TEMPERATURE VARIATIONS

IN A FINE

SANDY LOAM

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IN A
FINE SANDY LOAM

By

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SCOPE AND CONTENTS:

Six plots on the McMaster University campus were instrumented with thermocouples down to a depth of 225 cm. The choice of instruments and procedures was outlined and justified. A complete description of the site soil and climatic characteristics was made. Throughout the year soil temperature observations were taken to provide a complete picture of the conditions prevailing. In addition to studying the annual march of temperature, experiments were conducted by applying simple surface treatments to test plots and comparing the results with an untreated control plot. These experiments were conducted both over a period of weeks and on the daily scale.

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CHAPTER 1

INTRODUCTION

This thesis is a study in Micro-climatology, in that field of the subject concerning the climate of the soil, more particularly involving soil temperatures. The aim is to provide some account of the temperature variations experienced in a fine sandy loam under a middle-latitude climate.

In order to implement this aim, a natural soil profile was instrumented with temperature sensing devices down to a depth of 225 cm in the Hamilton area. Readings of temperatures were made in the period November 1963, until September 1964, to provide results under two major programmes:

1. First a study of the general soil temperature regime of this area. This programme entailed two inter-related phases:

a) Observations taken once every day or two to enable a continuous picture of soil temperatures throughout the year to be established.

b) To supplement the general observations, intensive short period observations were also made. These results were based on a 24-hour period with readings taken at least every hour. Thus, in this manner, the small-scale elements combining to produce the general trends were studied to give a more complete understanding of the results obtained.

2. The second programme involved experiments run concurrently with the general observation, at two specific times, one in the winter, the other in the summer. The aim of these experiments was to provide quantitative results of the extent to which the natural soil temperatures may be modified by the application of simple surface treatments. The treatments used were as follows:

a) Winter experimental period

i) Application of a 6 inch thick straw mulch

ii) Removal of all incident natural snow cover

b) Summer experimental period

i) Colouring the surface with Lamp-Black

ii) Colouring the surface with white Talc.

iii) Stripping the natural grass cover and planting a crop of oats.

Such experiments, involving artificial modification of ground temperatures, provide results which lead to a further understanding of the processes involved in the natural course of heat flow within the soil. In addition to the theoretical results, conclusions of immediate practical importance to agronomists, ecologists, foresters, engineers and many other workers may result. An indication of the value of soil temperature work to other subjects follows.

<u>Biological Sciences</u> - Zoologists, Botanists, Ecologists and workers in related fields all have a very keen interest in the climate of the soil. For instance plant growth is found to be accelerated within certain ranges of soil temperature, and inhibited beyond such

boundaries. Especially temperature extremes influence the germination of seeds, root development, rate and duration of growth, and the control of weeds and diseases. Entomologists and Zoologists find ground temperature an important habitat factor in determining the distribution and activity of animal life, even affecting such animals as rodents and lizards. The growth, multiplication and activities of soil micro-organisms are also affected by soil temperatures.

Agronomists and Foresters - Both agronomy and forestry depend upon the ability of the soil to yield its maximum. It is not unusual therefore to find that much of the data on soil temperatures was acquired specifically for its use in these two fields. Of special importance has been the influence upon ground temperatures of a cover, and the ability of various crops and trees to withstand abnormal extremes; the influence of fertilizers and methods of cultivation have also been studied.

Engineers - The construction of highway pavements, airport runways, the design of building foundations, the installation of water, gas and oil pipelines all require a knowledge of temperature conditions within the ground. In this respect it is usually of greatest importance to know the depth of frost penetration, and the liability of the ground to frost-heaving. Similarly when installing a pipeline temperature fluctuations which may cause expansion and contraction of the pipe joints have to be minimized. The Hydrologist must forecast the moisture supply in the soil. Because the ability of the soil to hold water decreases with an increasing temperature, he also must understand the micro-climate of the soil.

Geographers - The influence on Climatology will be discussed later, but a knowledge of soil temperature is also necessary in other geographical fields. For instance Biogeographers are constantly referring to the distribution of Vegetation zones, and Great Soil zones. As Keen[1] points out, soil temperatures play a large part in these divisions. Soil profile development depends on the weathering of parent materials by mechanical and chemical action. Both these processes are affected by ground temperatures, mechanical weathering by frost heaving, and heat expansion; and chemical reactions are dependent upon van't Hoff's Law, which states that the speed of chemical reactions doubles with each rise of temperature of 10° C. Equally in processes concerned with patterned ground, and other perma-frost features, and the formation of laterite in geomorphology, soil temperatures must be consulted. Indeed the study of soil climate provides a typical example of the way in which Micro-climatology can provide a link for the integration of many seemingly unrelated facets, of not only a single subject, but also many schools of discipline.

Climatologists - One of the fundamentals of climatology states that "the atmosphere is heated from below"; because the solar energy absorbed by a unit area of the earth's surface far exceeds that absorbed by the atmosphere directly. Consequently most of the atmos-

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1 B. A. KEEN, "Soil Physics in relation to Meteorology", "Quarterly Journal Royal Meteorological Society Vol. 58, 1963, p. 229

phere's heat must be gained indirectly from the earth's surface by the processes of conduction, eddy diffusion, and both long wave and diffuse-sky radiation. As the atmosphere is heated from below then it is of great importance in climatology to fully understand the processes and conditions of this source region. The air layer adjacent to the ground is drastically affected by ground conditions, and in particular by its temperature. As an example of this inter-relationship, Siegenthaler[2] has calculated the correlation coefficient between the 10 cm soil depth and the air temperature of the macro-climate to be as high as 0.87. In addition to temperature, other elements such as humidity, and wind velocity are greatly influenced by the ground and so the fields of micro-climatology and micro-meteorology are devoted to the study of conditions in this complex zone adjacent to the earth's surface. However, these processes do not halt at the boundary layer, many extend down into the soil, and so as Blanc[3] says, "Soil temperature measurements are an important and an appropriate field of investigation for the climatologist".

As an example of how soil temperatures may affect the overlying atmospheric climate Sutton[4] emphasizes the importance of soil

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[2] J. SIEGENTHALER, "Bodentemperaturen in Abhängigkeit von äusseren meteorologischen Faktoren" Beitrage zur Geophysik Vol. 40, 1933, p. 305-332.

[3] M. L. BLANC, "The Climatological investigation of soil temperature", World Meteorological Organization, Technical Note No. 20, 1958, p. 10.

[4] O. G. SUTTON, "Micro-meteorology", McGraw-Hill, 1953.

temperatures on fog occurrences, and the frequency of frosts. Blanc[5] refers to the work of Kuhn, Darkow and Suomi, which indicates that soil temperature "hot-spots" are related to the occurrence of tornadoes. Similarly, the effectiveness of precipitation in arid areas, and the insulation provided by a snow cover in colder areas is directly governed by the temperature of the ground. Through turbulence the ground temperature plays a part in modifying air masses of the general circulation. These and many other examples led Sutton[6] to the statement, "any detailed study of the temperature field in the lower atmosphere must necessarily consider conditions at the surface itself, beginning with the properties of the ground".

A short review of the literature follows, to establish what work has already been done in this field of soil temperatures, and therefore what is known and proven. The review is broken down into 3 sections specific to this thesis:

1. General soil temperature work
2. Canadian material
3. Work on modification of soil temperatures.

1. <u>General soil temperatures</u>

The first well documented evidence of soil temperature work comes from Forbes[7], working in the Edinburgh vicinity as long ago as

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[5] M. L. BLANC, Op. cit. 1958, p. 3.

[6] O. G. SUTTON, Op. cit. 1953, p. 192.

[7] J. D. FORBES, "Account of some experiments on the temperature of the earth at different depths and in different soils near Edinburgh", Transactions Royal Society (Edinburgh) Vol. 16, 1846.

1837. However, Forbes notes that Sir John Leslie had taken soil temperature observations in the same area from 1815-19, and the same author credits a German mathematician, Lambert, with the first systematic analysis of soil temperatures. The instruments used by Forbes, as described in Chapter 2, were far from ideal; the advent of modern instruments at the turn of the century made the study of subsurface temperatures considerably more simple.

Callendar and McLeod[8] working in Montreal were amongst the first to use these new instruments and a rash of important work followed. Rambaut[9] conducted experiments at Oxford with electrical resistance thermometers similar to those of Callendar and McLeod, for a period of twelve years, and again similarly excellent results were obtained. Some of the most basic soil temperature problems were attacked by Patten[10] in 1909, especially concerning the nature of soil conductivity with changing moisture content. Following this in the period 1913-22 Dr. C. J. Bouyoucos[11] of Michigan State College conducted his pioneer work in most of the basic problems encountered

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[8] H. L. CALLENDAR, C. H. McLEOD, "Observations of soil temperatures with resistance thermometers" Transactions Royal Society Canada 1895-6-7 and 1901, Vols. 1, 2, 3 and 7 respectively.

[9] A. A. RAMBAUT, "Underground temperatures at Oxford as determined by five platinum resistance thermometers" Results of Meteorological Observations at Radcliffe Observatory, Oxford 51, 1916, p. 103-204.

[10] H. E. PATTEN, "Heat transference in Soils" U. S. Department of Agriculture, Bureau of Soils, Bulletin No. 15, 1909.

[11] C. J. BOUYOUCOS, Michigan Agricultural College Experimental Station, Technical Bulletins Nos. 17, 22 and 26.

in the study of soil temperatures. His classic papers concerning the factors involved in ground temperatures are still a standard reference. At the same time Franklin[12] was conducting valuable research on various aspects of soil temperatures, especially the manner and degree to which they are influenced by weather changes. In the 1920's and 30's Smith[13] in California, and Keen[14] in England further contributed to the general understanding of the subject. Since this date workers have tended to concentrate on more specialized aspects of soil temperatures and more than 200 papers in English have been published. Present avenues of research include perma-frost studies, heat transfer problems, moisture migration, and the effect of applications for horticultural purposes.

2. Canadian Soil Temperatures

The first known soil temperature measurements made in Canada were those of Callendar[15] at McGill University, Montreal in 1894,

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[12] T. B. FRANKLIN, "The effect of weather changes on soil temperatures", Proceedings Royal Society, Vol. 40-41, 1919-20, p. 56-79.

[13] A. SMITH, "Diurnal, average and seasonal soil temperatures at Davis, California", Soil Science Vol. 28 (No. 6), 1929, p. 457-68 and "Seasonal subsoil temperature variations", Journal of Agricultural Research, Vol. 44 (No. 5), 1932, p. 421-28 and HILGARDIA, Vol. 4 (No. 3) 1929, Vol. 2 (No. 10) 1927, Vol. 6 (No. 6) 1931, and Soil Science, Vol. 22, 1926, p. 447-57.

[14] B. A. KEEN, "Soil temperature" in Physical Properties of Soils, 1931, p. 295-333 and "Soil physics in relation to Meteorology", Q.J.R.M.S. Vol. 58, 1932, p. 229-250 and E. J. RUSSELL, "Factors determining soil temperatures", Journal of Agricultural Science, Vol. 11, 1921, p. 211-239.

[15] H. L. CALLENDAR, Op. cit. 1897-8.

according to Crawford and Legget[16]. Using platinum resistance thermometers at 6 depths down to 9 feet, observations were made in the period 1894 to 1900. The results are exceptionally good and illustrate well many important features. In particular the extreme steadiness of the winter curves, due to the protective effect of snow was brought out well; also over the period of years the depth of freezing was found to vary widely depending especially upon the depth and date of fall of snow. The effects of rainfall were marked, both in raising spring temperatures, and lowering them in the summer.

Soil temperatures were taken by Harrington[17] at Saskatoon, Saskatchewan in the period 1921 to 1923. Nickel resistance thermometers were buried down to depths of 8 feet, and connected to a continuous recorder. Mean daily temperatures were plotted on an annual scale and several interesting points were noted. For instance in three months, beginning in March, the 8 foot level never varied more than 1 degree Fahrenheit (^{o}F) from a temperature of 35^{o}F. The reduced amplitude of waves with depth, and a similar time lag with depth were observed. The familiar "overturn" of soil temperatures was well illustrated, and analyzed. Harrington[18] at the end of his paper indicates possible means by which man might modify ground temperatures.

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[16] C. B. CRAWFORD and R. F. LEGGET, "Ground Temperature Investigation in Canada" The Engineering Journal, Vol. 40, 1957, p. 263.

[17] E. L. HARRINGTON, "Soil Temperatures in Saskatchewan" Soil Science Vol. 25, 1928, p. 183-194.

[18] Ibid. 1928, p. 194.

From 1929 to 1934 Thomson[19] conducted similar experiments at Winnipeg, Manitoba, at various depths down to 15 feet, again using electrical resistance thermometers. Readings were only taken weekly, so as Ruedy[20] says no true mean values were obtained. Nevertheless important results emerged, especially again illustrating the protective influence of a snow cover, and the lag in minima and maxima at each depth before the "overturns" (Chapter 4). The penetration of frost into the soil, with and without a snow cover was also investigated.

At Guelph, Ontario, in the period 1930 to 1932, Kimball, Ruhnke and Glover[21] obtained soil temperatures in a light sandy soil by use of mercury-in-steel thermographs down to only 2 feet. The results are not well documented, but the authors report a considerable lag in the response of soil to air temperatures, and that this lag increases with depth. The pattern of winter soil temperatures even without much snow cover was a relatively steady one, compared to the summer variations.

From 1924 to 1939, and again from 1945 until 1952 soil temperatures were observed at the Meteorological Office in Toronto.

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19 W. A. THOMSON, "Soil Temperatures at Winnipeg, Manitoba", Scientific Agriculture, Vol. 15 (No. 4), 1934, p. 209-216.

20 R. RUEDY, "Soil Temperatures in Canada", National Research Council, Ottawa, February 1937, p. 1-11.

21 D. A. KIMBALL, G. N. RUHNKE and M. P. GLOVER, "A Comparison of temperatures in air and at various depths in a light sandy soil in Southern Ontario", Scientific Agriculture, Vol. 14, 1934, p. 353-59.

More recently the Department of Agriculture has set up 8 soil temperature stations across Canada using thermistor thermometers down to a depth of 150 centimetres (cm). The Division of Building Research has also determined temperatures at various sites across Canada, especially in the north. Much of this work is concerned with the problem of construction in perma-frost regions.

The field of soil temperatures in Canada may therefore be said to have been investigated but certainly not completed, and because of the almost numberless factors involved in soil temperatures, each area is distinctly unique and does not usually provide anything approaching a duplication of work elsewhere. Certainly work on the intensive, diurnal scale is sadly lacking in Canada.

3. Artificial Modification Experiments

Man has known for a long time that treatments made to the ground's surface will either beneficially or adversely affect its ability to yield produce. By making these treatments the heat, and often the moisture budget, of the soil is affected. Wollny[22], in 1878 was one of the first to scientifically explore the reasons and results of such applications. He was especially interested in the influence of the colour of the soil upon its warming. Wollny[23] notes a number of authors who observed increased yields from dark

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[22] E. WOLLNY, "Untersuchungen über den Einfluss der Farbe des Bodens, auf dessen Erwärmung", Agrikultur Physik 1, 1878, p. 43-72.

[23] Ibid. p. 44, 45.

coloured soils in Europe, and credits Schübler as being the first to establish these influences by experiment. His own experiments show conclusively the importance of colour upon the absorption of heat. Bouyoucos[24] made significant contributions in this field, especially in concluding that colour has no effect upon radiation, but that it considerably affects absorption.

Continuing the experiments on the effect of colour, Ramdas and Dravid[25] covered plots black and white in India in 1934; their results are striking and will be presented later in this thesis. In 1949 Everson and Weaver[26], using carbon black obtained similar results.

A straw mulch is known to produce similar results to those of a paper mulch, in reducing temperature variations in the soil. Work has been conducted on both these treatments by Shaw[27], Smith[28],

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[24] G. J. BOUYOUCOS, Op. cit. Bull. 17, p. 31.

[25] R. K. DRAVID, "Studies in Soil temperatures", Indian Journal of Agricultural Science, Vol. 10 (Pt. 3) 1940, p. 352-87 and L. A. RAMDAS and R. K. DRAVID, "Soil Temperatures in relation to other factors controlling the disposal of Solar Radiation at the Earth's Surface", Proceedings National Institute of Science, India Vol. 2 (No. 3), 1936, p. 131-43.

[26] N. EVERSON and J. B. WEAVER, "Effect of carbon black on properties of Soils" Industrial and Engineering Chemistry, Vol. 41, 1949, p. 1798-1801.

[27] C. F. SHAW, "Effect of a paper mulch on soil temperature" Hilgardia, Vol. 1 (No. 15) 1926, p. 341-64.

[28] A. SMITH, "Effect of mulches on soil temperature during the warmest week in July, 1925" Hilgardia, Vol. 2 (No. 10), 1927.

