This chapter discusses the influence of ground temperature on air temperature. The principal processes are molecular conduction, convection, terrestrial radiation, and evaporation.

2. It refers to works that have used models and gives some of the equations available. However, many of the processes involved are very complex and no models have been used.

3.

4. In order to show how much heat is conducted into the soil, we need to know the incoming energy and out going energy not in the soil this involves transfer into the air. So some parts of the model must include the influence of ground temperature on the air.

5. A. Temperature gradient in the air layer near the ground.
   B. Processes of heat transfer from ground to the air.
      (1) molecular conduction
      (2) convection
         (a) thermal convection
         (b) dynamic convection
         (c) roughness of surface reduces losses due to convective exchange
      (3) Terrestrial radiation
         (a) the direct effect of longwave radiation from the ground is confined to an air layer of several meters near the ground
         (b) the high air layer at night, cool by radiating to lower air layers, not directly to the ground
         (c) gives a formula for determining back radiation on cloudless nights

(4) Evaporation
(a) influenced by
(i) temperature
(ii) salinity
(iii) wind velocity
(iv) air pressure
(v) difference in vapor pressure between water surface and the air
(b) very complex mathematical problem

C. Variation in Ground Surface, Thermal Admittance.
(a) thermal admittance
$= \sqrt{KC\rho}$
where K = thermal conductivity
C = specific heat of soil
ρ = soil density
the fraction of heat entering the soil is roughly proportional to the $\ln\sqrt{KC\rho}$ and increases with increased moisture
(b) ideally, in the absence of turbulence, the air adjacent to the ground at night is colder and denser than the air above
Brunt's Equation
cooling of the ground surface in t hours from sunset, of soil with conductivity K, heat capacity C is

$$2R_t\sqrt{\frac{t}{\pi KC}}$$

where R_t = net rate of heat loss from ground

$$R_t \approx \sigma (T + 273)^4 (.48 - .065\sqrt{e})$$

where T is temperature in °C
e is vapor pressure in mm

No. 17

Title: Ground Temperature Vol I

Pub: Blue Hill Meteo. Obser.

Date: 1958 Vol: I Pages: 256-270 (Chapter 9)

Author: Jen-Hu-Chang

1. The chapter outlines methods used to modify ground temperature mainly to retard frost and to warm soil by adding sand to the top layer to increase insolation.

2.

3.

4.

5. A. Artifical Ground Cover
   (1) paper mulch
   (2) straw mulch
   (3) polyethylene
   (4) screen and cap
   B. Carbon Black
   C. Heating and Smudging
   D. Wind Machine
   E. Irrigation and Sprinkling
   F. Sanding

No. 18

Title: Ground Temperature Vol II

Pub: Blue Hill Meteorological Observatory, Harvard University

Date: 1958 Vol: II Pages: 1-196

Author: Jen-Hu-Chang

1. This is a summary of data on ground temperatures from around the world. The data are generally monthly averages at various depths. Additional information is generally latitude, longitude, and altitude with remarks on method of data collection, if possible.

2.

3.

4.

5.

No. 19 File No. 4849

Title: The Response of Spring Wheat Yield to Anomalous Climate Sequences in the United States

Pub: Journal of Applied Meteorology

Date: August 1978 Vol: 17 No: 8 Pages: 1101-1115

Author: Staar, T. B.; Kastrow, P. I.

1. The authors have used monthly temperature and precipitation averages, after detrending wheat yields, to predict residual wheat yields. The detrending was done to compensate for changes in farming methods over the period from 1932 to 1975.

The independent variables were first standardized to have mean zero and variance one and then were transformed into principal variates by a principal component analysis. Each eigenvector was used to identify a different type of anomaly in the distribution of temperature and precipitation.

2. The approach shown in this paper has given a deeper insight into the type of anomaly that influences wheat yields than multiple regression can. Also this approach has been proposed by others to deal with the problem of highly interdependent explanatory variables. A variation of this approach has been proposed for time series analysis, so the method used has great generality.

3. The method is based on linear relationships but extension to some non-linearity relationship is possible, particularly for interaction terms between temperature and precipitation that would be most interesting.

4. The approach of the paper would be useful in reducing the number of independent variables to explain winter kill of wheat. The paper considers independent variables including temperature of various time periods throughout the winter. Each time period temperature or average temperature would be an independent variable, by reducing the consideration to the linear conbinations most variable that are most likely to explain the differences in the winter kill.

If a particular linear combination of temperatures is constant or near constant for all cases then it is not useful to explain differences in winter kill percentages.

5. The eigenvector coefficients actually describe patterns of temperature and moisture conditions.

No. 20 File No. 4523

Title: Soil Temperature Estimation by a Numerical Method

Pub: Proceedings of Soil Science Society of America

Date: September-October 1971 Vol: 35 No: 5 Pages: 665-667

Author: Hanks, R. J.; Austin, D. D.; Ondrechen, W. T.

1. The authors use a numerical method to solve the one-dimensional heat equation with variable thermal diffusivity and make comparisons with actual data for accuracy. Generally errors increase with the time period and with increased intervals of depth. An error of 1°C - 1.7°C plus or minus was reported. Also comparisons assuming uniform thermal diffusivity were made and increases in errors of .1 - 1.4°C were reported. It appears that an assumption of uniform diffusivity would be in error by about ± 3.5°C at most.

2. This paper gives some insight into the size of error likely to be made by ignoring the variation of diffusivity with depth.

3.

4. Outlines a numerical method of solution of the heat equation that may be useful for the complex equations that we will need to solve.