Oskamp[29], Bushnell and Welton[30], and Daigo and Maruyama[31], the results in all cases show the same general pattern of insulation, especially during the winter months.

All investigators agree that snow is a leading factor in protecting the soil from severe frost, although its exact protective influence is in dispute. Bouyoucos[32], Franklin[33], Thomson[34], Harrington[35], Mail[36], have all commented on its general effect. However, the relation between depth of snow and the reduction of the frost-line is still not satisfactorily proven. In this regard the works of Atkinson and Bay[37] and Crawford and Legget[38] are standard references.

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29 J. OSKAMP, "Soil temperatures as influenced by cultural methods", Journal of Agricultural Research, Vol. 5, 1915-16, p. 173-179.

30 BUSHNELL and WELTON, "Effects of straw mulch on yield of potatoes", Journal of Agricultural Research, Vol. 43, 1939, p. 837-45.

31 Y. DAIGO and E. MARUYAMA, "Micrometeorological study on the effect of straw-matting", Journal of Agricultural Meteorology, Vol. 7, 1952, p. 74-76.

32 G. J. BOUYOUCOS, Op. cit. Bull. 26.

33 T. B. FRANKLIN, Op. cit. 1919-20.

34 W. A. THOMSON, Op. cit. 1934.

35 E. L. HARRINGTON, Op. cit. 1928.

36 G. A. MAIL, "Soil temperatures at Bozman, Montana during Subzero weather", Science, Vol. 83 (No. 2163), 1936.

37 H. B. ATKINSON and C. E. BAY, "Some factors affecting frost penetration" Trans. Amer. Geophys. Union (Pt. III), 1940, p. 935-48.

38 C. B. CRAWFORD and R. F. LEGGET, "Soil temperatures in Water Works Practice" Journal of American Water Works Association, Vol. 44 (No. 10) 1952, p. 923-39.

Information pertaining to the effect of a crop on soil temperatures has usually been of direct use only in agriculture, but again the fine work of Ramdas and Dravid[39] has provided an excellent general account.

Much more work is needed concerning the modification of the soil climate, because the possibilities for practical application are enormous. Intensive study may make agriculture an economic proposition in areas previously rendered useless by a disadvantageous soil climate.

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39 L. A. RAMDAS and R. K. DRAVID, Op. cit. 1936, p. 141 and R. K. DRAVID, Op. cit. 1940, p. 372.

CHAPTER 2

INSTRUMENTATION

The number of factors influencing the temperature of the soil is very great. Bouyoucos[1] divides these factors into two groups a) Intrinsic, b) External. The intrinsic factors are those contained within the soil, including specific heat, heat conductivity, moisture content, topographic position, soil texture and structure and other such parameters. The external factors however comprise the meteorological elements and include radiation, air temperature, sunshine, wind, pressure, rainfall, snow and related influences acting upon the intrinsic factors of the soil.

This chapter is designed to illustrate and justify the methods employed to measure these various parameters, mainly 'external', which govern the temperature of the soil, and also the instrumentation and procedures used to actually obtain these ground temperatures.

Any scientific study requires a statement concerning the instrumentation used; in a micro-climatic work this necessity becomes critical, as Thornthwaite[2] says, "Instrumentation remains the basic

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[1] G. J. BOUYOUCOS, Op. cit. 1913, 1916.

[2] C. W. THORNTHWAITE, "Topo-climatology", UNESCO Arid Zone Research, Canberra Symposium, Vol. XI, 1958.

problem in micro-climatic research". With this in mind the section here dealing with a description of the instrument and the reasons for their choice is a detailed one. The selection of instruments was made not only with reference to their performance, but also to those general limitations which must be considered in every project - expense involved, time and personnel available.

Subsurface Temperature Equipment

Instruments which might be used for the measurement of sub-surface temperatures can be classified in accordance with the following principles:

A. Thermal expansion of liquids

1) Mercury-in-glass thermometers

a) Bent-stem thermometer

b) Sheathed earth thermometer (Symons pattern)

d) Penman brass-strip and Assmann thermometer

e) Maximum and minimum thermometer (Six's pattern)

2) Mercury-in-steel thermometers

B. Electrical resistance

1) Electric resistance wire - usually platinum or nickel

2) Thermistors

C. Thermo-electricity

Thermocouples - usually base-metal combinations such as Copper : Constantan or Iron : Constantan.

All the above instruments use the 'contact' method of recording temperatures. Contact methods are defined in British Standard Specification 1041 : 1943 as depending on translational and vibrational energy forms, the thermo-dynamic equilibrium between the hot body and the testing body being arrived at by physical contact between the two. 'Non contact' methods are not suitable for subsurface temperature measurement because the testing body is usually a form of radiometer which is placed at some distance from the hot body. Non-contact methods are therefore usually used for surface temperature measurements.

A short discussion of the inherent merits and defects of the various methods of measuring ground temperatures seems necessary to justify my choice of equipment.

A. Expansion thermometers

1) Mercury-in-glass thermometers

As long ago as 1837 Forbes[3] used mercury-in-glass thermometers, with up to 26 foot stems to obtain ground temperature information in the area around Edinburgh. In 1923 McColloch and Hayes[4] used mercury thermometers lowered into auger holes; a Symons pattern thermometer was used at Campden Square[5] and Johnson and Davies[6] used

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[3] J. D. FORBES, Op. cit. 1846

[4] McCULLOUGH and HAYES, "Soil temperature and its influence on white grub activities" Ecology, Vol. 4 (No. 29).

[5] Earth temperatures at Campden Square, QJRMS, Vol. 69, 1943, p. 198.

[6] JOHNSON and DAVIES, "Some measurements of temperatures near the surface in various kinds of soils" QJRMS, Vol. 53, p. 45-57, 1927.

maximum and minimum thermometers buried to a depth of 1 cm. Penman[7] designed a simple brass strip for use with a mercury-in-glass thermometer to measure the average temperature of the topmost 1/2 inch of soil, and Dravid[8] used Fuess bent-stem thermometers in his modification of subsurface temperature experiments in Poona.

These methods have much to offer in simplicity of installation and observation, but they suffer from serious deficiencies. The thermometers are usually very fragile and thus become hard to insert into, or retract from, the soil. Certainly to reach a depth of 7 feet 6 ins. would involve considerable instrument breakage and disturbance of the soil. When using expansion thermometers at different depths, unequal lengths of column are exposed to the overlying ground, and atmosphere, and in this way conduction and radiation errors are introduced into the observations. Pressure on the bulb has also been known to introduce errors.

When the stem is underground breaks in the mercury column may pass un-noticed.

2) Mercury-in-steel thermometers

These instruments have been used in conjunction with a recording thermograph by most workers such as Penman[9],

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7 H. L. PENMAN, "Daily and seasonal changes in the surface temperature of fallow soil at Rothamstead" QJRMS, Vol. 69, p. 1-16, 1963.

8 R. K. DRAVID, Op. cit. 1940.

9 H. L. PENMAN, Op. cit. 1943.

Coutts[10], McCulloch[11], and Kimball, Ruhnke and Glover[12]. In this way they were able to obtain continuous records of soil temperatures. These instruments are good for soil work in that they are more rugged than mercury-in-glass thermometers, but they are less accurate. The steel casing reaching up to the surface introduces the possibility of conduction errors from overlying soil layers to the sensing bulb. It would not be practical to instrument this experiment using six plots and 59 depths in all with mercury-in-steel thermometers.

B. Electrical Resistance Thermometers

1) Resistance wires

A number of classic investigations have been made using electrical resistance wire thermometers. Most notable are those conducted by Callendar and McLeod[13] in Montreal in 1894; by Rambaut[14] in Oxford in 1915; by Smith[15] in California in 1926; by

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10 J. R. H. COUTTS, "Soil in an afforested area in Aberdeenshire" QJRMS, Vol. 18, p. 72, 1955.

11 McCULLOCH, "Soil temperatures near Nairoir", QJRMS, Vol. 85, p. 51, 1959.

12 KIMBALL, RUHNKE and GLOVER, Op. cit., 1934.

13 H. L. CALLENDAR and C. H. McLEOD, Op. cit., 1895-6-7, 1901.

14 A. A. RAMBAUT, Op. cit., 1916.

15 A. SMITH, Op. cit., 1926.

Thomson[16] in Winnipeg in 1934, and Harrington[17] in Saskatchewan. Some workers prefer platinum resistance wires, others those made of nickel; whichever type is chosen the results are very accurate and lend themselves to continuous recording techniques. However, these instruments are extremely delicate and therefore to position them at the required soil depths requires considerable disturbance of the profile and a suitable time must subsequently be allowed for the soil to re-settle to its natural state. Accuracy is assured but the expense involved and time required to allow re-settling of the soil precluded their use in this investigation.

2) Thermistors

The Canadian Department of Agriculture is currently using thermistors in its national study of soil temperatures at eight localities. The thermistor is small, rugged and very sensitive, but also relatively expensive. Each thermistor is an individual element and must be calibrated as such, in addition to which, slow shifts in this calibration have been reported. At the present level of development thermistors do not appear to be wholly reliable, as evidenced by breakdown in the records of two of the Department of Agriculture's[18] stations. They are also susceptible to chemical corrosion.

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16 W. A. THOMSON, Op. cit., 1934.

17 E. L. HARRINGTON, Op. cit., 1928.

18 "Soil temperature records at 8 localities in Canada, 1959-60" Department of Agriculture, Canada, March 1962.

C. Thermo-electricical Thermometers

The last of the methods of temperature measurement is that used in this investigation, namely the thermo-electrical method. This method of observing not only subsurface, but also air and water temperatures, has gained considerable favour amongst micro-climatologists of late. For instance Thornthwaite[19] used Copper/Constantan thermocouple in most of his investigations, especially those recording multiple processes in a short period of time. Rider[20] used Copper/Constantan thermocouples in conjunction with a tufnol tube for some of his investigations. Algren[21] also used Copper/Constantan whereas Ward[22] favoured Iron/Constantan. None of these workers notes any difficulties incurred in the use of this method, in contrast to some of the setbacks encountered by other workers using non-thermoelectric methods.

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19 C. W. THORNTHWAITE, "Report on micro-climatic investigations at Seabrook, New Jersey" Interim Report No. 10, Rutgers University.

20 E. RIDER, "An instrument for continuous recording of soil temperatures" Meteorological Magazine, Vol. 84, p. 329, 1955.

21 A. B. ALGREN, "Ground temperatures as affected by weather conditions" Heating, Piping and Air-Conditioning, Vol. 21, p. 111-116, 1949.

22 W. C. WARD, "Temperature measurements from 10 feet above to 10 feet below the soil surface" U. S. Navy Ordnance Station, NOTS, TM, 243, 17 p., 1952.

The use of thermoelectricity began in 1821 when Seebeck discovered that an electric current flows continuously in a closed circuit of two dissimilar metals when the junctions are maintained at different temperatures. A pair of electrical conductors so joined as to produce such a thermal electromotive force (E.M.F.) is known as a "thermocouple"; and a thermoelectric thermometer consists basically of a thermocouple and an indicator for measuring this E.M.F. developed. Depending on the constitution of the metals used, the E.M.F. varies in a set manner related to the temperature difference between the two metal junctions; if the E.M.F. is measured the temperature difference can be calculated. To this end a potentiometer is introduced into the circuit. Essentially the potentiometer consists of (i) a 1.5 volt cell able to emit a current in the circuit, in the opposite direction to that of the thermally induced E.M.F. and thus "opposing" it; (ii) a standard cell and rheostat to balance the 1.5 volt cell; (iii) a sensitive suspended-coil galvanometer to indicate whether or not a current is flowing within the circuit. By adjusting the galvanometer reading to zero just enough current is taken out of the 1.5 volt cell to exactly equal the opposing thermal E.M.F. When the galvanometer needle reads zero, there is no current in the circuit, thus the thermal E.M.F. has been equalled. The instrument now indicates how much E.M.F. from the 1.5 volt cell was required to equal the thermal E.M.F. and is thus a direct measurement of it, in millivolts. From a knowledge of this E.M.F., the "temperature difference" between the junction is obtained from standard tables. If one junction is immersed in a flask containing a mixture of ice and water, that junction's temperature is known absolutely to be 32.0° F, and it is termed the "cold junction". It is then a simple matter to find the temperature of the other junction, known as the "hot junction".

This then is essentially the theory lying behind the use of thermo-electricity for measurement of temperatures - the "hot" junction remains the unknown to be determined and is therefore used as the sensing element. The "cold" junction is kept at a constant temperature to provide a reference and thus facilitate the calculation of the sensing element's temperature. The potentiometer is included within the circuit to measure the thermal E.M.F. developed by the thermocouple, in millivolts, which from a calibration graph or table can be converted into a temperature reading.

This method was chosen for the investigation in hand because it contained a number of special advantages:

1. <u>Accuracy</u> - As Weber[23] says "thermoelectric pyrometry has attained a degree of precision inferior only to that of resistance thermometry below 900° C" - but as already stated resistance wires have disadvantages which ruled them out of this study. Providing suitable thermo-couple materials are used, the precision obtained depends upon the sensitivity of the galvanometer, and therefore the scale can be made open to permit precise reading. Indeed with Copper/Constantan thermo-couples of the purity used in this investi-

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[23] R. L. WEBER, "Heat and temperature measurement", Prentice-Hall Inc., p. 62, 1950.

gation, and with a galvanometer accuracy of 0.01 millivolts, temperatures can be attained to within ±0.4°F with absolute certainty, and usually even greater sensitivity is a practical possibility.

2. One calibration - The thermocouple wire now being produced by wire manufacturers is sufficiently homogeneous in chemical composition to prevent any change in its electrical characteristics along its length. It is thus only necessary to calibrate one or two couples out of a reel of wire. Even more important, this calibration remains virtually stable throughout the life of the thermocouple, and it is not suspect to shifts of calibration as in the case of some thermistors. Thus broken thermocouples may be replaced in the field from similar wire without the need to recalibrate.

3. Zero current - When the galvanometer is balanced (i.e., when the thermal E.M.F. is exactly opposed by a known output from the 1.5 volt cell) there is no current in the circuit. This means there is no heating of the sensing element as in some other electrical methods. Since, in addition, the value to be measured is an E.M.F., not a resistance, the length of lead wire is immaterial.

4. Balanced for ambient temperature - Some potentiometers can only be used if they are kept within a defined temperature range because outside these limits the working characteristics of the instrument change. However, in the case of the instrument used in this investigation, it may be operated in any ambient temperature provided it is allowed to acquire this temperature. As Roeser[24] says

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[24] W. F. ROESER, "Thermo-electric thermometry", American Institute of Physics, Manual on Temperature, Reinhold Publishing Corporation, p. 188, 1941.

"as long as the instrument is at essentially a uniform temperature, all the junctions in the instrument, including the terminals, will be at the same temperature, and the resultant thermal E.M.F. developed in the circuit is not modified by including the instrument". In a recent report of tests on this potentiometer carried out by Messrs. Vickers Armstrong Instrument Testing Division, it was stated that it may take up to 3 days to acquire the ambient temperature subsequent to a large change in the temperature of its environment due to the temperature hysterisis of the standard cell. In this investigation, however, the instrument is permanently "in situ" and so is completely able to follow changes in its surrounding temperatures.

5. Adaptability - Most instruments have a specific applicability which precludes their use in experiments other than those of a special nature. The potentiometer and thermocouple on the other hand are renowned for a tremendous adaptability and range of uses. Using the correct wire gauges and possibly shielded thermocouples they can be used to obtain temperatures almost anywhere - in water, in air, on a surface, within a solid. They may be used to measure molten metal temperatures, or those under the epidermis of a leaf. As will be described in the succeeding headings, thermocouples in conjunction with the same potentiometer, were used in this study to obtain not only subsurface, but also surface, snow and air temperatures.

6. Portable - Should the instrument be required at another site it can be carried with the greatest of ease, and used

immediately with the greatest confidence, providing the ambient temperatures between the two sites are not radically different.

7. Rugged - The Weston normal standard cell and galvanometer used in this instrument have been designed and constructed in such a way as to withstand rough handling, and thus adds confidence in its portability.

8. Inexpensive - Once the initial cost of the potentiometer has been met, any number of sensing elements can be situated at only the low cost of the wire. Maintenance is negligible.

9. Speed - The sensing elements are so small that unlike mercury-in-glass thermometer bulbs they have a very low thermal capacity and therefore almost no thermal lag. In this way the element records temperature changes almost immediately.

Also, any number of thermocouples may be joined into thermocouple switches and so brought into the measuring circuit at will and with the rapidity only governed by the operator's speed of observing. Any number of sensing elements can thus be used in co-operation with one potentiometer.

10. Easy insertion - Due to the small size of the measuring element and its rugged construction, the thermocouple is easy to instal with the minimum of disturbance of the body whose temperature is to be measured.

11. Durability - The lead wires are usually covered in some inert, durable sheathing and the junction is either soldered or welded and then covered with a coating of an expoxyresin. In this way the thermocouple is made resistant to corrosion, abrasion and

oxidation which might affect its thermal properties.

Naturally no one would claim this method to be perfect; it does have its disadvantages:

1. Reference temperature - One junction, the "cold" junction, must be kept at a known temperature to provide a reference against which the temperature of the sensing element can be evaluated. The usual method is to employ a vacuum flask containing a mixture of ice and water in equilibrium and use this as a 32.0°F unit for comparison. However, during extreme temperature conditions some minor difficulties have been encountered. During weather with near zero temperatures the tendency is for the flask contents to freeze solid; conversely in hot summer weather the tendency is towards melting. In either case the equilibrium is upset and the reference junction provides a faulty unit of comparison. Thus the mixture must be kept well stirred and all possible air excluded. To this end the "cold" junction wires were inserted through a hole in the covering cork, and air excluded by packing glazier's putty around them. Constant attention is required, and the possibility of a more efficient "built-in" reference junction will be sought in the future.

2. Stray E.M.F.'s - The principle of two dissimilar metals producing an E.M.F. provides a source of error as well as a method of measuring. If the switch gear used in the circuit should contain anything but the exact same metal as that composing the lead wire, a "stray E.M.F." is developed causing erroneous observations. To avoid this source of trouble all connections in switches are manufactured

of pure copper, i.e., the same metal as the lead wires.

3. Continuous recording - By using an automatic recorder highly desirable continuous traces of thermocouple temperatures can be obtained. However, at the present stage of instrument development portable, transistorized, automatic recorders for field use are not available to give the required sensitivity. It is, however, hoped that these instruments may soon be developed and available.

Specifications

a) Potentiometer - The instrument used is a Mini Thermocouple Potentiometer made by Doran Instrument Company Limited, Stroud, England; a member of the Derritron Group. The instrument, as described, is a light (7 3/4 lb), compact (8 3/4" x 5 3/4" x 5 3/4"), portable unit with an accuracy (0.01 millivolts) equal to that of larger more expensive potentiometers. This potentiometer has a range of 20 millivolts and readings can easily be made direct to 10 microvolts. The whole is housed within a durable laminated, black bakellite box, with handle attached.

b) Wire - The wire used in this investigation is manufactured by Thermoelectric (Canada) Limited, and is designed purely for thermocouple use. The Copper and Constantan are solid wires, individually insulated and then bound together. To construct a thermocouple it was merely necessary to strip the two wires apart, bare the ends of insulation and then mechanically twist the wires together to make the junction. This being completed the junction was soldered and then double coated with a durable expoxyresin to prevent abrasion or corrosion of the sensing element. Because the wire was for use below ground, and therefore not open to direct radiation, the factor of wire gauge was not a critical one. For reasons of availability and ease of use, 24 gauge B and S Copper and Constantan was used, and the insulation material was either nylon or polyvinyl. It was found that the polyvinyl covered wires were by far the easiest to work with, the nylon tending to be rather "springy" and unmanageable. The accuracy of the wire guaranteed by the manufacturers was ± $3/4^{\circ}F$ in the range 75-200°F. This means that the calibration curve will be within ± $3/4^{\circ}F$ of the Standard Calibration Curve as stated in the Handbook of Physical Constants, using a perfectly balanced mixture of Nickel and Copper in the Constantan wire. To determine the exact E.M.F./Temperature relationship, calibration was carried out and is later discussed fully.

c) <u>Thermocouple switches</u> - Two makes of switches were used during the year. First, 20-point thermocouple switches manufactured by the Doran Instrument Company Limited, and secondly a 24-point switch made by Thermoelectric (Canada) Limited. Both were designed especially for use with thermocouples and so incorporate all-copper contacts to eliminate any possibility of the development of stray E.M.F.'s within the switch gear.

d) <u>Vacuum flask</u> - The vacuum flask was similar to the normal domestic fluid carrier except in its feature of possessing a wide neck. The wide-neck was used to facilitate easy insertion of the "cold junctions" into the flask.

Calibration

If one chooses to use Copper and Constantan in the construction of thermocouples, it is possible to attain Copper which is 0.999 pure, and Constantan which is a mixture of 0.55 Copper and 0.45 Nickel, in those exact proportions. If such materials are used the resultant Temperature/E.M.F. relationship fits a well established set of values as defined in the Handbook of Physical Constants. However, it is much more often the case that the Constantan constituents are slightly out from this strict 45 : 55% ratio. As Coxon[25] says "In the manufacture of base metal thermocouples it is inevitable that some impurities will be present, therefore their existence must be accepted and allowed for when the primary standard E.M.F./Temperature relationship for the particular thermocouple class is obtained". In consequence of these impurities, the electrical properties change and the Standard Calibration Curve no longer remains accurate. To establish the particular Temperature/E.M.F. function of a reel of wire a separate calibration becomes necessary. As Roeser and Wensel put it, "The object in the calibration of any thermocouple is to determine an E.M.F./Temperature relation in which the temperature is expressed on a definite and reproducible scale".[26]

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[25] W. F. COXON, "Temperature Measurement and Control", Heywood and Co. Ltd., 1960.

[26] W. F. ROESSER and H. T. WENSEL, "Methods of testing thermocouples and thermocouple materials" in 'Temperature - its measurement and control in Science and Industry', Amer. Inst. of Physics, Reinhold Publishing Corp., p. 285, 1941.

The E.M.F./Temperature relation of a homogeneous thermocouple is a definite physical property due to the characteristics of the metals used, and therefore does not depend upon the details of the apparatus or method employed in determining this relation. In consequence there are innumerable methods of calibrating thermocouples, the choice depending upon the type of couple, the temperature range in which it is to be used, the accuracy required, the wire gauge, apparatus available, and personal preference as to number of calibration points required.

The methods used in the calibration of thermocouples may be conveniently divided into two classes:

a) Calibration at fixed points - This method uses the known melting and boiling points of various substances as the units of reference. However, within the narrow temperature range required for this study, approximately 0-110°F, the number of such points would be extremely limited. This would seriously endanger the required accuracy, as according to Weber "a reduction in the number of calibration points increases the uncertainty proportionately"[27].

b) Calibration by comparison with standard instruments - The comparison method of thermocouple calibration was the one used in this experiment. It requires a minimum of apparatus and personnel, and produced extremely accurate results. Furthermore the number of calibration points obtainable is unlimited and their values can be

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[27] R. L. WEBER, Op. cit. 1950, p. 82.

arbitrarily chosen.

The only equipment required consists of (Plate 1):

a) The potentiometer and vacuum flask for measuring the temperature recorded by the thermocouple under examination.

b) A well insulated or "lagged" container. In this case a flask enveloped in cotton wool and wood shavings was used. The insulation helps to keep the flask and its contents at a steady temperature, unaffected by outside influences.

c) A simple stirrer to ensure the water or other fluid is well mixed, and thus both the thermocouple under test and the standard instrument are at the same temperature.

d) The standard instrument clearly graduated on the correct temperature scale. A well established and verified 4" bent stem thermometer graduated from 0-100°F, manufactured by C. F. Casella, was used in this case. This particular thermometer had two distinct advantages. First, the bulb is large and therefore has a large thermal capacity, thus changes in temperature are recorded slowly and are not subject to minor fluctuations. Secondly, the reading stem lies horizontal when the bulb is placed into the flask thus facilitating ease of accurate observation

e) A liquid for the flask. The liquid used should be capable of being stirred readily at any temperature at which it is to be used, and should not be highly inflammable. As at the National Bureau of Standards water was used in the range from 32.0°F up towards 212°F. Below 32.0°F the Bureau uses a mixture of carbon tetrachloride and

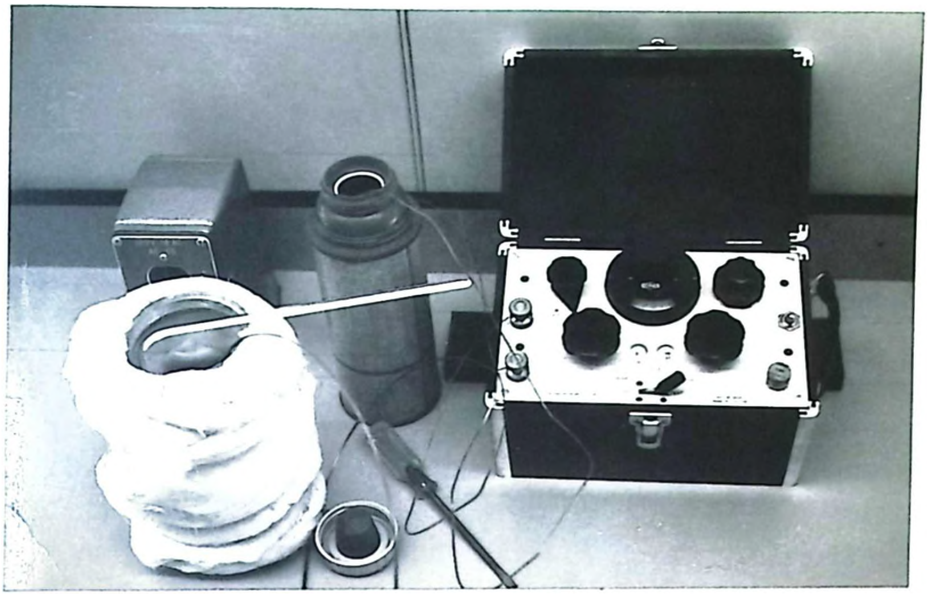

Plate 1. Calibration Equipment

Plate 2. Mechanical shovel excavating pit.
Note the flat, open aspect of the site.

chloroform but in this study a brine mixture was used down to 0°F. Unfortunately, at very low temperatures it became hard to maintain a steady temperature and so a paucity of readings was obtained. This should not hamper this study as only a very few snow temperatures ever became as low as 0°F.

The procedure to be followed is simple and requires at a maximum two observers, one to read the potentiometer, the other to read the mercury-in-glass standard and to record both results as they are made simultaneously. The temperature range for calibration is decided, in this case, from 0-110°F. The liquid in the flask is now cooled or heated to whatever temperature is required, the liquid being continually stirred. When a steady reading is assumed on the standard instrument this temperature and the thermocouple E.M.F. are observed simultaneously - thus a comparison is made. This procedure is repeated at various points throughout the range required, the number of points depending on the accuracy required.

The comparison method is almost certainly the best method for use within this restricted range. According to Roesser and Wensel, "the most accurate calibrations in the range -190 to 300°C are made by comparing the couple directly with a standard instrument in a stirred liquid bath"[28]. The success of this method depends upon four considerations:

a) The accuracy of the potentiometer directly influences the accuracy of the calibration. In this respect this calibration is sound because

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[28] W. F. ROESER and H. T. WENSEL, Op. cit. 1941, p. 285.

the potentiometer used is of considerable sensitivity.

b) Likewise, the accuracy of the standard must be unimpeachable. The thermometer used was checked against others before use, and is graduated to allow accurate observation to 1/10 °F.

c) The ability to maintain the reference junction at a constant known temperature is also a vital factor. The "cold junction" was maintained at 32.0°F in a flask of ice and water in the normal manner. Its temperature was checked constantly with another 4" bent stem mercury-in-glass thermometer.

d) The success of the calibration also depends on the ability of the observer to bring the thermocouple junction to the same temperature as the actuating element of the standard. To this end the liquid was continually stirred to eliminate any sources of discrepancy between the two measuring points.

e) Naturally the homogeneity of the wire is a most vital factor. Calibration is necessary because impurities may exist, but these might also vary along the length of the wire. Here the manufacturer of the wire gives his guarantee - in this case ± 3/4°F from the standard curve in the range 75-200°F.

After a thermocouple has been calibrated, as above, at a number of set points within the required range, the next requirement is a convenient means of obtaining corresponding values of E.M.F. and temperature at other points throughout the range. A curve may be drawn, or a table prepared, which will supply this information. For the purposes of this investigation the former method was chosen and the resultant graph is presented here (Fig. 1). It will be noticed that the calibration presents a gentle curve rather than a straight line, this indicates that equal increments of temperature do not correspond to equal increments of E.M.F.; this is a well recognized physical fact. As will be seen two calibrations were carried out, one a preliminary test run; it is reassuring to note the almost exact correspondence of the two separate calibrations. Even more important of course is the fact that all points lie on or very close to a gentle curve constructed through their median positions. A complete table of the calibrated values is presented in Appendix I.

There are two other methods of obtaining calibration results: 1) by using an equation with constants calculated at set points and interpolating imtermediary values; 2) by drawing difference curves from Adams' tables. Neither method has been proved more accurate but it is felt that within such a small range as is being used here, neither the method using tables or that using an equation can compare for accuracy with that involving the drawing of a curve through calibrated points.

It is one of the advantages associated with thermocouple use that only one calibration is required because there are no slow shifts in its calibrated characteristics. The only things which might change the calibration are:

a) Exposure of the couple to temperatures near the extremities of its possible range (for Copper/Constantan these limits are usually -300 to 650°F with a maximum of 1100°F). However, the range used in this study, 0-110°F is well within these stipulated limits.

b) Attack of the junction by soil acids or oxidation of the couples' constituents. Oxidation of copper only occurs at temperatures greater than 400°C and of Constantan at greater than 600°C, so this factor also will not enter. The attack by soil acids is combated by coating the junction well in an inert expoxyresin.

However, to be absolutely certain no changes in calibration occurred during the course of the experiment, a thermocouple was extracted and recalibrated. The resultant satisfactory number of points is shown on Fig. 1.

Layout and Insertion

Having chosen the subsurface instrumentation, constructed and calibrated it, the next problem is to design an experimental layout which will make the best use of this equipment. The layout designed for this study involved the use of six separate plots, one control plot (A), and five experimental plots (B, C, D, E, and F), each being four feet square (Fig. 2a). Insertion of the thermocouples was made by use of a 14' x 3' x 8' trench, the plots were accordingly arranged around this outline with a centrally located junction box.

The choice of the depths at which ground temperatures are to be taken has unfortunately varied greatly from country to country and station to station. In 1947 the International Meteorological Committee recommended that "the standard depths for earth temperature measurements should be 10, 20, 50 and 100 cms". The Canadian Department of Agriculture[29] uses these depths in its Soil Temperature

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29 Department of Agriculture, Op. cit. 1962.

EXPERIMENTAL LAYOUT

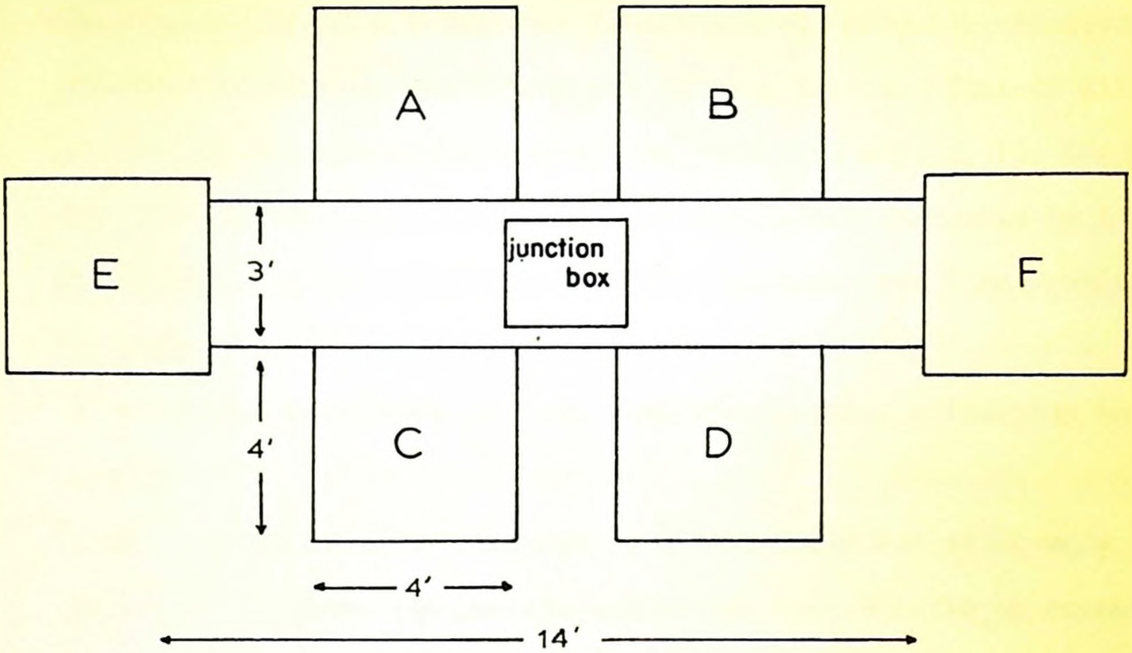
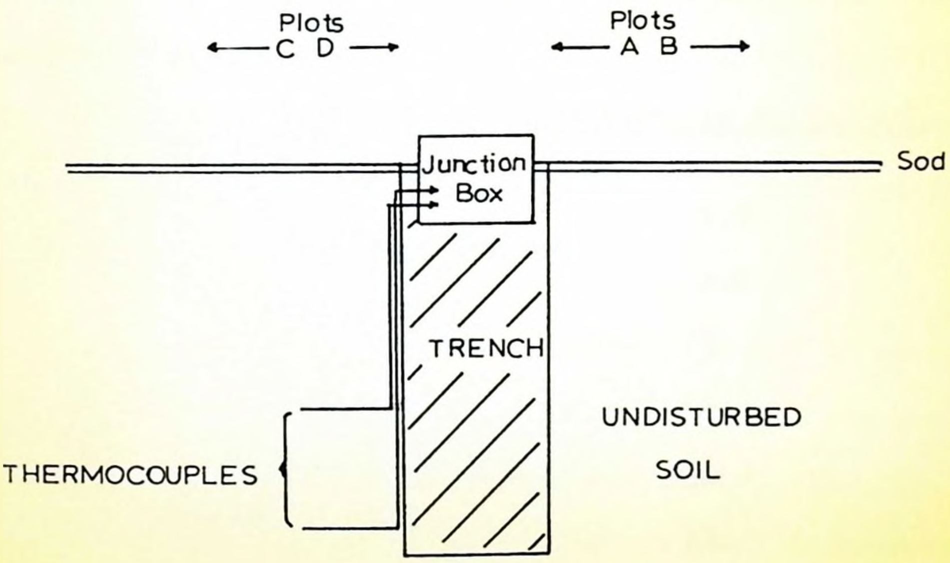


FIG. 2a PLAN VIEW



Scale 1 Inch = 4 Feet

FIG. 2b CROSS SECTION

records and makes the addition of the 1 cm and 150 cms depths. In this study the choice was to use both the World Meteorological Organization's and the Canadian Department of Agriculture's depths plus the addition of the 2.5, 5 and 225 cms levels. Thus in all plots there are nine recording depths, viz: 1, 2.5, 5, 10, 20, 50, 100, 150 and 225 cms. In addition it was deemed desirable to include the 15, 25, 30, 40 and 75 cms depths in control plot A to provide one really detailed study.