5. Additional References

1. de Vries, D. A., 1963
Thermal properties of soils.
p. 210-235 In W. R. van Wijk
Physics of plant environment
John Wiley and Sons, Inc. New York

2. Hanks, R. J. and S. A. Bowers, 1962
Numerical solution of the moisture flow equation for infiltration in layered soils.
Soil Science Society of America Proceedings
26: 530-534

3. Hanks, R. J.; Klute, A. and E. Bresler, 1969
A numerical method for estimating infiltration, redistribution, drainage and evaporation of water from soil.
Water Resources Research 5: 1064-1069

4. Hanks, R. J.; Jacobs, H. S.; Schimmelpfennig, H. and M. Nimah 1971
Evapotranspiration estimated from oats by the energy budget, aerodynamics and combination methods.
Utah Agr. Exp. Sta. Utah Resources Report 54

5. Wierenga, R. I. and C. T. de Wit, 1970
Simulation of heat flow in soils
Soil Science Society of America Proceedings 34: 845-848

No. 21 File No. 4855

Title: Modeling Tillage Effects on Evaporation and Seedzone Water Content During Fallow in Eastern Washington

Pub: Doc Thesis from Washington State University, Department of Agronomy and Soils

Date: 1979 Pages: 1-65

Author: Hammel, J. E.

1. Develops a mathematical model of soil moisture and soil temperature allowing for the interaction of moisture on temperature and temperature on moisture by using numerical methods to solve the equations. It tests the model with experimental data and uses the model to explore the effect of tillage on soil moisture and temperature at seed level.

2. The model developed here considers the influence of changing moisture on temperature flow as well as the influence of temperature gradients on moisture flow. Most other models consider the moisture constant when discussing temperature changes or consider the flow of water with temperature constant. Hammel's model shows the importance of considering jointly moisture distribution and temperature distribution.

3.

4. This model appears to be one of the most comprehensive models for predicting soil temperatures and soil moisture. Since moisture has a large influence on temperature both factors should be included in a model of soil temperatures. If this model or a more complex model can be shown to accurately predict soil temperature with experimental data, then when using the model one could evaluate the accuracy of other methods of predicting soil temperature based on less information than this model.

5. The two main equations of the model are:

$$1)\ \frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left((D_{\theta liq} + D_{\theta vap}) \frac{\partial \theta}{\partial t} + D_{T vap} \frac{\partial T}{\partial z} \right.$$

and

$$2)\ \rho_s C_s \frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left(K_T \frac{\partial T}{\partial z} + L D_{\theta vap} \frac{\partial \theta}{\partial z} \right)$$

The model considers both liquid and vapor movement in the soil and influences on heat transport by movement of liquid and vapor.

No. 22

Title: Criticism of a Viewpoint on "Thermodynamic and Soil Moisture."

Pub: Soil Science

Date: 1954 Vol: 77 No: 4 Pages: 303-312

Author: Takagi, Shunsuke

1. The author comments on misconceptions of early workers. The discussion is on Gibb's Theory and discusses energy considerations like Helmholtz free energy enthalpy, Gibbsian free energy and entropy.

2.

3.

4. No direct use in project.

No. 23

Title: Movement and Equilibrium of Water in Heterogeneous Systems with Special Reference to Soils

Pub: Soil Science

Date: 1953 Vol: 75 No: 1 Pages: 187-202

Author: Law, P. F.; Deming, J. M.

1. The approach of the paper is basically thermodynamic using free energy, etc. Little is said about the distribution of moisture in the soil. The discussion is very micro-detailed considering electrostatic effects, etc.

2.

3.

4. The paper does not help to predict moisture in the soil and its relationship to the soil temperature, since the discussion was limited to constant temperature processes.

No. 24

Title: The Theory of Infiltration: 1. The Infiltration Equation and its Solution

Pub: Soil Science

Date: 1957 Vol: 83 No: 4 Pages: 345-357

Author: Philip, J. R.

1. Considers infiltration in soil under constant temperature conditions. It uses the equation $\partial\theta/\partial t = \nabla\cdot(D\nabla\theta) + \frac{\partial K}{\partial z}$
The K is a potential function generally used for gravitational potential.

2. The author applies a numerical method he developed, since the Crank-Nicholson Method didn't give accurate results. This method is developed in a separate paper by the author given in item 5 of this report.

3.

4. Since accurate prediction of soil temperature requires knowledge of the moisture distribution in the soil, some part of the model will need to predict the moisture content. However this paper considers only isothermal movement of moisture, but the methods of approximation used in the paper should be investigated for possible use in the project.

5. Philip, J. R., 1955
"Numerical solution of equations of the diffusion type with diffusivity concentration-dependent."
Trans, Faraday Soc. 51: 885-892

No. 25

Title: Water Flux in Moist Soil: Thermal Versus Suction Gradients

Pub: Soil Science

Date: 1965 Vol: 100 No: 3 Pages: 168-175

Author: Cary, J. W.

1. Flows of heat and moisture were measured experimentally through a loam soil and the results presented. The conclusion was that large amounts of heat are transported by movement of water vapor and liquid. Moreover, temperature gradients are important in the movement of water as well.

2. Presents experimental evidence of the importance of temperature gradients to move water.

3.

4. Shows that simultaneous consideration of moisture and temperature will be needed to predict temperature accurately.

5. Important equation from text.

$$J_w = -L_w R \nabla \ln \frac{P}{P_o} - L_{wq} \frac{1}{T^2} \nabla T$$

$$J_q = -L_{qw} R \nabla \ln \frac{P}{P_o} - L_q \frac{1}{T^2} \nabla T$$

$$L_{qw} = L_{wq}$$

J_w, J_q are flux's.

No. 26

Title: Frost action in soils

Pub: National Research Council Highway Research Board

Date: 1952 No: 1 & 2

1. Volume one is a survey of the literature on frost action. Volume two presents empirical information on frost action. This is of interest mainly to engineering.

2. Used an unusual method of approximation. (see 5)

3.

4. Of little use to developing a model of soil temperature. Very little data are available in the book.

5. One novel idea in volume two was the use of an unusual analog computer to caluclate temperatures in the soil, based on an approximation the details of which are given below.