These depths were chosen with five guiding principles in mind:

1) The levels at which temperature measurements are to be made should not be uniformly placed, but rather according to an exponential law because the temperature gradient is known to decrease with depth in such a relation. Thus there is a cluster of four measuring points within the topmost 10 cm, and after this the frequency becomes wider spaced with depth, viz:

Depth (cm)	Difference in depth (cm)
1	
	1.5
2.5	
	2.5
5	
	5
10	
	10
20	
	30
50	
	50
100	
	50
150	
	75
225	

2) Depths chosen should be comprised of integers convenient in both metric and English systems. With approximately 2.5 cm equal to 1 inch it can be seen that the above depths are easily converted into whole numbers in the English system.

3) Preference should be given to those depths for which a large amount of data has already been accumulated. By incorporating the World Meteorological Organization and Canadian specified depths this is known to be achieved. In addition the 30 cm (or 1 foot) depth was chosen because of the wealth of data already obtained at this level.

4) The records should meet practical needs. In particular it is recognized that for the purposes of micro-climates, agriculture, soil science and ecology, the shallow depths are most useful; this reinforces the choice of a high frequency of measuring depths near the surface.

5) The greatest depth should be below the level where the diurnal temperature variation is observable. Below this depth the sinusoidal annual waves can be inferred with reasonable accuracy. As will be shown later in this work the depth of diurnal penetration is well above the 225 cm lowest measuring point.

With the measuring depths selected the next stage is to insert the measuring devices at these points within the soil without disturbing the "natural" condition of the ground. However, insistence upon maintaining the soil in an undisturbed state introduces problems concerned with the actual physical emplacement of the sensing elements.

Subsurface measuring equipment could be introduced into the ground from a point immediately above the position at which the observation is required. However, this method may introduce errors into the readings by:

a) Possibly altering the surface cover immediately above the point of measuring;

b) Boring a hole from the surface down will introduce outside air to the measuring point;

c) Having the lead wires in a vertical position may encourage conduction of heat and cold down from the extreme temperature regions at, or near, the surface.

d) The bore hole may well provide an excellent channel for water to percolate. This water will carry its own temperature, not that of the soil, and may also lead to the development of ice pockets in unnatural positions.

A better method of insertion was employed involving the digging of a pit to facilitate emplacement. A hole just deeper than the lowest required measuring depth was excavated (Plates 2, 3). The soil in the surrounding experimental plots remained undisturbed. At the required depths below the surface, a welding-rod was inserted horizontally into the pit face. The experimental plots were 4 feet square; thus to locate the measuring junction vertically beneath the centre of each plot the rod was pushed in 2 feet from the face. After withdrawing the rod, the junctions and their lead wires were fed into the narrow hole left, and the extension leads pinned up the pit face (Plate 4). These leads all met in the centrally located junction box (Plates 5, 6). The pit was then carefully re-filled, compacted and re-sodded (Fig. 2b).

Plate 3. The excavated pit.

Plate 4. Pinning the thermo-couple lead wires along the pit-face in bundles.

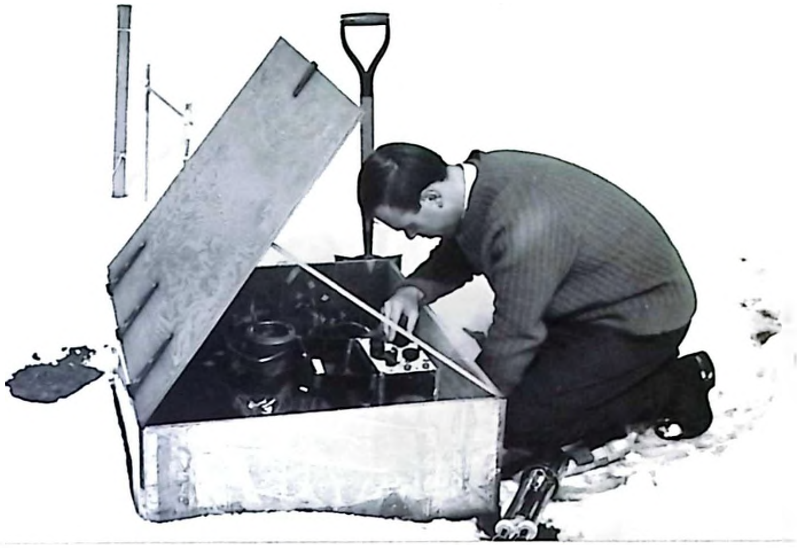


Plate 5. The position of the winter control box, well above the ground surface.

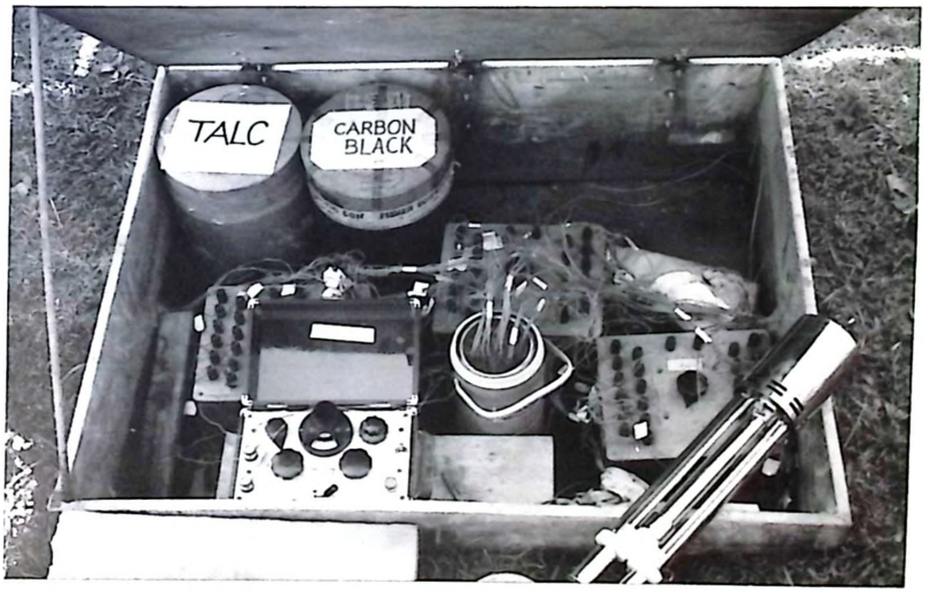


Plate 6. The sunken summer control box, including Potentiometer, switch gear, flask and Assmann Psychrometer.

By use of this method, the four previously specified problems were all eliminated. The wires leading away from the junction were for the first 2 feet at the same depth as the sensing element. Eggert[30] has shown conclusively that if the junction and wires lie in this horizontal, and therefore isothermal, position for at least 3 inches, then any errors which may arise due to conduction to and from the junction along the wires, is dissipated. This then eliminates any errors due to conduction; those due to the introduction of air, the percolation of water and the disturbance of the natural cover are combated in a more obvious manner. The only disadvantages in the use of the pit method of insertion concern the infilled pit itself. This disturbance of the soil may lead to errors due to horizontal inhomogeneity of the soil layers, perhaps causing differential water movement and an unrepresentative temperature profile. It is thought that these errors are usually of a minor nature, but two precautions were observed when filling in the pit:

a) The soil was replaced in such a manner as to reconstruct its original profile as closely as possible;

b) The replaced soil was firmly tamped to exclude most of the air and thus provide as near the normal degree of compaction as possible.

Soil Surface Temperature Equipment

During the summer programme of observations some soil

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[30] R. EGGERT, "The Construction and Installation of Thermocouples for Biological Research", Journal of Agricultural Research, Vol. 72 (No. 11), 1946, p. 341-355.

surface measurements were made. The first problem, as encountered by physicists, is to define exactly what a "surface" is. The best one can say in this thesis is that the temperatures were those of an instrument in contact with the surface layer. The next problem encountered in these measurements involved a major one of instrumentation not found in subsurface observations. Namely the introduction of errors due to direct radiation received by the sensing element. If the sensing point is so large as to be sensitive to radiation, then it will record the temperature of itself and not the temperature of the body with which it is placed in contact. To make the element insensitive to radiation one method is to shield it by a highly polished reflector, while another is to make the sensing point very small. Very fine gauge thermocouple wire can produce a measuring junction "so tiny that their radiation errors are vanishingly small" according to Geiger[31], and thus "the surface temperature can be obtained electrically with quite satisfactory accuracy".

Surface temperatures in this investigation were measured by using pure 42 gauge B and S Copper/Constantan wire. Being pure Constantan no calibration was necessary; the standard E.M.F./ Temperature relationship was directly applicable. The thermocouples could be used in conjunction with the same switches and potentiometer used in the subsurface work.

Some observations were made by using a Cole-Parmer Tele-Thermometer based on the thermistor principle with a specially

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[31] R. GEIGER, "The climate near the ground", 2nd edition Harvard University Press, 1959. p. 131.

designed surface contact probe. The limited results obtained were satisfactory.

Thermocouple Ladder

Instrumentation was required to measure temperatures within a cover of snow. The acquisition of snow temperatures is not as straightforward a problem as taking subsurface measurements. Errors are introduced into "single readings" due to the peculiar properties of snow. A snow cover, and especially a freshly fallen one, contain innumerable small pockets of air which account for its amazingly low density. A "spot-reading" may well not be representative of that depth, and so it was deemed necessary to obtain an average temperature from several points at the same depth.

Using thermocouples there are three methods of acquiring this average temperature of a number of junctions placed at the same height:

a) Each couple can be read separately and the accumulative total averaged. However, this takes time, and the readings will not then be simultaneous.

b) The couples can be joined together in parallel and the total E.M.F. recorded and averaged. Using this method the total E.M.F. may be too great to be measured, and a short circuit might reduce the E.M.F. of one junction without it being detected.

c) It can be shown that by applying Kirchoff's Laws that the potential difference across the terminals of a number of thermocouples of equal resistance joined in series is the average of the E.M.F.'s of the individual thermocouples. This method of joining the junctions in series means that the E.M.F. developed can be measured with the same instrument used for measuring that of a single thermocouple.

This method of using "opposed thermocouples" in series was chosen for this investigation.

The junctions were constructed of 34 gauge B and S Copper/ Constantan wire, being reasonably rugged and yet small. Five junctions were constructed to run as a horizontal line at each of 18 heights, all 1" apart, starting at 1" above the ground. These lines of junctions were held taut between a dowel wood ladder 2 feet wide and 2'6" high. Each junction was separated from the next by 3" and the junctions closest to the uprights were inset 6" (Plate 7).

These opposed thermocouples were also used in junction with the switch gear and potentiometer in operation for surface and subsurface observations.

Air Temperature and Humidity Equipment

A record of air temperature and humidity was kept at a height of 4'6" by means of an Assmann Hygrometer. This is the standard hand instrument for temperature and humidity, manufactured by C. F. Casella, London. This instrument was of special use during 24-hour runs to provide a rough picture of the macro-temperature pattern and to provide an accurate absolute temperature at the time of observation.

Other Equipment Used

a) Wind Speed and Direction - A few observations of wind speed were made by using the Sheppard type sensitive anemometer, made by

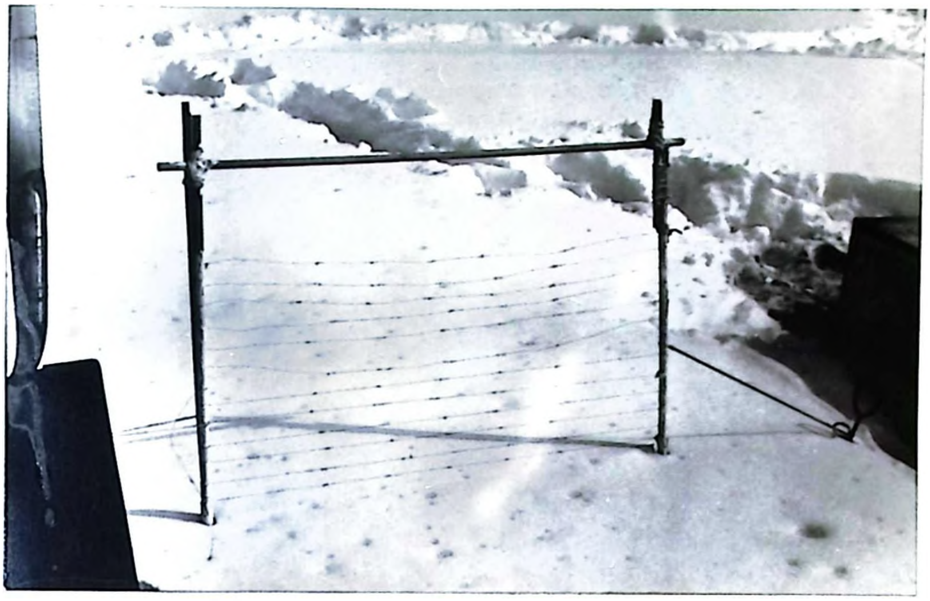

Plate 7. Thermocouple ladder for measuring winter snow temperatures.

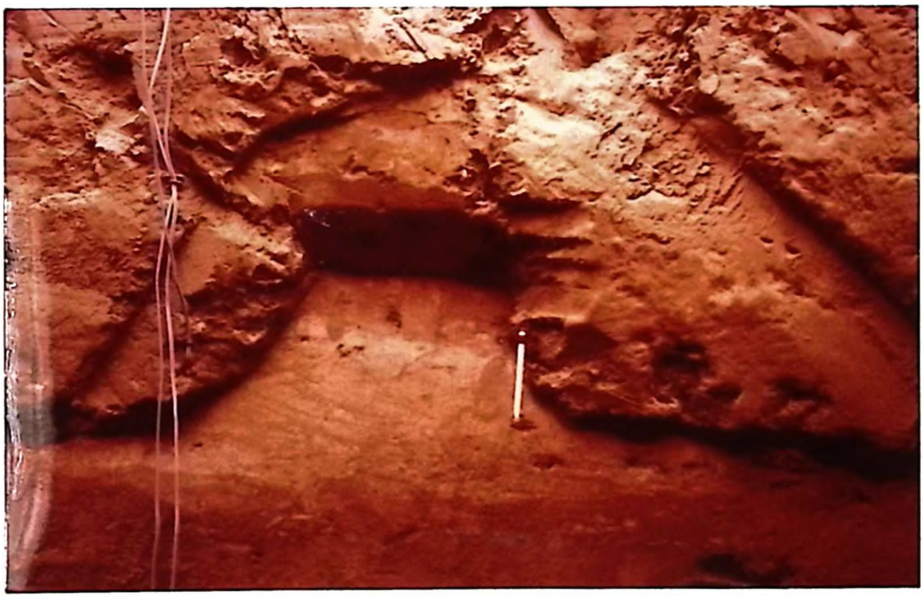

Plate 8. Section of pit profile about 80 cm below surface. Note reddish-brown plastic clay layer.