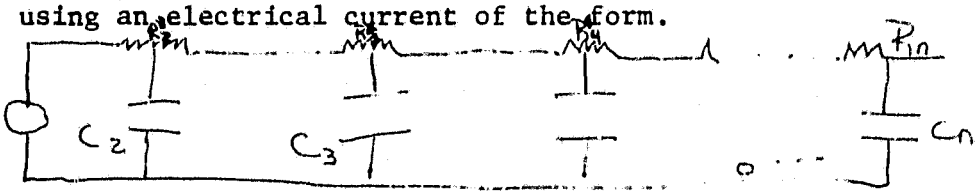
Basic Heat Equation:

$$\frac{\partial T}{\partial t} = K \frac{\partial^2 T}{\partial z^2}$$

Approximate Equation:

$$\frac{\partial T(n\Delta x, t)}{\partial t} = K \left\{ \frac{T((n+1)\Delta x, t) - 2T(n\Delta x, t) + T(n-n\Delta, t)}{\Delta x^2} \right\}$$

This is found by subsituting the difference approximation for , but not changing
This system of equations can now be solved by using an electrical current of the form.



The approximate equation may also be solved analytically as well and this can easily be modified to consider nonhomogenous diffusivity, etc.

No. 27

Title: Heat Conduction

Pub:

Date: 1954

Authors: Ingersoll, L. R., Zobel, O. J., and Ingersoll, A. C.

1. An introductory text on basic heat flow theory. No examples related to soils.

2.

3.

4.

No. 28

Title: Heat Conduction in Soils

Pub:

Date:

Authors: Jager, C.

Not in library. Found in No. 26.

No. 29

Title: Physics of the Environment

Pub:

Author: Inhaber, H.

1. Discusses how physics can be applied to environmental problems, mainly pollution.

2.

3.

4. No discussion of soil temperatures at all.

No. 30

Title: Heat Transfer in the Soil

Pub: by Israel Program for Scientific Translations for National Science Foundation and Department of Agriculture

Date: 1948 Pages: 1-164

Author: Chudnovskic, A. F.

1. Discusses the processes of heat transfer in the soil and between air and soil. Uses mathematical models of the heat transfer in soil and between soil and air. The approach does not develop a single complete model.

Detailed discussion is made of the measurement problems and various instruments are analyzed mathematically and many new instruments are presented.

2. Good discussion of instruments and measurement errors. New methods are presented.

3. The models are mainly of the one-dimensional heat equation type assuming homogenous diffusivity, and linearly variating idffusivity.

4. Not much insight into the modeling problem is given by this work. However, the methods of measurement of diffusivity, conductivity, and heat content could be useful.

No. 31

Title: Simultaneous Flow of Water and Heat Under Periodic Heat Fluctuations

Pub: Soil Science Society of America Proceedings

Date: 1968 Vol: 32 No: 3 Pages: 297-301

Author: Hadas, A.

1. An experiment was conducted to test the accuracy of a mathemetical model for simultaneous flow of moisture and heat. The results showed sizable errors with relative errors of 700% being the largest.

2. The work shows the need to consider a more complete model than that used in the paper.

3. Assumes that temperature flow is not influenced by moisture changes. Used a constant thermal diffusivity, in time and space. In short, the model is too simple to reasonably represent the experimental data.

4. Shows the need for a more complex model than they used in this paper.

5. Details of the model assumptions:
   1. Relative humidity of soil is 100%
   2. Moisture changes are small
   3. Temperature is sinosoidal in time
   4. Thermal diffusivity is constant in time and space and there is negligible transfer of sensible heat and latent heat of vapor transport.

Equations:

$$\frac{\partial \theta}{\partial t} = 2 \cdot S \frac{\partial}{\partial z}\left[D(t)\frac{\partial P(T)}{\partial z}\right]$$

$$T = T_{AVE}\, T_{A0} \exp\left\{-\frac{2\pi z}{\lambda}\right\} \sin\left(2\pi\left[t/p - z/\lambda\right]\right)$$

O is moisture content
T is temperature
L is tortuisity factor .67
S is air porosity (cm^3/cm^3)
P(T) is saturated water vapor as a function of temperature
D(T) is vapor diffusion coeff - temp dependent (cm^2/sec)

No. 32

Title: Soil Moisture Transport Due To Thermal Gradients: Practical Aspects

Pub: 1966 Vol: 30 No: 4 Pages: 428-433

Author: Cary, J. W.

1. The author discusses four proposed mechanisms of thermally induced moisture, vapor and liquid flow. The mechanism for vapor transport appears satisfactory, but the mechanisms proposed for liquid don't completely explain all the facts satisfactorily.

2. A good qualitative discussion of thermally induced moisture flow.

3. No discussion of moisture movement on heat flow.

4. Since no model is proposed for the interaction of heat flow and moisture flow, the paper is of no interest for the project.

5. $J_{vap} = \left(-B \frac{D \rho H}{p^2 T^2}\right) \frac{dT}{dz}$ (Vapor flux)

$J_{liq} = \left(-\frac{KQ}{\rho T}\right) \frac{dT}{dz}$ (Liquid flux)

Note: ( ) coeff, depend on T.

No. 33

Title: The Interaction of the Simultaneous Diffusions of Heat and Water Vapor

Pub: Soil Science Society of America Proceedings

Date: 1962 Vol: 26 No: 5 Pages: 413-416

Authors: Cary, J. W. and S. A. Taylor

1. Discusses some predictions of the theory of irreversible thermodyamic processes about steady-state flux of vapor due to temperature gradients and energy flux due to temperature gradients. In general good agreement was found between experimental results and the theory.

2. Good agreement was found between experimental data and theoretical predictions.

3. Only the steady-state conditions were studied, assumed contant moisture distribution and constant temperature distribution.

4. The assumptions made in this paper are very restricted in nature, ie. steady-state conditions and only vapor flow was considered.

No. 34

Title: Thermally Driven Liquid and Vapor Phase Transfer of Water and Energy in Soil

Pub: Soil Science Society of America Proceedings

Date: 1962 Vol: 26 No: 5 Pages: 417-420

Authors: Cary, J. W.; Taylor, S. A.

1. A comparison of experimental results with predictions from the general theory of irreversible thermodynamic process was made. The agreement was good.

2. A good test of general theory was made.

3. The assumptions are steady-state conditions and constant moisture distribution. These assumptions limit application of equation to field conditions which are very rarely steady-state conditions.

4. Very strong assumptions of steady-state conditions limit application of results and equations of this paper to the project.

No. 35

Title: Linear Equations for the Simultaneous Flow of Matter and Energy in a Continuous Soil System

Pub: Soil Science Society of America Proceedings

Date: 1964 Vol: 28 No: 2 Pages: 167-171

Authors: Taylor, S. A.; Cary, J. W.

1. This paper derives general equations for mass and energy transfer and applies them to the soil system. This work shows that older equations for moisture flow are special cases of this general approach, namely Darcy's Law and the diffusion equation, if we assume isothermal conditions and no hysteresis. The equation of Philip and de Vries is also a special case which assumes that water is the only mass that can move.

2. A general equation is developed that extends previous work to possible application where older theories give poor fit to experiment.

3. No experimental evidence is given to show this approach works where older methods do not.

4. Could be explored if older and simpler equations break down.

5. Basic Theory Used.

I. Conservation of Mass

II. Conservation of Energy

III. Law of Thermodynamics

IV. Result from the Theory of Iffeversible Processes.

No. 36 File No. 4762

Title: Crown-Depth Soil Temperature and Winter Protection

Pub: Submitted to Soil Science Society of America

Date: 1980 Pages: 1-23

Authors: Aase, J. K.; Siddoway, F. H.

Location: Sidney, Montana

1. In order to study the blanketing effect of snow cover, an experiment was performed. On various plots of soil, barriers were erected of various heights, 8, 15, 23, and 30 cm, in order to maintain snow at roughly the same heights. Soil and air temperature were recorded at 15 minute intervals, again at various depths in the soil, namely 0, 3, 10 cm, and at the 150 cm height for air temperatures. The authors conclude that 7 cm of snow appear sufficient to protect winter wheat from occasional air temperatures of -40°C.

2. Certainly valuable information has been found in this study on what conditions are most favorable to survival of winter wheat.

3. What does "occasional air temperatures approaching -40°C" mean exactly, a large number of possible air temperature plot meet that requirement, greater precision is needed on that point.

The statistical analysis in this paper has a number of problems. First there is a basic set of assumptions for reasonable application of regression analysis. One in particular is "reasonable" independence for cases. In the data of this paper, it is unlikely this type of data calls for time series analysis, and most frequently does not meet the requirement of standard regression analysis. However, with suitable modifications, regression-like methods can be used, but this was not done in this paper.

Secondly, due to the objection above, the significance levels could be very misleading.

Lastly, a large amount of data was not used since daily minimums were the only data analyzed and 96 observations per day were collected. Hourly observations may be enough.

4. First of all, the data collected is very much like the data that this project is to collect. Consequently this data could be useful in comparing with models of soil temperature although soil moisture was not recorded which also affects soil temperature distribution. But the data would be useful in designing the data collection for this project and for checking the assumptions used in this paper for the purpose of analyzing our own data.

5. Additional References

Kulik, M. S.; Sinelshchikov, V. V., 1966 Lectures onAgricultural Meteorology. Indian National Scientific Documentation Centre, New Delhi, India. Available from National Technical Information Service, United States Department of Commerce, Springfield, VA 22151 (Translated from Russian, 1978) 402 p. Chapter 10 was file number 4573.

Let Y = Min soil temp at 3 cm (°C)

Let X = Min air temp at 115 cm (°C)

$Y = 2.39 + .826X$ Bare soil

$Y = -1.84 + .383X$ 6-7 cm of snow

$Y = -1.17 + .279X$ 15-17 cm of snow

Let Y = min soil temp at 5 cm

Let X = min air temp at 115 cm

in absence of snow

$Y = 1.54 + .773X$ Bare soil

$Y = 1.33 + .637X$ 19 cm Stubble

$Y = 1.54 + .627X$ 35 cm Stubble

No. 37

Title: Heat Transfer in Soils

Pub: Heat and Mass Transfer in the Biosphere

Date: 1975 Pages: 5-28

Author: de Vries, D. A.

1. Presents a survey of models and state of the knowledge on heat transfer in soils. The author is very active in this area and has contributed much to the subject.

2. An excellent summary on heat transfer in soils.

3.

4. The model developed by Philip and de Vries is the most advanced model on this subject to date.

5. Additional References

Lefur, B.; Balaille, J.; Aguirre-Picente, J. C. R. Acad. Sc. B. 259, 1483-1485, 1964 (Ref. no. 10)

Jury, W. A. "Simultaneous transport of heat and moisture through a medium sand." PHD Thesis Univ. of Wisconsin, 1973 (Ref. no. 19)

Philip, J. R.; de Vries, D. A. Trans. Amer. Geophys. Union 38. 222-232, 594. (1957) (Ref. no. 24)

de Vries, D. A. Trans. Amer. Geophys. Union 39. 909-916, 1958 (Ref. no. 25)

Van der Kooi, "Moisture transport in cellular concrete roofs." PHD Thesis Eindhoven, Univ. of Technology; Waltman, Delft, 1971

Cary, J. W. Soil Science Society of America Proceedings 30, 428-433, 1966.

No. 38

Title: Simulation of the Thermal Behavior of Bare Soils for Remote Sensing Purposes

Pub: Heat and Mass Transfer in the Biosphere

Date: 1975 Pages: 109-123

Author: Rosema, A.

1. This paper gives the results of a simulation of soil temperature of bare ground. The equations of Philip and de Vries were used for the soil temperature and soil moisture part of the model. The paper concludes that near the surface the equation of soil moisture does not describe moisture movement well.

2. Presents a mathematical model for soil temperatures that could serve as a starting point for this project.

3. Presents no experimental data.

4. The approach of this paper appears to be the standard model for this problem and represents a likely starting point for modeling of this problem.

No. 39

Title: Moisture Movement in Porous Materials Under Temperature Gradients

Pub: Tran. Amer. Geophy. Union

Date: 1957 Vol: 38 No: 2 Pages: 222-232

Authors: Philip, J. R.; de Vries, D. A.

1. The authors discuss some of the shortcomings of previous models and develop a more detailed model which is compared with existing data. However, most of the available data does not include all of the required variables for a complete comparison with the theory. What could be checked agreed with observed data better than previous work.