C. F. Casella, and direction was recorded by a simple dust puffer.

b) Height of Snow and Crop - The height of snow and of the crop of oats was measured on a permanently installed wooden ruler.

c) Soil Moisture - During the summer experiments a "Speedy" moisture tester, made by Thomas Ashworth and Co. Ltd., England, was used. The instrument proved extremely useful and reliable for easy field use.

Procedures

As outlined in the Introduction, two major programmes were undertaken; one to study the general soil temperature regime in this locality, and the other involving experiments concerned with modification of the general patterns found.

1. Frequency and type of observations.

The first programme involved two scales of approach:

a) The annual curve of soil temperature was obtained from readings made at 1400 hours on most days throughout the period of observation. During the winter, under more stable conditions, readings were made every one or two days; during the summer readings were made almost every day to catch the fluctuations of this period. Each set of E.M.F. readings was then converted into temperatures from the calibration curve constructed, and plotted on a large diagram for appraisal and analysis. At the end of each month readings were averaged to provide monthly means of all depths.

b) The diurnal curves, needed to illustrate the small-scale movements which combine to produce the annual curve, were constructed from hourly observations over a 24-hour period. They also were converted into temperatures and graphed for analysis.

On both the above two scales simultaneous observations of air temperature, amount of cloud, and wind velocity were made, together with measurement and comments upon the state of the ground, including snow depth and soil moisture. Any additional observations on the conditions such as time of sunrise and sunset, were also noted.

The second programme, involving modification experiments, was divided into two phases:

a) Winter - Observations were made once a day at 1400 hours. In this way direct comparison with the normal untreated course of soil temperatures was available.

b) Summer - Due to the wide fluctuations of ground temperature experienced in the summer, single daily readings were not considered sufficiently accurate. To provide a daily mean, observations were made at the minimum temperature epoch, about 0600 hours as well as at 1400 hours.

2. Site conditions.

The experimental area was cordoned off to keep it free of any human interference which might have affected the readings. The control plot was left untouched throughout the study period except for periodic trimming of the grass cover. Treated plots were tended as and when necessary.

CHAPTER 3

PHYSICAL SITE

The temperature regime beneath the ground surface is the result of the interplay of a large number of factors which Bouyoucos[1] divided into two groups, A Intrinsic,

B External.

Some factors in each group favour a high, and others a low, soil temperature and the resultant temperature is determined by the balance which is achieved. The intrinsic factors are relatively passive and allow themselves to be acted upon by the more active external elements. Large scale regional differences of ground temperature are dictated primarily by the external factors while the variation from soil to soil or within a single soil are determined mainly by the intrinsic factors.

Presented here is a brief description of the micro-climatic influences exerted by some of the more important of these factors, and this is followed by a description, and where relevant, an appraisal, of the intrinsic and external factors encountered in this study.

A. Intrinsic

(i) Soil texture. Three basic soil textures are recognized viz: sand, loam and clay. Micro-climatically each is radically

[1] G. J. BOUYOUCOS, Op. cit. 1913, 1916.

different. Sandy soils heat up and cool down more quickly, and hence they are more responsive to weather changes. At the other end of the scale, the heavy clay soils warm up more slowly but remain warm longer due to a higher heat capacity and better thermal conductivity. Also the layer of soil affected in a poorly conducting sandy soil is much thinner than in clay, but this layer experiences extremes of temperature. In general the loam soils are intermediate in texture and micro-climatic character.

(ii) Moisture Content. Moisture influences soil temperature by (a) changing heat capacity. Owing to the increase in specific heat, a bigger input is required to raise the temperature of a wet sample than a dry one.

(b) evaporation. Transport of this moisture away from the soil surface as water vapour releases latent heat of evaporation and leads to cooling.

(c) conduction. Patten[2] has shown conclusively that the thermal conductivity of a soil increases with its moisture content up to a certain limit.

(d) percolation. The downward drainage of water carries with it its own temperature.

(iii) Organic Matter and Soil Colloids. Bouyoucos[3] found that the addition of organic matter reduced the soil conductivity.

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[2] H. E. PATTEN, Op. cit. 1909.

[3] G. J. BOUYOUCOS, Op. cit. 1916.

On the other hand Franklin[4] deduced that soil colloids formed a film around soil particles and with a rise in temperature this film swelled, compacted the soil, and presented a decreased resistance to heat transfer. The presence of organic matter also increases its water holding capacity and usually has a dark colour which increases its absorptivity.

(iv) Colour. This influence will be discussed in more detail later. Briefly it has been shown that the colour of the soil radically affects its albedo and therefore its heat budget.

(v) Structure, cultivation and compaction. Structure affects heat transfer; a granular soil transmits heat less readily than one with large peds. Cultivation destroys soil aggegates, creates a mulch and reduces downward heat flux, thus concentrating the heat in a narrow surface band of extreme conditions. Compaction produces the exactly opposite effect to cultivation, in that it increases conductivity and reduces the soil surface extremes, by promoting penetration.

(vi) Topography. The effects of topography on soil temperatures are fourfold:

(a) Aspect-incident radiation depends upon the aspect of the site. It is well recognized that in the Northern Hemisphere south-

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[4] T. B. FRANKLIN, "The relation of the soil colloids to the thermal conductivity of the soil", Proceedings Royal Society (Edinburgh), Vol. 40-41, 1920-21, p. 61-67.

facing slopes receive more insolation per unit area that northern exposures. These insolation variations continue around the compass and consequently soil temperatures are dependent upon aspect. It is necessary to distinguish between direct solar radiation from diffuse-sky radiation, because the latter is essentially uniform at all azimuths. Geiger's[5] measurements on the Hohenkarpfen, 1926 show well that the greater the ratio of diffuse-sky radiation to total radiation, as on overcast days, the less is the effect of slope aspect on the energy received.

(b) Slope, as Jen-Hu-Chang[6] states: "The degree of slope determines the insolation received per unit area. By changing the degree of slope, the effect of latitude is simulated on a small scale. The temperature differences between exposures are usually accentuated by the slope".

(c) Altitude - as altitude increases, the air becomes rarified. As a result direct insolation is less impeded and diffuse-sky radiation becomes smaller. Likewise there is a higher rate of outward long-wave radiation by night at high altitudes. However, it has been shown by Lauscher[7] that this increased loss by night is more than balanced by the incoming daily insolation. It may be said that the microclimate of high mountains is subject to large temperature variations, and the amount by which the ground temperature exceeds the air temperature increases with altitude.

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[5] R. GEIGER, Op. cit. 1959, p. 218.

[6] JEN-HU-CHANG, "Ground Temperature", Blue Hill Meteorological Observatory, Vol. 1, 1958, p. 159.

[7] F. LAUSCHER, "Dampfdruck und Ausstrahlung in einen Gebirgsland" Gerlands Beitrage zur Geophysik, Vol. 51, 1937, p. 234-49.

(d) Concavity and convexity - On clear radiation nights the air close to the ground is cooled, becomes dense and "flows" downslope. These "katabatics" flow off convex slopes and accumulate in concave areas imparting a cold temperature to the valley area.

(vii) Vegetation Cover. A growth of vegetation over the soil, whether it is of grass, a forest or a crop, effectively raises the "active surface" from the ground level to some height above it, usually equal to somewhere just below the crest of the vegetation. This new "active surface" conducts all the activities once handled by the ground surface, and the soil's role is relegated to a subservient one. The new surface now receives and transmits radiation, intercepts precipitation, retards wind, varies humidity and temperature and influences many other elements. Besides acting upon external factors it also modifies the intrinsic factors of the soil by supplying organic matter, changing the moisture content, porosity and colour. The extent to which these external and intrinsic factors are altered is dependent upon the physical characters of the vegetation - its height, density, colour and so on. As an example the effects of the transposition of an oat crop over the soil surface will be dealt with in more detail in Chapter 6.

In addition to the above intrinsic factors one should perhaps mention that influences may also be exerted if the site lies in an urban environment.

B. External

(i) Solar radiation. The direct and diffuse-sky radiation incident at the ground's surface by day represents the most important factor in heating the soil. A portion is reflected from the surface, depending upon the albedo, but most is absorbed, and heats the ground. Other things being equal, ground temperature follows the trend of solar radiation closely, especially during the summer months when insolation is strong. In fact at the 6" depth Keen and Russell[8] obtained a correlation coefficient between the soil temperature and incoming solar radiation of +0.877. By night the sun's rays are cut off and the reverse process takes place. The nocturnal heat exchange concerns the long-wave terrestrial heat radiation from the ground's surface, especially on clear nights. According to the Stefan Boltzmann law of radiation, "every body radiates heat with an intensity proportional to the fourth power of its absolute temperature". Since the sun's temperature is about 6,000°C while the earth's average temperature is only about 14°C, it can be seen that the nocturnal radiation exchange is relatively negligible compared to that of the diurnal condition.

(ii) Cloud. The presence of a cloud cover greatly reduces radiation receipts and losses. By day the passage of cloud may radically lower soil temperatures close to the surface; by night the cloud cover may intercept outgoing terrestrial radiation and

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[8] B. A. KEEN and E. J. RUSSELL, Op. cit. 1921, p. 232.

thus help to keep up the nocturnal minima. The combined effect of clouds by day and by night is to reduce the diurnal temperature range, and as Siegenthaler[9] has shown their correlation with ground temperatures is positive in winter and negative in summer.

(iii) Rain. Rainwater and snowmelt carry their own temperatures as they percolate downwards into the soil. The effect produced therefore depends on the temperature difference between the water and the soil. Normally it acts as a cooling agent, but during the cold season it may impart some heat, and it is claimed that in the spring precipitation definitely tends to raise soil temperatures. Both Bouyoucos[10] and Keen and Russell[11] however consider the effect of rainfall to be considerably less than is generally accepted. Individual instances in tropical areas (Taylor[12], 1928) and observations after very heavy thunderstorms (Becker[13], 1936) do seem to show considerable effects for a short period of time. Rainwater diffuses heat and equalizes differences between the surface and subsoil, and reduces the diurnal range. This is very noticeable during a long, wet spell of weather.

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[9] J. SIEGENTHALER, Op. cit., 1933.

[10] G. J. BOUYOUCOS, Op. cit. Bull. No. 17, 1916.

[11] B. A. KEEN and E. J. RUSSELL, Op. cit. 1921, pages 216 and 217.

[12] E. M. TAYLOR, "Soil Temperatures in Egypt" Journ. Agric. Sci., Vol. 18, 1928, p. 90-122.

[13] F. BECKER, "D. Erdbodentemp. als Indikator d. Versiekerung", Meteorologische Zeitschrift, Vol. 54, 1937, p. 372-77.

(iv) Snow. A cover of snow is recognized by most authorities to exert a considerable influence upon soil temperatures. A more complete discussion is given in the section devoted to the Winter Experiments. Here it will suffice to say that the snow's influence falls under two general headings; first, its value as an insulator dependent upon its peculiar thermal properties, and secondly, its role as a source of moisture after the thaw commences.

(v) Air temperature. As Keen and Russell[14] point out, "Since the air temperature is determined by the temperature of the soil surface it should show some relationships with the soil temperature at 6"", and indeed it does. Siegenthaler[15] has shown a correlation coefficient between the 10 cm soil temperature and that of the macro-climate as +0.87. Similarly a change in air mass, and therefore air temperature, has been shown by Decker[16] to considerably alter soil temperatures due to the introduction of a thermal gradient. It seems an axiom to state that the combination of the two related factors of air temperature and radiation outweigh all other factors in determining soil temperature.

(vi) Humidity. The humidity of the air is only important in the field of soil temperatures in that it controls processes

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[14] B. A. KEEN and E. J. RUSSELL, Op. cit. 1921, p. 222-3.

[15] J. SIEGENTHALER, Op. cit., 1933.

[16] W. L. DECKER, "Determination of soil temperatures from meteorological data", Iowa State College, Ph.D. Thesis, 134 p., 1955.

liberating or taking up latent heat. Small amounts of heat may be transmitted by latent heat of condensation. More important is the loss of latent heat of evaporation at the soil surface. The results of Ramdas[17] show this chilling effect of evaporation on the soil layers closest to the surface.

(vii) Wind. The wind has a cooling effect on soil temperatures by (a) increasing evaporation, (b) introducing cooler air above the surface. It may also have a heating effect; if a warm moist wind blows over a cold dry soil, condensation occurs and the liberation of heat warms the soil surface. Wind movement may be laminar or turbulent. If it is laminar soil temperatures may not be affected, but turbulent movement may lower the soil surface by 2-3° F. Keen and Russell[18] discount the effects of wind, but it should be remembered they were using thermometers inserted at a depth of 6", and the wind's influences are restricted to a very thin layer of the topsoil.

These then are basically the factors which exert, to at least some degree, an influence over soil temperatures. Ideally, therefore, one would wish to measure all of them to provide a comprehensive treatment of the subject. From the instrumentation outlined in Chapter 2 it is obvious that this is not being done in

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17 L. A. RAMDAS, "Natural and Artificial Modification of Micro-Climate", Weather, Vol. 12, Table 2, 1957, p. 238.

18 B. A. KEEN and E. J. RUSSELL, Op. cit., 1921, p. 217 and 232.

this study. Indeed at such a level it would be impossible to process all the data, even if it could be acquired. Most of the intrinsic factors have been covered and nearly all the most important external factors. The most obvious omission is that there are no measurements of radiation. Various forms of pyrheliometers are used to observe radiation, but they are expensive and to date no such equipment is available in the Department.

A description and appraisal of the pertinent intrinsic and external factors of the site follows.

Palaeozoic Geology

In order to satisfactorily explain the macro-climate of the site, and the soil profile in which the measurements were made, it seems necessary to present a brief Geological History of the area and its Major Soil Types.

Hamilton lies on the Southern Ontario Palaeozoic Plain, known physiographically as the St. Lawrence lowland. On the continental scale this lowland lies in the corridor between the Pre Cambrian Canadian Shield, to the North, and the complex Appalachian Highlands to the South. In the Pre-Pleistocene geological picture (Fig. 3) the area is seen to consist of Ordovician and Silurian deposits which have been well described by Caley[19]. The junction between the two systems is dramatically highlighted by the precipitous Niagara Escarpment which overlooks and skirts the main periphery of the city

[19] J. F. CALEY, "Palaeozoic Geology of the Toronto-Hamilton Area", Geological Survey of Canada, Memoir No. 224, 1940.

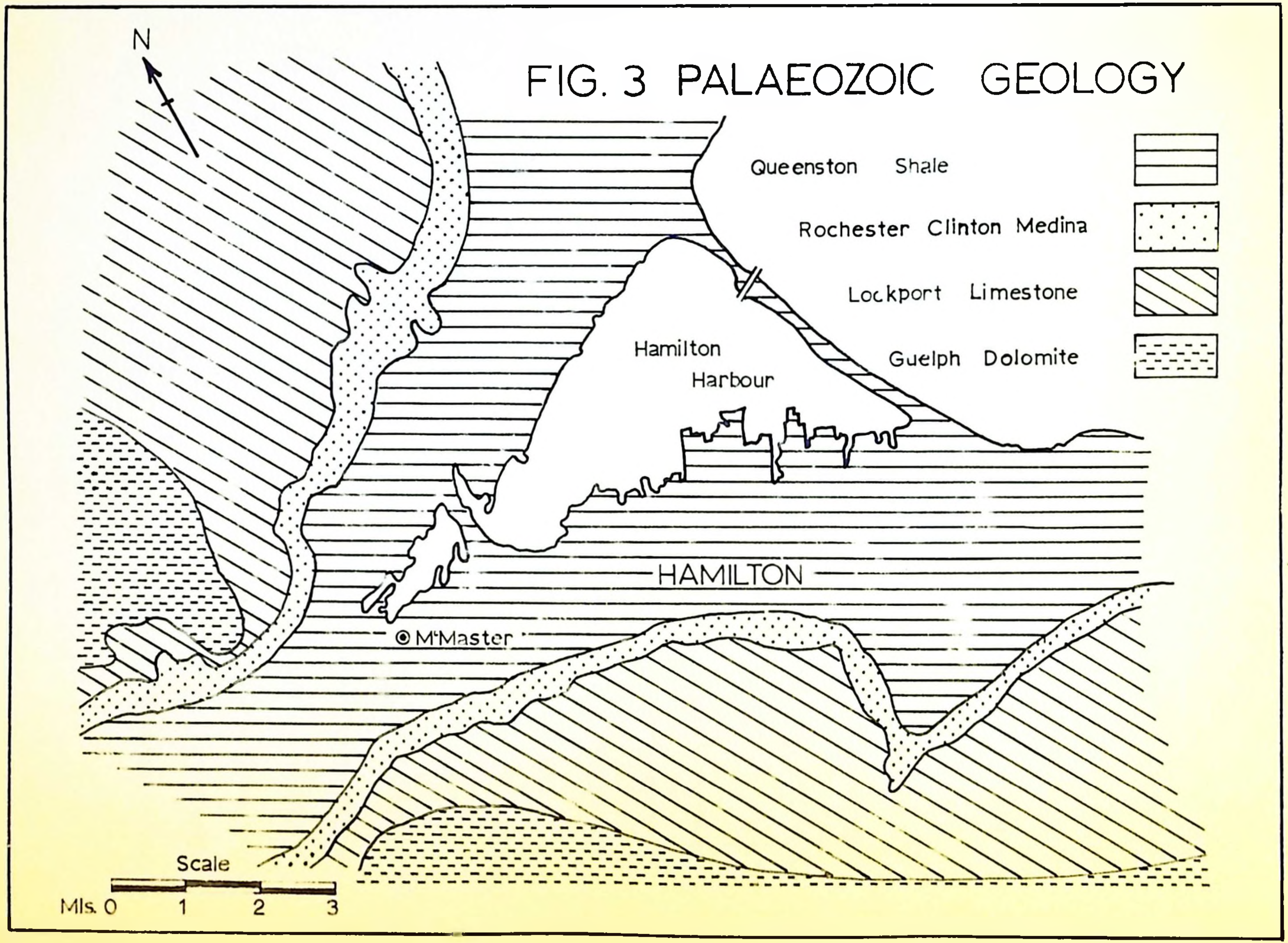
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FIG. 3 PALAEOZOIC GEOLOGY
Queenston Shale
Rochester Clinton Medina
Lockport Limestone
Guelph Dolomite
Hamilton Harbour
HAMILTON
McMaster
Scale
Mls. 0 1 2 3

of Hamilton. To the East lies the Ordovician, and composing the escarpment and all the area above it is the Silurian. In this manner the escarpment marks the edge of the younger, overlying Silurian bedrock mantle.