2. Improves the theory of heat and moisture flow in soils.

3. A complete and total comparison with experimental data is needed to further support this model.

4. A mathematical model for heat and moisture flow is presented that appears to be the best to date. This is a good starting point for model heat flow in the soil.

No. 40

Title: Simultaneous Transfer of Heat and Moisture in Porous Media

Pub: Trans. Amer. Geophy. Union

Date: 1958 Vol: 39 No: 5 Pages: 909-916

Author: de Vries, D. A.

1. In this paper the author extends the model given by Philip and de Vries by separating transport by water vapor and water liquid. Only steady-state experiments were used to compare with theory.

2. This should be a better model, since vapor and liquid transports are very different in nature and also heat transport is considerably affected by evaporation and condensation in the soil.

3. More extensive testing of the model is needed.

4. The model of Philip and de Vries and modified by de Vries in this paper is the most frequently referred to model of heat and moisture flow in the soil.

No. 41 File No. 4573

Title: Lectures on Agricultural Meteorology

Pub: Indian National Scientific Documentation Centre, Hillside Road, New Delhi, for U. S. D. A. Soil Conservation Service and the National Science Foundation, Washington, D. C. (translated from Russian)

Date: 1966 Pages: 217-220

Authors: Kulik, M. S.; Sinelshchikov, V. V. (editors)

1. Gives an empirical relationship between minimum soil temperature at the 3 cm depth, minimum air temperature, depth of freezing, and depth of snow.

2.

3.

4. Gives empirical relationships that may be useful for comparison.

5. Let y = Min soil temp at 3 cm depth (°C)

t = Min air temp. (°C)

x = Depth of soil freezing (cm)

$$y = \begin{cases} .76t + 2.88 & \text{if no snow cover and } x < 30 \text{ cm} \\ .81t + .26 & \text{if no snow cover and } x > 30 \text{ cm} \\ .64t - .07x + 5.2 & \text{if snow depth} = 5 \text{ cm} \\ .15t - .06x + .43 & \text{if snow depth} = 10 \text{ cm} \end{cases}$$

No. 42 File No. 4895

Title: A Model to Predict Tillage Effects on Soil Temperature

Pub: Soil Science Society of America Journal

Date: 1980 Vol: 44 No: 2 Pages: 378-383

Authors: Cruse, R. M.; Linden, D. R.; Radke, J. K.; Larson, W. E.; and K. Larntz

1. Presents a model of soil temperatures in order to study the effects of tillage on modifying soil temperatures. A number of factors are included in the model - solar radiation, wind speed, soil water content at 5 cm depth and stage of evaporation.

2. The analysis of the data used to form the simulation model is good using time series methods of Box and Jenkins.

3. Heat flow is assumed to be by conduction only and the "simple" theory of heat flow is used.

4. Many empirical relationships useful for heat flow modeling are given in this paper, such as soil roughness effects on solar radiation, absorption, water-content effect on reflectivity and surface residue effects. All of these and more will be needed.

No. 43 File No. 1463

Title: On the Influences of Fields of Motion, Baroclinicity and Latent Heat Sources on Frontogenesis.

Pub: Journal of Applied Meteorology

Date: 1966 Vol: 5 No: 4 Pages: 377-387

Author: Rao, G. V.

1. Discusses some effects of the release of latent heat of evaporation on frontal weather.

2. .

3.

4. In the soil, consideration of the release of latent heat of evaporation and freezing will be an important consideration but, since the air in the soil is different in nature than free air, little in this paper could be used except the qualitative similarity of the two problems.

No. 44 File No. 1474

Title: Closed-System Freezing of Unsaturated Soil

Pub: Soil Science Society of America Proceedings

Date: 1966 Vol: 30 No: 2 Pages: 168-173

Authors: Dirksen, C.; Miller, R. D.

1. Presents laboratory experiments to study freezing and heaving in unsaturated soil. In general, as soil freezes water is drawn to the freezing zone and into the freezing zone, but thermal gradients alone appear to account for only 20% of the total flow to the 0°C region. The rest appears to be due to a hydraulic gradient that is formed in the freezing region.

The authors rejected the models of Cary and Taylor because the equations are largely for steady-state conditions and this process is not steady-state. In general, no model gave a satisfactory explanation for the observed process.

2. This shows that the model of moisture and heat transfer does not apply well to an unsaturated freezing soil - a likely condition in the field.

3. No complete explanation is given for all of the results of the experiments.

4. Since the period of most interest to this project includes the period of freezing and after, this paper suggests that the model of Cary and Taylor as well as other models generally used do not reasonably predict the events during freezing.

No. 45

Title: Water Potentials Unit 2

Pub: Applied Soil Physics

Date: 1980 Pages: 20-61

Authors: Hanks, R. J.; Ashcroft, G. L.

1. This chapter presents an introduction to the various potentials acting on water in the soil. It also discusses how to measure the various potentials.

2. This is easy to read and presents a number of examples.

3. Considers isothermal water flow and potentials.

4. This gives a background on the potentials acting on soil water, but since the project involves temperature changes the discussion in this chapter needs to be modified to include temperature effects.

5. Notes on the various potentials.

Yz = Gravitational potential

Ywater = Ypressure + Ysolute + Ymatrix

Yhydraulic = Yz + Ym + Yp

Ytotal = Ywater + Yz

Ymatrix is related to moisture content but is not strictly a single-valued function of moisture content, but depends also on the history of moisture. ie) drying vs. wetting, two different curves. Also strongly depends on soil type.

Ypressure applies mainly to saturated soils. Zero at and above water level in the soil.

Yhydraulic = Yz + Ym + Yp

Soil Water Characteristic Curves relationship of Ym to Ov (volume water content).

Ysolute is present mainly in a system with a semipermeable membrane. Air is a good membrane.

$Ys = -RTCx$

R = Gas content

T = absolute temperature

Cs = moles/cm^3 of solute

No. 46 File No. 4554

Title: Water and Salt Movement in Unsaturated Frozen Soil: Principles and Field Observations

Pub: Soil Science Society of America Journal

Date: 1979 Vol: 43 No: 1 Pages: 3-8

Authors: Cary, J. W.; Papendick, R. I.; Campbell, G. S.

Soil Type: Palouse silt loam. One site was bare, another covered with wheat stubble.

Location: Pullman, Washington

Solute was of a low concentration.

1. The paper presents a comparison of field data to an equation for liquid water flux in frozen soil. The equation is based on the assumption that hydraulic conductivity in frozen soil is similar to that in unfrozen soil. The factors required are soil temperature, solute concentration, soil water release curve and saturated hydraulic conductivity. The authors report general agreement of the equation and field data.

The solute proved to be an important factor in the movement of water to the freezing zone. Heat flux is also an important factor.

2. The data, unlike most, are field data. The authors state that few, if any, field data are known that would be able to test the equation.

3.

4. The period of most interest to this project is when the ground is frozen and water movement does transport a sizable amount of heat, so a joint model of moisture and heat flux is necessary to accurately model soil temperature.

No. 47

Title: Chapter 3 Theoretical Analysis

Pub: Soil Water

Date: 1972 Pages: 21-63

Authors: Edited by Nielsen, D. D., Jackson, R. D., Cary, J. W., and Evans, D. D.

1. This chapter presents a summary of the various mathematical models used to study soil water flow and related problems, such as heat transfer and dispersion of solutes.

2. This is an introduction to the field, but not as basic as Hanks and Ashcroft.

3.

4. Useful as a partial list of the mathematical models for heat and moisture.

No. 48

Title: Chapter 5 Effect of Temperature on Unsaturated Soil Water Transport

Pub: Soil Water

Date: 1972 Pages: 96-120

Authors: Edited by Nielsen, D. D., Jackson, R. D., Cary, J. W., and Evans, D. D.

1. This chapter presents, with more details than Chapter 3, the joint modeling of soil water and soil temperature. It discusses the diffusion equation model, the model of Cary and Taylor and the model of Philip and de Vries. It makes comparisons of each with experimental data.

Generally the model of Cary and Taylor gives better fit, but is not as general as the model of Philip and de Vries.

2.

3.

4. Useful as a summary of the most popular moisture and heat models.

No. 49 File No. 348

Title: The Annual and Diurnal Heat-Exchange Cycles in Upper Layers of Soils

Pub: Journal of Applied Meteorology

Date: 1963 Vol: 2 No: 3 Pages: 397-406

Authors: Carson, J. E.; Moses, H.

Location: Argonne, Illinois

Soil Type: Yellow clay of glacial origin.

1. This paper discusses the yearly and daily variation of temperature. The model used for most of the calculations assumes a homogenous soil. The results agree qualitatively with conclusions of other investigators.

2. Some thermal property information is given in the paper. Various graphs of soil temperature versus depth are presented.

3. Generally the authors ignored the importance of moisture and its effect on temperature distribution.

4. This paper could be useful to compare the results of this project to the results in this paper.

No. 50

Title: Temperature and Soil-Water Diffusivity Relations

Pub: Soil Science Society of America Proceedings

Date: 1963 Vol: 27 No: 4 Pages: 363-366

Authors: Jackson, R. D.

1. This paper discusses the relationship of diffusivity and temperature to soil-water flow based on the capillary analogy. The experimental work presented shows reasonable predictions based on the theory.

2. This gives a laboratory test of the temperature effect on soil-water diffusivity.

3.

4. It gives a qualitative relation between the soil-water diffusivity and temperature since the complete model of temperature requires simultaneous consideration of moisture movement and diffusivity is very important in moisture movement.

No. 51

Title: Water Movement and Loss Under Frozen Soil Conditions

Pub: Soil Science Society of America Proceedings

Date: 1964 Vol: 28 No: 5 Pages: 700-703

Authors: Ferguson, H.; Brown, P. L.; Dickey, D. D.

1. Presents data of soil temperature and soil moisture at depths 3 inches, 12 inches, 24 inches, 36 inches, 48 inches, 60 inches, and 72 inches during a period of time when the soil was frozen. The authors concluded that water movement in the unfrozen part is sizable where the matrix potential is less than 2 atm, but if tension is 5 atm or greater no flow to the freezing zone is observed.

2. Gives data on soil temperature and soil moisture at various depths.

3. No comparison to a model.

4. Some small amount of data is available in the paper.

No. 52

Title: The Temperature Dependence of Soil Water Vapor Pressure

Pub: Soil Science Society of America Proceedings

Date: 1964 Vol: 28 No: 5 Pages: 595-599

Authors: Kijne, J. W.; Taylor, S. A.

1. The relationship of soil water vapor pressure and temperature are explored using a psychrometric method for .96 to 1.00 relative vapor pressures and gravimetric and calorimetric heat of immersion below .96. The authors conclude that in the liquid state soil water is more random than free water and soil water vapor is less random than over free water.

2. It relates that a tensiometer measures only the matrix potential where as psychrometric measures include solute effects and soil matrix potential.

3.

4. Useful as a background on the soil water and its relationship with temperature. No new equations are developed.

No. 53

Title: Effect of Temperature and Trapped Air on Matric Suction

Pub: Soil Science

Date: 1965 Vol: 100 No: 4 Pages: 262-266

Author: Chahal, R. S.

1. The author proposes that the difference between observation and the classical theory of surface-tension and temperature effects is due to the entrapped air in the water. Indirect evidence is presented showing qualitative agreement with the author's hypothesis.

2. This represents a step toward a better explanation of the relationship of matrix potential and temperature.

3. No direct experimental evidence is given and no complete quantitative theory was developed.

4. During the freezing process water flows toward the freezing zone and estimates of the amount based on temperature alone underestimate the amount of flow. Perhaps the "true effect of temperature" is on the matrix potential. This is not the only mechanism for temperature effects.

No. 54

Title: Effect of Temperature and Trapped Air on the Energy Status of Water in Porous Media

Pub: Soil Science

Date: 1964 Vol: 98 No: 2 Pages: 107-112

Author: Chahal, R. S.