The only member of the Ordovician system represented here is the Queenston shale, a sedimentary clay laid down in the Palaeozoic sea, subsequently metamorphosed to become a strikingly brick-red shale. This shale outcrops at the base of the Niagara Escarpment and so underlies the whole of the study area. The shale is really a red mudstone with green siltstone bands about 500 ft. thick. This deposit erodes easily and breaks down to a red clay soil.

The lowest three members of the Silurian here compose most of the fact of the escarpment. These Medina, Clinton and Rochester series are inter-bedded limestones, shales and dolomites and are relatively more resistant than the underlying Queenston shale. However, these members are not as hard as the cuesta cap-rock, called the Lockport Dolomite, to which the 'scarp face owes its existence. This light grey dolomitic capping is extremely resistant; the softer shales and limestones beneath are more easily erodible and so undercut the cap rock. The result is the almost overhanging precipitous 'scarp face which reaches 300-350 ft. vertically. The youngest series occurring in the area, the light grey, porous Guelph Dolomite extends back from the cuesta edge as a bedrock plain, especially in Beverley Township.

Pleistocene Geology and Physiography

Three of the most outstanding physiographic features of the Hamilton area, the Niagara Escarpment, the Dundas and the Albion Valleys are pre-glacial features. But apart from these, all features are due to the great continental glaciation of the Quaternary Glacial epoch.

The Niagara Escarpment then, was in existence before the Ice Age and was formed in the manner described above. The very deep Dundas re-entrant valley is the most notable break in the escarpment. It is thought that it is the valley of the pre-glacial river joining the basins of Lake Erie and Lake Ontario and providing route all the way from the Georgian Bay depression to the Mississippi Valley, and Grabau[20] thinks the Dundas Valley was in effect a tributary of the Mississippi. The Albion Valley is also felt to be a deep river channel of pre-glacial times.

Glacial evidence in the Hamilton area does not begin until the Early Wisconsin, and even these deposits are of questionable age. During Late Wisconsinan the ice moved generally westward and reached its greatest extent in Southern Ohio 18 or 19,000 years ago. During the next 5,000 years the lobe retreated back rapidly to reach the Niagara Escarpment before it pushed south again. This was followed by an oscillatory retreat, and another strong ice-advance which stopped south of Galt. With the next retreat 13,000 years ago,

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[20] A. W. GRABAU, "Guide to the Geology and palaeontology of Niagara Falls and Vicinity", Albany, New York, 1901, p. 43.

Lake Whittelsey formed in present-day Lake Erie, until its level was reduced 50 ft. by drainage, to become Lake Warren I. Yet another re-advance followed blocking Erie drainage and forming Lake Warren II. At re-entrants in the escarpment, projecting tongues of ice stagnated to form kame deposits, and this is probably when such material was dumped in the Dundas re-entrant.

Finally, the last retreat of the ice allowed Lake Warren II and the short-lived Lake Peel to drain, and heralded the events which are of most immediate purport to this study. After the ice retreated from the head of the Dundas Valley temporary lakes formed there leaving remnants of deltas and beaches. Gradually lower and lower outlets were freed of ice and the lake levels fell. When the Ontario lobe withdrew to the eastern end of the Lake Ontario Basin, the entrance to the Mohawk Valley at Rome, New York was uncovered. Evidence indicates that at a low level of 230-240 ft. Lake Iroquois was initiated in the present basin of Lake Ontario, about 12,000 years ago. The water in this Lake Iroquois existed from the time the Rome outlet was breached until it was replaced by the St. Lawrence outlet due to further retreat of the ice.

After this low water level formation, Coleman[21] points to merging strandlines as marking a continual rising water-level condition. As Hurst[22] notes, these conditions led to the formation of numerous

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[21] A. P. COLEMAN, "The last million years", Toronto: University of Toronto Press, 1941.

[22] D. L. HURST, "Pleistocene Geology of the Dundas Valley, M.Sc. Thesis, McMaster University, 1962.

beaches, in this area especially at 310, 350 and 360 feet, following around the base of the 'scarp. During this time a large area was receiving the fine grained sediments of Lake Iroquois and the alluvium carried in by streams, blanketing what is now known as the Westdale Plain[23] (the study area) with fine sand.

Crustal rebound during the next stage of the glacial retreat tilted the lake basin southwestwards, causing the water to rise in this corner of the lake. At this time large gravel bars were built in the Hamilton and Aldershot districts. The building of this bay-mouth bar separated the Westdale deposits from other offshore deposits and a lagoon developed. Continued ice retreat from the west of the Champlain valley allowed access through the Hudson valley to the sea. Thus as Karrow, Clark and Terasmae[24] say, Lake Iroquois was drained close to 10,400 - 10,600 years ago. This lowered water to the stage known as Lake Kenilworth when most water had drained from Burlington Bay and possible near-dessication conditions set in on the floor of the lake. At the time of this low water condition the Westdale Plain deposits were open to flash-flood erosion which cut through these lagoonal deposits, eroding much of the present area known as Cootes Paradise.

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23 P. F. KARROW, "Pleistocene Geology of the Hamilton Map Area", Ontario Department of Mines, Geological Circular, No. 8, 1959, p. 5.

24 P. F. KARROW, J. R. CLARK and J. TERASMAE, "The age of Lake Iroquois and Lake Ontario", Journal of Geology, Vol. 69, 1961, p. 666.

Isostatic rebound due to the release of the weight of the retreating ice continued to raise the eastern end of the basin raising the water level slowly, until it reached this western corner about 3,000 years ago, and the present Lake Ontario was formed. The recent deposits being laid down in Lake Ontario are generally submerged due to the still rising water condition.

In summary Fig. 4 illustrates that the area is part of an ancient lowland, divided by a well defined escarpment. Below the 'scarp the terrain is the result of wave action and deposition by former glacial Lake Iroquois and includes:

(a) Ontario Coastal Plain - site of Hamilton.

(b) Aldershot-Freeman Terrace - a level section, which is really a continuation of the Ontario Coastal Plain on the north shore of Burlington Bay.

(c) Dundas-Westdale Terrace (i) South shore - wide plain of horizontally stratified offshore, and deltaic fine sands. The "marsh" has been eroded out of this 325 foot terrace, and this is the site of the University and therefore the experiment; (ii) North shore - narrow and highly dissected.

(d) Cuesta-base - Talus, outwash and faint terraces.

(e) Sand and gravel bars - built by Lake Iroquois consisting of coarse grained, rounded material.

(f) Dundas and Albian re-entrants - pre-glacial river valleys now filled with glacial debris. The Dundas valley contains irregular, morainic hills to an unknown depth, which completely cover the escarpment near Copetown. The mouth of the Albian re-entrant is blocked off with a gravel bar.

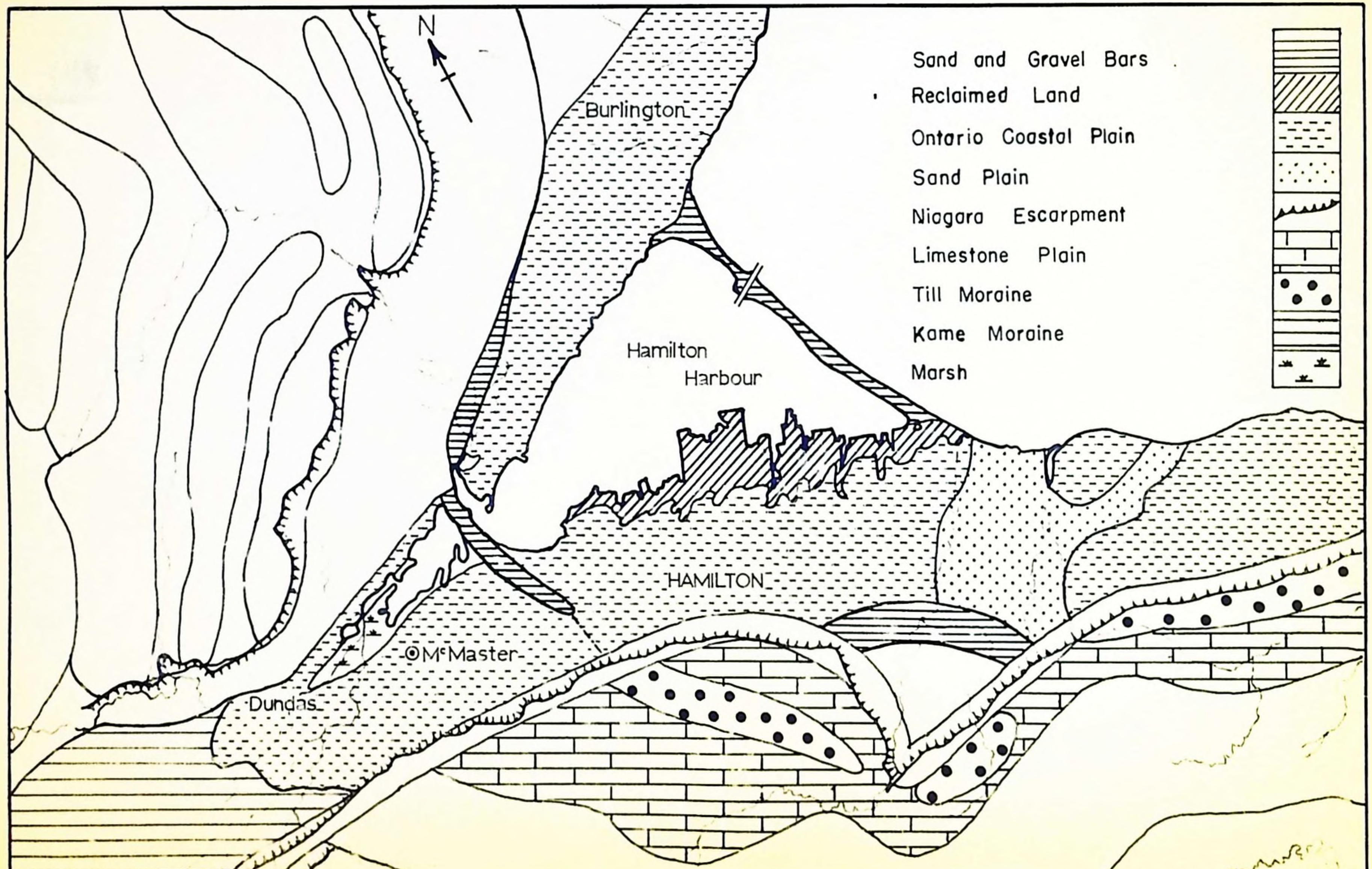

FIG. 4 PLEISTOCENE GEOLOGY

The Niagara Escarpment forms the striking divide between these lower glacio-fluvio-lacustrine deposits and the terrain above, which shows all the evidences of extensive glacial deposition.

Soils

The soils of the Hamilton map area belong, according to Morwick[25] to the Grey-brown Forest soils having been developed under predominantly broad leafed vegetation in a cool sub-humid climate. Halliday[26] confirms the existence of densely wooded mixed forest about 200 years ago, including predominantly maple, beech, elm, hickory and oak, with cedar in swamp areas and hemlock on the better drained sites. This then is the Major Soil Group from which differences in parent material, slope and micro-climate have produced the soil type subdivision.

In this area the soils can be broken down into 3 groups:

(1) Above the escarpment - here the differences in parent material govern the soil types, and to a lesser extent the slope conditions. For example, the Haldimand Clay Plain supports imperfectly drained clay loams; the Limestone Plain exhibits a sandy, stoney loam; and the Sand Plain has sandy loams.

(2) Dundas Valley - the morainic hills of this area have loam and sandy loam soils with good drainage.

(3) Below the escarpment - the soil development below the 'scarp has been dominantly influenced by the extensive distribution of

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[25] F. F. MORWICK, "Soils of S. Ontario", Scientific Agriculture, Vol. 13 (March - August) 1933, p. 449-54.

[26] W. E. D. HALLIDAY, "A forest classification for Canada", Dept. of Mines and Resources (Lands, Parks and Forests Branch), Bull. No. 89, Ottawa, 1937.

parent materials associated with Lake Iroquois. These glacial lake deposits are mostly clay and sand, and give rise to clay, sandy loam, and loamy soils.

The experimental site, therefore, lies in the third of these areas at the position indicated on Fig. 3 and Fig. 4. This site is known as the Westdale Plain or Terrace, occurring at a height of 320-30 feet, and formed during late Lake Iroquois times associated with glacial retreat. Probably the lowest deposits are cold-water glacial-lacustrine due to the damming of Lake Iroquois by the Ontario ice-lobe. As the lobe retreated the sediments would become lacustrine, and with the formation of the Aldershot bar isolating this part of the bay they would finally become lagoonal[27]. The sand plain is formed of deep, off-shore and deltaic deposits consisting of horizontally stratified sand and silt bands.

Deep boring information concerning the campus deposits has been obtained from the following:

(1) Soil Engineering Service, Toronto - a set of four boreholes down to 117 feet in the vicinity of the Nuclear Reactor.

(2) E. M. Peto Association Ltd. Report - using 2 bores down to 30 feet near the University Refectory.

(3) W. R. Souter and Associates - incorporating 4 bores down to 100 feet around the General Sciences Building.

All three investigations encountered roughly similar conditions, involving alternation of silty sands and silty clays. A

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[27] P. F. KARROW, "Pleistocene Geology of the Hamilton-Galt Area", Ontario Dept. of Mines, Geological Report No. 16, 1963, p. 47.

diagrammatic summary of their results is shown in Fig. 5a. General characters encountered in the profile included:

(a) Increase of silt with depth. At lower levels an increase of clay and some gravel.

(b) Down to 5 feet the soil was loose; below this depth it became compact to dense.

(c) Colour ranged from reddish-brown near the surface to light brown and grey at depth.

(d) Moisture content varies considerably.

(e) The height of the water table was usually between 25 and 32 feet below the surface, certainly it was never encountered above 21 feet.

(f) Soil sampling showed about 63% silt, 22% clay and 15% sand at depth.

Hurst[28] states that from a personal communication with Kirk, the total thickness of this deposit is calculated as being between 112 and 134 feet. This seems in accord with bore-hole "refusals" at 112 and 117 feet recorded near the Nuclear Reactor.

Soil Profile

Immediately after the excavation of the trench, designed to facilitate thermocouple insertion, descriptions of the site characteristics and soil profile were undertaken. These are presented in Appendices IIa and IIb. A more general outline and diagrammatic profile (Fig. 5b) are now to be considered.