1. This paper derives an equation that relates the energy status of the water and that considers the effect of entrapped air.

2. Extends the work of Wilkinson and Klute to a more complete theory.

3. The distribution of bubble radius is implicitly assumed to be uniform.

4. Useful as a detailed model that considers the effect of temperature on matrix potentials.

No. 55

Title: Movement of Water in Soil Due to a Temperature Gradient

Pub: Soil Science

Date: 1952 Vol: 74 No: 5 Pages: 335-345

Authors: Gurr, C. G.; Marshall, T. J.; Hutton, J. T.

1. The authors performed an experiment to detail the movement of water in the liquid and vapor state. Chloride concentration was used as a "tag" for liquid water and changes in chloride concentration were used to measure liquid flow. The general conclusion is that liquid and vapor flow results from temperature gradients--liquid from cold to hot and vapor flow from hot to cold.

2. They conducted an experiment to detail the mechanism better than previous work.

3.

4. General background on the interaction of moisture and temperature.

No. 56

Title: A Non-Stationary Method for Determining Thermal Conductivity of Soil in Situ

Pub: Soil Science

Date: 1952 Vol: 73 No: 2 Pages: 83-89

Author: de Vries, D. A.

1. This paper describes a method for measuring thermal conductivity and in place gives some data collected by this method.

2. One of the few methods usable in the field.

3.

4. Useful as a background on measuring techniques, since thermal conductivity is a very important property and must be known in order to use the various theories since estimation based on temperatures do not provide a test for the theory.

No. 57

Title: Soil-Water Movement in Response to Imposed Temperature Gradients

Pub: Soil Science Society of America Proceedings

Date: 1969 Vol: 33 No. 4 Pages: 493-500

Authors: Cassel, D. K.; Nielsen, D. R.; Biggar, J. W.

1. The authors conducted an experiment to test three different theories of soil-water movement, simple diffusion, the Philip-de Vries theory, and the Cary-Taylor equations. The conclusion was that the Philip-de Vries was the closest and that the assumptions in the Cary-Taylor equation are too strong.

2. Some limited data is present in this paper.

3.

4. By providing a comparison of the three main theories of soil-water movement, this paper should help in selecting the most useful theory to use in this project.

No. 58

Title: Salt and Water Movement in Unsaturated Frozen Soil

Pub: Soil Science Society of America Proceedings

Date: 1972 Vol: 36 No: 4 Pages: 549-555

Authors: Cary, J. W.; Mayland, H. F.

1. This presents a qualitative theory for the movement of water and salt in frozen soil and compares theory with laboratory experimental data. The agreement is reasonable.

The movement of liquid water toward the freezing zone transports salt but the returning vapor flow doesn't move salt, so salt becomes concentrated near the freezing edge.

2.

3.

4. The apparent influence of salt concentration seems very small and probably can be ignored.

No. 59

Title: An Analysis of Sensible and Latent Heat Flow in a Partially Frozen Unsaturated Soil

Pub: Soil Science Society of America Proceedings

Date: 1978 Vol: 42 No: 3 Pages: 379-385

Authors: Fuchs, M.; Campbell, G. S.; Papendick, R. I.

1. This paper presents a quantitative system of equations that consider solutes and latent heat into the heat equation. Some comparisons are made with laboratory experiments with reasonable results. The use of the equation, like most other theories, involves a large number of very microclimate variables.

2. This paper presents a theory for heat flow in partially frozen soil. Prior to this, most theories applied to unfrozen soils only.

3.

4. Most of this project concerns frozen soil, so models of the type presented here should be useful in this project.

No. 60

Title: On the Interaction of Water and Heat Transport in Frozen and Unfrozen Soils: I. Basic Theory; The Vapor Phase

Pub: Soil Science Society of America Proceedings

Date: 1974 Vol: 38 No: 3 Pages: 395-400

Authors: Kay, B. D.; Groenvelt, P. H.

1. By using energy methods, the authors develop transport equations for vapor phase transport of water and heat. The equations are of the same form as Cary and Taylor's equations, but use equilibrium equations in developing the theory.

2. By deriving the same basic equations from different points of view, we can believe that maybe the equation will work.

3. They make a number of simplifying assumptions mainly ignoring sloute and streaming potentials.

4. Serves as a supplement to the equation of Cary and Taylor, et al., but the form of the equations are all about the same.

No. 61

Title: On the Interaction of Water and Heat Transport in Frozen and Unfrozen Soils: The Liquid Phase

Pub: Soil Science Society of America Proceedings

Date: 1974 Vol: 38 No: 3 Pages: 400-404

Authors: Groenvelt, P. H.; Kay, B. D.

1. This is an extension of a previous paper by the authors to include liquid phase transport of water. (See K. S. No. 60)

2.

3.

4. (See K. S. No. 60)

No. 62

Title: Thermal Properties of a Soil Based Upon Field and Laboratory Measurements

Pub: Soil Science Society of America Proceedings

Date: 1969 Vol: 33 No: 3 Pages: 354-360

Authors: Wierenga, P. J.; Neilsen, D. R.; Hagan, R. M.

1. They measured thermal conductivity in situ and soil temperature at various depths in dry soil and under irrigated soil conditions. The usual method of measuring soil temperature and computing thermal conductivity was compared with the direct measurement and they found that the direct method is far better. Also, the wetter the soil the more homogenous the thermal conductivity.

2. This paper presents a comparison of the direct measurement of thermal conductivity and the usual calculation of the conductivity from temperature measurements.

3.

4. It shows that if thermal conductivities are needed the best way to find them is by direct measurement or secondly by many closely spaced temperature probes.

No. 63

Title: Transport of Water and Heat in a Frozen Permeameter

Pub: Soil Science Society of America Proceedings

Date: 1975 Vol: 39 No: 6 Pages: 1029-1036

Authors: Miller, R. D.; Loch, J. G. G.; Bresler, E.

1. This extends the models of Kay and Groenvelt, et al, to include soild phase movement. Detailed equations are given in the paper.

2. .