The topmost 25 cm consists of a grey, fine sandy loam which is probably the A_2 horizon. From 25 cm down to 40 cm the B_1 horizon

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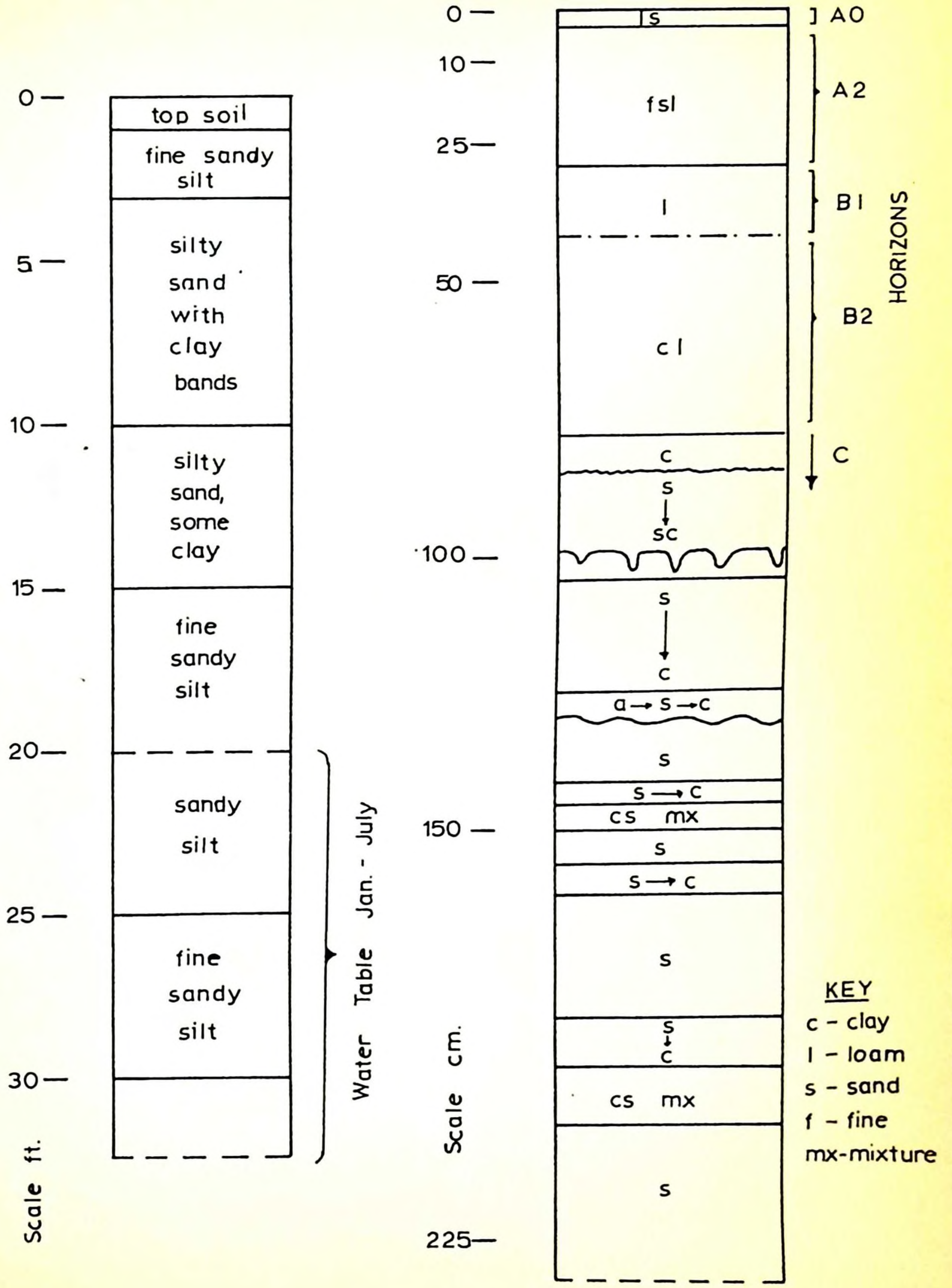
[28] D. L. HURST, Op. cit. 1962, p. 101.

FIG. 5a General Profile

5b Pit Profile



is a mellow loam with a tan colour. The B_2 grades from the overlying loam into a more cohesive, redder, clay loam down to 75 cm. Between 75 and 88 cm a striking red, plastic, hard clay is encountered which takes a polish easily (Plate 8). The clay layer here is seen as being the result of either:

(a) Leaching of colloidal material from overlying sedimentary layers. However, the band is so distinct and the time period since deposition so short that this is unlikely. Or:

(b) It is more likely that this clay band is "in situ", and that the development of the profile has been held up here by its presence. Karrow[29] says "where streams have eroded the shale (Queenston), red alluvial clay may be deposited downstream. This is the origin of layers of red clay in the eastern part of the lagoon deposits of Westdale and Aldershot".

Below this clay lies a 14 cm thick band which is both interesting and complex; Plates 9 and 10 illustrate the features of this band. The constituents vary from coarse sand through fine sand to clay. The clay is usually a grey-brown colour and occurs as round nodules, thin flakes, wavy bands and at the base peculiar downward projecting "pipes" with a rounded lip. Several suggestions might be put forward to explain these pipes:

(a) They are in-filled sun cracks, possibly at the stage when Burlington Bay floor was exposed by Lake Iroquois being drained, and flash-flooding was rife.

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[29] P. F. KARROW, Op. cit. 1959, p. 6.

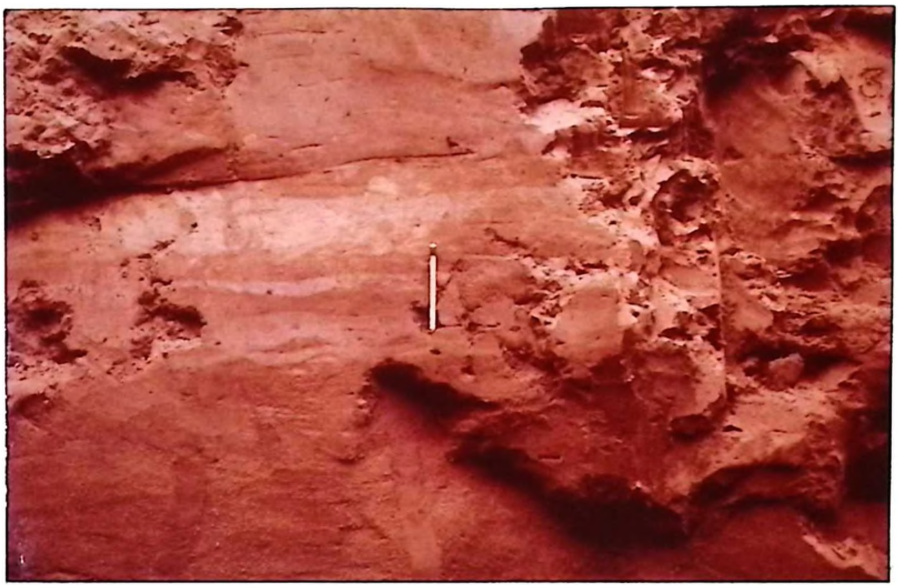

Plate 9. Complex zone in soil profile, consisting of fine sand clay lens and peculiar down-ward projecting clay pipes.

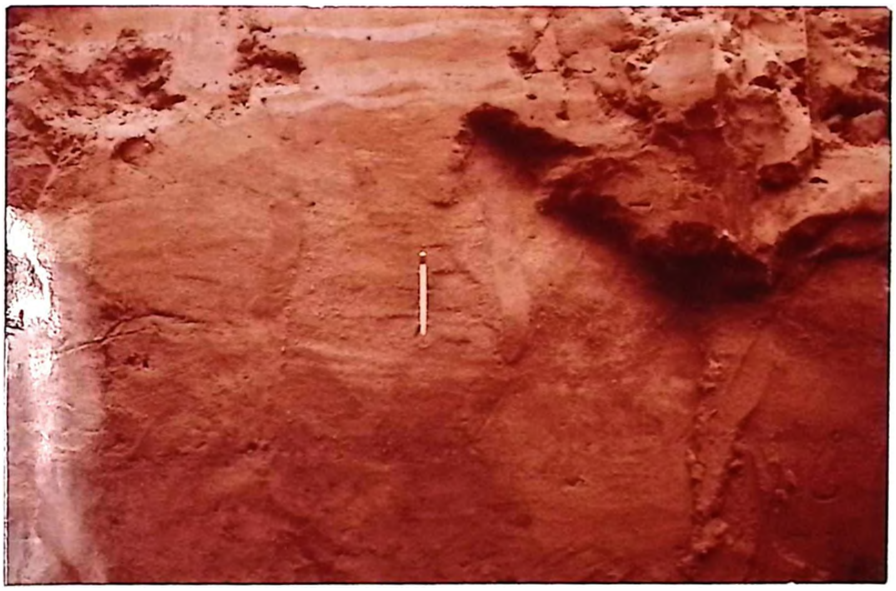

Plate 10. Same clay pipes as Plate 9; matchstick for scale.

(b) They are the result of animal borings in the lake sediments.

(c) They are some form of non-diastrophic feature such as basal-deformation of sandstone.

Beneath this complex zone the profile fixes itself in a repeating pattern to at least 240 cm. The pattern consists of alternating clay and sand horizontally stratified sediments. In addition to textural repetition there is also one of colour. A red, or reddish brown sand blending down into a brown or tan clay.

These textural and colour bandings may be due to:

(a) Seasonal inwashings, similar to varving, but this is unlikely because the bands are too thick.

(b) The raising and lowering of water levels in the lake as the ice lobe retreated. Hurst[30] has clearly indicated that the retreat was not an even one.

From the detailed samples taken from the topmost 2 feet of the profile, the soil type was discovered to be similar to that of a Grimsby Fine Sandy Loam. This soil is then dominantly a light, fine particled sand. As Geiger[31] points out the soil type considerably affects its micro-climate. This particular soil may be expected to possess certain special characters:

(a) Lower heat capacity than a heavier soil.

(b) Low thermal conductivity - due to its high air content.

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[30] D. L. HURST, Op. cit. 1962.

[31] R. GEIGER, Op. cit. 1959, Chapter 14.

(c) Dry - due to its many pore spaces.

These various characters combine to produce a soil climate peculiar to such a soil. For instance due to its low thermal capacity a fine sandy loam heats up and cools down quicker than a heavier soil, such as a clay. Due to the poor thermal conductivity of such a soil the energy received is mainly concentrated in a thin layer close to the surface and thus:

(i) The depth of diurnal penetration is small compared with other soils.

(ii) Equally the depth of winter frost penetration is less.

(iii) The temperature gradients are very steep close to the surface, both by day and by night. But the temperature range decreases rapidly with depth.

Of greatest importance, especially to the farmer, is the ability of such a soil to heat up and cool down rapidly. Because of the lower heat capacity and thermal conductivity, and less evaporation chilling, this fine sandy loam will thaw first, and warm up for plant growth first, in the spring. This is a great advantage. However, conversely, in the autumn this soil will be cooled by radiation, and by the percolation of cold rain, and so become adverse for agricultural purposes earlier than a heavier soil.

Climate

Geiger considered, "The first thing to do, naturally, is to consider the macro-climatic relationships of the nearest observation points. They always furnish the essential basis for all micro-climatic studies".[32] The meteorological elements which combine to produce this macro-climate of a locality, also form the "External Factors" involved in the micro-climatic regime of its soil. These external factors are of extreme importance because they play an active role in contrast to that of the passive intrinsic factors. The degree of soil temperature for instance, is almost wholly controlled by the external factors, especially the air temperature, and only slightly modified by the intrinsic factors, which have already been discussed.

The intention of this section is then to fully describe the climate of the Hamilton area, and the McMaster University campus in particular, and to suggest how such a climate may be expected to influence the micro-climate of the soil. In addition to a description of the past climate, the weather conditions of the year of this investigation will also be given. The weather characters of this year will be examined in an attempt to answer two questions:

(1) How did the weather of this year differ from the long-term average conditions for this area?

(2) How would these differences be likely to affect the soil temperature?

Climate of Hamilton

The sources used for this description of the climate of Hamilton, Ontario are as follows:

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[32] R. GEIGER, Op. cit. 1959, p. 260.

(a) "The Climate of Hamilton, Ontario" by the late Professor H. R. Thompson of this Department. This is a report prepared in 1956, "as a guide to the climatic conditions prevailing at the McMaster University campus"[33]. This excellent report is tailor-made for this study as it was designed to highlight conditions around the then proposed University Nuclear Reactor, which is now situated less than 500 feet from the experimental site.

(b) Both the Annual Meteorological Summary for 1963, and the Monthly Meteorological Summaries issued by the Hamilton City Weather Office of the Department of Transport (Meteorological Branch) were used, plus the valuable personal advice of Mr. J. M. Wingfield, its Director.

(c) For the general picture the classic paper "The Climate of Southern Ontario" by D. F. Putnam and L. J. Chapman[34] was consulted.

Climatic Controls

Hamilton's climate is generally accepted to be Continental in character but with substantial modification due to the proximity of Lake Ontario and other unique climatic controls. In general the weather regime consists of warm summers and cold winters.

The factors controlling the climate of any region are basically these:

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[33] H. R. THOMPSON, "Climate of Hamilton, Ontario", unpublished report, 19th November 1956, page 1.

[34] D. F. PUTNAM and L. J. CHAPMAN, "The Climate of Southern Ontario", Scientific Agriculture, Vol. 18 (No. 8), 1938, p. 401-446.

(1) Latitude (2) Altitude (3) Physiography (4) Distribution of land and water (5) Proximity to cyclonic storm belts. Each of these will be dealt with here indicating their relative importance in determining the broad climatic features of the locale.

(1) Latitude. The latitudinal position governs both the length of day and the amount of the sun's heat received at the Earth's surface. McMaster University lying at about $43^{o}16'$ North lies in the middle latitudes. Thus the sun's rays impinge at an angle of $70^{o}15'$ on the summer solstice, and at $23^{o}15'$ at the winter solstice giving typically wide climatic fluctuations between the extreme seasons. Since all the energy in the circulatory system is acquired from the sun, the latitude of a region must always be regarded as of the utmost importance.

(2) Altitude. An increase in altitude usually has three climatic effects, viz: (a) decreased atmospheric pressure, (b) increased precipitation, (c) decreased mean temperature. However, the campus site on the Westdale Plain only lies between 320 and 330 feet above sea level. Theoretically this could mean temperatures of approximately $1^{o}F$ lower than those at sea level. There are so many more important influences acting upon this site that it would seem that altitude is one of the least effective factors.

(3) Physiography. The influence of the relief of the area upon the climates in its vicinity, or "topoclimatology", is of extreme

importance in this area. The University campus lies on the flat Westdale plain at the base of a 200 foot high dolomitic cuesta, and also at the mouth of the re-entrant Dundas valley (Fig. 4). Both features provide considerable influences upon the climatic elements.

(a) Niagara Escarpment. This outstanding feature exerts considerable influence. Air forced to rise over this continuous obstacle induces the condensation of humid air blowing in from Lake Ontario. During spring and autumn this ascending air which is adiabatically cooled may well form a solid bank of fog as it condenses, reducing visibility drastically along, and some way backward of the 'scarp face. During the winter, winds blow moisture-laden air from Lake Ontario up towards the escarpment. The resultant orographic cooling may be sufficient to induce heavy snowfall. In the summer unstable Maritime Tropical air may be forced to rise over this barrier and become triggered into convectional uplift producing violent motion and rapid cooling, resulting in heavy thunderstorms.

The reverse process also occurs. When air moving down from the 'scarp plateau is adiabatically warmed, it becomes capable of holding more moisture and the tendency is towards evaporation.

The 'scarp shelters the city, to some degree, from southerly winds; however, during the winter months at least it provides its own cold-air drainage, resulting in what are known as "Katabatic winds".

(b) Dundas Valley. This deep glacial valley trends W.S.W.-E.N.E. and acts as a wind funnel, channelling the air along its long axis and producing dominantly westerly wind movements across the city.

This directional funnelling is augmented by the dominant S.W.-N.E. or W.-E. winds associated with the "stormy westerlies" in whose path this region lies. This valley also provides orographic uplift for cool, moist air from Lake Ontario, Burlington Bay and Cootes Paradise, giving fog over the campus in spring and autumn. There is some Katabatic downslope drainage on cold, clear "radiation nights" with the normal associated "frost pockets".

(4) Distribution of Land and Water. If the influence of the land is dominant over the climate of an area it is termed "Continental"; if the water is uppermost in its effects, the station is "Maritime". Hamilton is located somewhere between these two extremes, being termed Continental but with strong modification due to the close presence of large water bodies.

Depending on the season, and therefore the temperature of Lake Ontario, air passing over the Lake either tends to be cooled and become more stable, or else warmed and more unstable, but in either case it nearly always acquires more moisture and becomes more humid. If the air becomes more stable and a stagnant weather system builds up it may produce a fog which with an easterly wind will be blown onto the city and adjacent lake shores. If, on the other hand, the air becomes more unstable an easterly wind results in showers of rain or a snowstorm over the city of Hamilton. The University campus lying as it does in the lee of not only Lake Ontario but also Burlington Bay and Cootes Paradise tends to have such conditions accentuated. During the winter, Lake Ontario remains relatively ice-free and so remains a moisture reservoir to furnish the cool, moist air necessary for snow. In spring and early summer the Lake warms very slowly and so easterly winds tend to bring very cool air to the lakeshores. In fact on some occasions, the city on the Lake Plain has been 10° F cooler than the area on top of the escarpment.