3. This movement of soil water is probably small and relatively unimportant.

4. The model presented is extremely complex. Simplification is needed if the movement of ice is to be included in the model.

No. 64

Title: A Parameterization of the Evaporation from Nonsaturated Surfaces

Pub: Journal of Applied Meteorology

Date: 1979 Vol: 18 No: 1 Pages: 43-47

Author: Barton, I. J.

1. The author presents a modification of a formula developed by Priestley and Taylor for evaporation by including a term to represent the water availability.

2. A more complete model is developed for evaporation than the Priestley and Taylor equation.

3. A fairly limited test of the formula is developed.

4. Evaporation at the soil-air interface requires heat and is an important effect to consider in modeling the amount of heat absorbed by the soil.

No. 65

Title: A Simple Procedure for Estimating Global Daily Radiation on Any Surface

Pub: Journal of Applied Meteorology

Date: 1978 Vol: 17 No: 8 Pages: 1126-1131

Author: Revfein, K. J.

1. The author presents a method estimating the solar radiation on a sloped site from data on a flat site. The method uses a Fourier series in the estimation.

2.

3.

4. To accurately estimate the temperature distribution in the soil we need information on the solar radiation at the surface.

No. 66

Title: Estimation of Manitoba Soil Temperatures from Atmospheric Meteorological Measurements

Pub: Canadian Journal of Soil Science

Date: 1960 Vol: 60 No: 2 Pages: 299-309

Authors: Riemer, A.; Shaykewich, C. F.

1. They discuss the analysis of data obtained from a five-year study that measured soil temperatures at various depths along with various atmospheric measurements at hourly intervals. The approach is a partial empirical and partly simple diffusion theory. The aim was to develop a prediction method based on atmospheric measurements only. The approach worked fairly well.

2. The amount of data is extraordinarily large for this type of work. Most other studies are based on one or two years and more frequently a matter of months.

3. The data analysis in this paper is fairly simple and possible could be improved on by use of time series techniques. Also, the authors did a good deal of smoothing prior to analysis which tends to inflate the goodest-of-fit, R^2.

4. This paper presents what appears to be the first method for predicting subsoil temperature based on atmospheric measurements and it is based on the largest amount of data.

5. More complete results are given in:

Reimer, A., 1978
Soil temperature estimation.
Thesis, University of Manitoba, 84 p.

No. 67

Title: On the Prediction of Soil Temperatures from Meteorological Data During the Winter Period

Pub: Boundary-Layer Meteorology

Date: 1976 Vol: 10 No: 3 Pages: 331-336

Author: Palagin, E. G.

1. The author proposes a physical model that considers the changing snow depth and the moving freezing front in the soil. The author reports reasonable agreement with real data.

2. The model is simple enough to be useful in applications and appears accurate enough. Since the snow layers can change depths in this model it is an extension of a previous model.

3. This requires many microclimate variables to be used, but not as many as most physical models.

4. The model presented needs more complete testing, but should not be overlooked for this project.

5. The mathematical model presented is a temperature-only type of model that considers varying parameters with time only and considers spatial differences very small.

No. 68

Title: A Mathematical Method for Estimating Soil Temperatures

Pub: Soil Science

Date: 1979 Vol: 128 No: 4 Pages: 226-242

Authors: Meikle, R. W.; Treadway, T. R.

1. The authors give a simple regression method to predict soil temperature at various points in the United States using the day of the year as the independent variable.

2. A very simple method to predict max and min temperatures at a depth of 10 cm.

3. A periodic analysis of the data in terms of cosine and sine functions may have fitted better, but in any case would have been on a more physical basis since the process is a large periodic function.

4. This would be useful in examining the variates of lattitude and elevation on soil temperatures, both max and mins.

No. 69

Title: The Prediction of Mean Monthly Soil Temperatures From Mean Monthly Air Temperature

Pub: Soil Science

Date: 1978 Vol: 126 No: 3 Pages: 181-189

Authors: Toy, T. J.; Kuhaida, A. J.; Munson, J. R.; Munson, B. E.

1. The authors provide a simple regression equation to predict soil temperature at 2 inches based on air temperature. Regressions are based on monthly averages for each variable.

2.

3. The method gives only monthly average predictions based on monthly average air temperature. Many other important variables are not included in this method.

4. The results of this paper are based on a limited number of locations (six), and are based on the data in the Annual Summary, Climatological Data for the United States by Section for the years 1962-1971. This source should be referred to instead of this paper.

No. 70

Title: Estimation of Wintertime Soil Temperatures

Pub: Journal of Economic Entomology

Date: 1970 Vol: 63 No: 4 Pages: 1051-1053

Authors: Bonham, C. D.; Fye, R. E.

1. The authors provide a simple linear regression equation to predict the soil temperature at various depths based on air temperature. R^2 values range from .96 to .77.

2.

3.

4. This is one of the earliest papers to predict soil temperature with air temperatures, empirically using simple linear regression.

No. 71

Title: Improved Models of Thermal Diffusion in the Soil

Pub: Transactions, American Geophysical Union

Date: 1954 Vol: 35 No: 1 Pages: 121-132

Author: Lettau, H.

1. The paper discusses the problems in using the homogenous simple heat equation to estimate thermal diffusivity based on temperature data only and uses an improved method that allows for non-homogenous soil.

2. This improves on the typical method of estimating thermal diffusivity to allow for non-homogenous soil with depth and/or time.

3.

4. This method of estimating thermal diffusivity should be used since it does not depend on a homogemous soil profile.

No. 72

Title: I. Relationships of soils to mountain and foothill range habitat types . . .

II. Predicting soil temperature regimes of mountain and foothill sites . . .

Pub: PHD Thesis, Montana State University

Date: 1977 Pages: 1-126

Author: Munn, L. C.

1. In the second part of this thesis, the author develops a predictive equation for average yearly soil temperature based on multiple regression using as independent variables, site latitude, aspect, slope, elevation and thickness of an O horizon, if present. The R for various regressions ranges from .69 to .97.

2.

3.

4. The independent variables used in this work most certainly will be used in any complete physical model to predict soil temperature.