(5) Proximity to Cyclonic Storm Belts. Lying in the mid-latitudes, Hamilton occurs along the critical, fluctuating line of contact between colder Polar air gravitating to meet the warmer Southern Sub-Tropical High Pressure system air. Along this dynamic line, "tongues" of colder Polar air may enclose warmer, lighter air. The familiar "Low" pressure system becomes spawned and migrates along distinct storm-paths probably tied to Upper Air movements. This is the belt of the "stormy-westerlies" characterized by exceedingly variable weather in which most of Southern Ontario finds itself.

(a) In winter, Hamilton lies slightly south of the mean position of the Arctic Front separating cold from milder air. The cyclonic disturbances associated with this front influence the weather of this district but precipitation is not usually great unless the air is moisture laden and forced to rise. This situation can arise with air travelling across Lake Ontario and then being uplifted to traverse the Niagara Escarpment, often resulting in heavy snowfall. Sometimes North-Eastern Modified Maritime Polar, and Southern Modified Maritime Tropical air over-ride the Continental air and provide cyclonic storms. These storms give strong winds and heavy precipitation, and their "warm sectors" often provide the familiar winter "thaws" which leave the ground flooded.

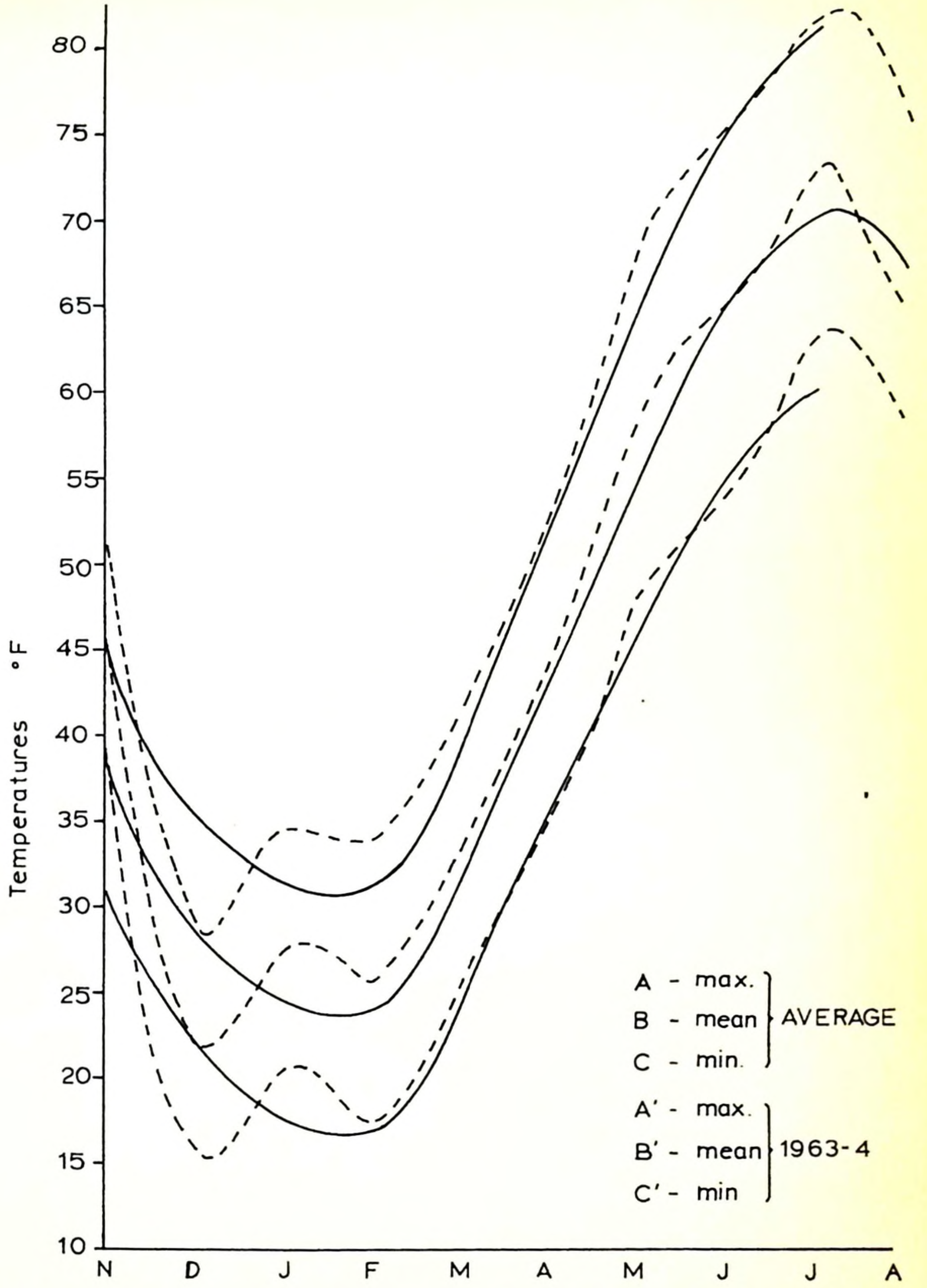
(b) In summer the major air-mass boundary runs directly across Hamilton, with Continental Polar air to the north and Maritime Tropical air to the south. The exact position of this front governs whether the summer is a hot or a cool one. Although the cyclonic movements are still evident in the summer, most of the precipitation is not provided by them, but by vigorous convectional thunderstorms, especially in the evening.

Climatic Elements

Due to the action of these controls a definite set of climatological element values is established for any particular station. Individually, at any time, any of these values may differ markedly from that normally experienced, but essentially the broad pattern of temperature, precipitation and wind follow a similar course annually. Such a set of broad patterns is presented here for Hamilton.

(a) Air Temperature. Fig. 6 shows the annual march of average daily maximum, mean and minimum temperatures as quoted in the Monthly Meteorological Summaries of the Hamilton Weather Office. The gradient of the curve can be seen to be a steep one, indicating the wide fluctuation between the extreme seasons. February is seen to be the coldest month and July the warmest, their average daily mean temperatures being separated by a range of 47.4° F. The record low temperature for Hamilton was -17° F recorded on January 13, 1914, and February 15, 1943. The record high was 103° F on July 3, 1911. Conveniently, as Thompson points out, the weather stations and the University all lie at the same altitude above sea level, and should

FIG. 6 MONTHLY AVERAGE AIR TEMPERATURES



therefore experience roughly similar temperatures - "an assertion confirmed by detailed comparison".[35]

(b) Precipitation.

(i) Total precipitation (including water equivalent of snow). The graph of average monthly total precipitation (Fig. 7a) shows a uniformity of rain and snow distribution throughout the seasons. Normal yearly precipitation totals 33 inches, made up of rain 28.41 inches, and snow 45.9 inches (i.e., 4.59 inches water equivalent).

(ii) Snow. Fig. 7b shows six of the normal seven months in which snow falls. Beginning in October, snowfall reaches a peak in January and diminishes again to finish in April. The total amount of 4.59 inches water equivalent, is quite small, but this is augmented by rain during the winter months.

(c) Wind. The data concerning wind direction and speed have not been gathered for long in Hamilton, so only the most tentative values are available. However, there is a strong predominance of west and south-westerly winds, influenced by the topography of the Dundas Valley. Winds with a north and easterly component are also of importance.

(d) Moisture Balance. Thompson[36], using C. W. Thornthwaite's potential evapotranspiration formula, and the actual precipitation of

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[35] H. R. THOMPSON, Op. cit. 1956, p. 2.

[36] H. R. THOMPSON, Op. cit. 1956, p. 9-10.

Fig. 7a Average Monthly Total Precipitation

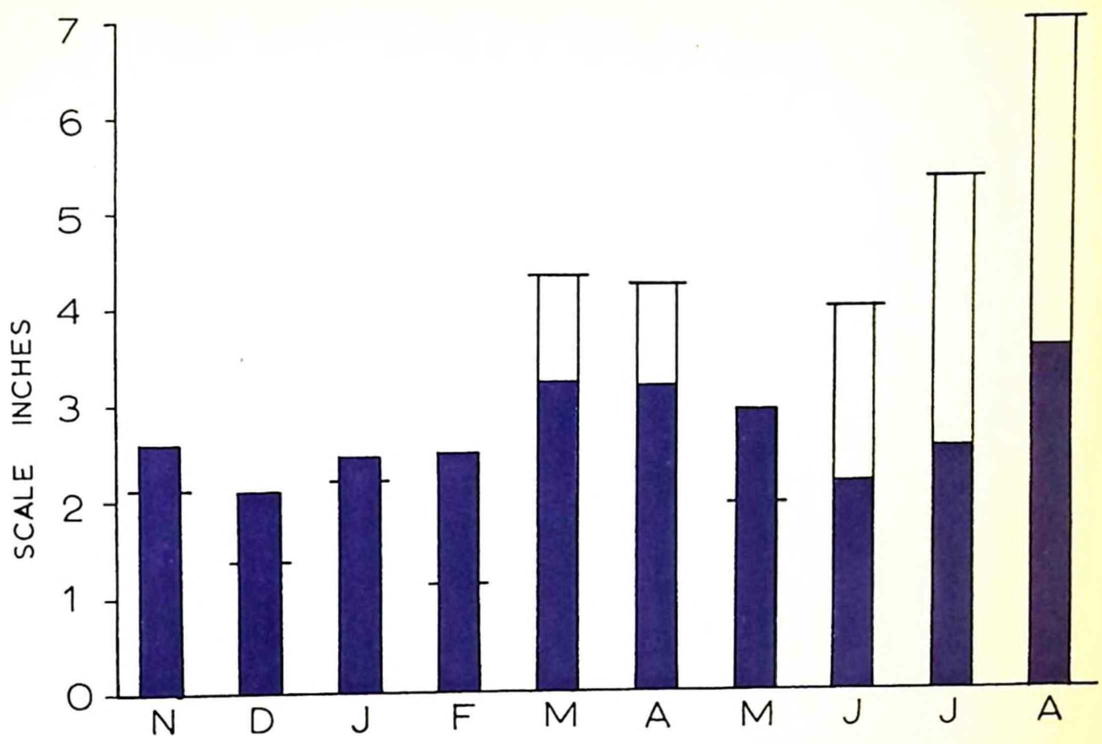
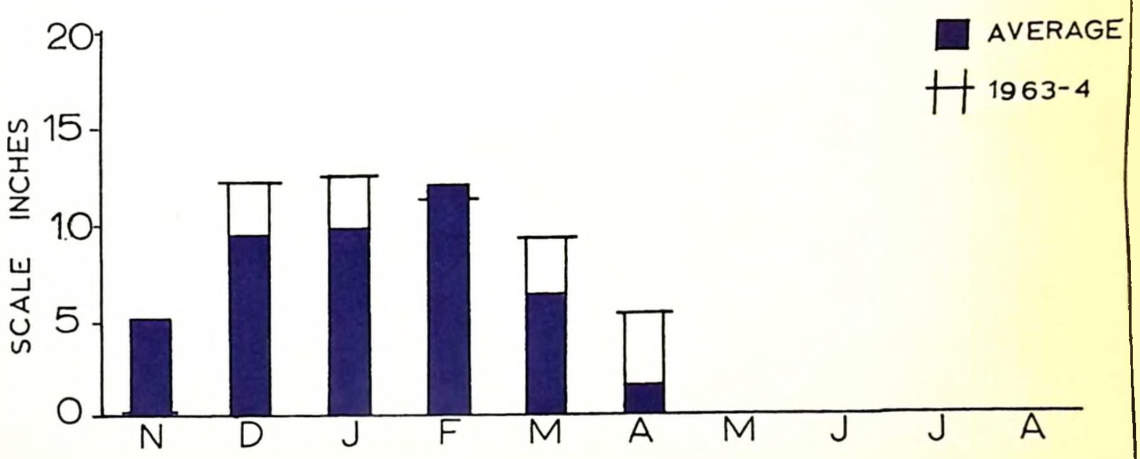


Fig. 7b Average Monthly Snowfall



Hamilton calculated the moisture balance of the area. His results show a large water surplus in the winter, and a small water deficit in the summer. In general, droughts do not cause serious effects, but in the summer months irrigation is widely practised to ensure good crop growth.

Relation Between Macro-climate and Soil Climate

These "external factors" peculiar to Hamilton will influence the soil micro-climate in a multitude of ways. However, a broad framework can be expected in such a situation:

(1) Winter. During the winter months the sun's elevation will be low in the sky and daylight hours short. As air temperatures fall under these conditions, so will soil temperatures, especially during the long clear "radiation" nights. Evaporation will decrease drastically, allowing soil moisture to build up a surplus. This increased moisture is likely to: (i) increase the specific heat of the ground, and thus dampen down diurnal variations, (ii) provide the necessary soil water to form ice crystals when the ground freezes. The winter cooling continues the depth of the frost-line will penetrate deeper.

The snow cover of the area will provide a reasonable source of insulation for the ground against outside air temperature changes, and an additional reduction in the diurnal temperature wave amplitude. This picture is likely to be periodically interrupted by breaks in the snow cover and flooding associated with the familiar "thaws" due to the passage of the warm sector of a cyclone.

(2) <u>Spring</u>. With the increased solar radiation and longer daylight hours experienced during springtime there is likely to be a steep up-grade in air temperatures. Associated with this will be the disappearance of the frost line from the ground and the rapid warming of the soil from the surface. Evaporation will re-commence and remove much of the soil moisture, thereby lowering the specific heat of the soil. This lowered specific heat will increase the heat penetration and thus the amplitude of the diurnal wave.

(3) <u>Summer</u>. The springtime warming and drying processes continue until mid-summer. As Patten[37] has shown moisture increases the thermal conductivity of the soil; the removal of it will, therefore, reduce the ability of the soil to transmit heat downward, and correspondingly the temperature fluctuations at depth will be reduced. This process may be augmented by dessication of the top layers of soil, increasing their air content and insulating lower depths from temperature changes. The soil surface temperatures may well be extreme, but only with difficulty will heat be transmitted downward through the dry, aerated soil. The numerous violent summer evening thunderstorms of the Hamilton area are likely to provide night cooling.

(4) <u>Autumn</u>. From mid-summer, when soil temperatures reach their peak, the cooling process will begin. It is a more gradual process than the corresponding "turnover" time in the spring, both the diurnal range and maximum values will decline and merge again into the winter conditions.

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[37] H. E. PATTEN, <u>Op. cit</u>. 1909.

The preceding normal course of soil temperatures presents obviously only the most general pattern, under normal conditions. However, conditions are never "normal"; and the year under consideration was no exception. Figs. 6, 7a, and 7b in addition to the monthly normals also show the particular values encountered during the period of this investigation. A comparison provides an idea of how typical this year was.

November was very mild compared to previous years. Air temperatures remained abnormally high and no snow fell. Rainfall was about normal, but due to the drought conditions of the preceding months soil moisture remained low. Soil temperatures would be expected to remain at a higher level than normal. The following month of December, however, provided a stark contrast. Temperatures fell to the lowest for the year, and snowfall was just about average. The ground would be likely to cool rapidly. Conversely, January temperatures rose above normal, providing a "bump" in the temperature curves (Fig. 6). With both rain and snow below normal, this was an exceedingly mild January. February also proved relatively mild, as did March. All together a mild winter for this locality, except for an abnormally cold December. Snowfall totalled about the average, and rainfall slightly below. All these conditions would favour less cooling than normal in the soil, and a reduced depth offrost penetration.

The springtime month of April was normal for this area, except for high rainfall which would tend to hasten the spring ground thaw by equalizing temperatures throughout the profile.

The summer period was started with a considerably warmer than usual month of May, and much reduced rainfall. Soil temperatures should rise sharply under such conditions. June and July experienced much about normal, but rainfall was about twice the average value. Alternating warm and cool days would cause extreme ground temperature fluctuations. August temperatures fell considerably, but the most outstanding feature was again rainfall, totalling 7.02 inches, double the average. Such conditions would be conducive to rapid soil cooling after the July heat.

Thus the autumn cooling was held up in November, but the very cold December brought on winter very quickly. The relatively mild months of January, February and March stopped the winter from being a harsh one. Spring came late, but temperatures warmed quickly and May brought summer early. Similarly the cool, wet August brought on the autumn cooling a little earlier than usual. As a summary one may say that the winter was milder than usual, and the summer wetter.

CHAPTER 4

ANNUAL MARCH OF SOIL TEMPERATURE

The following three chapters are devoted to the presentation and analysis of the data acquired in this study. The treatment of the results is to proceed from the large scale to the small scale; that is to present the annual curves, then break down the year into seasons, and finally further subdivide the time period into weeks or days. It is hoped in this way to provide a broad framework upon which the more detailed observations may be constructed.

Before discussing the results it is necessary to outline the four methods usually employed in their presentation:

(1) Isopleths - heating and cooling cycles are shown by lines of equal temperature, using time and depth as co-ordinates (e.g., Fig. 15 and 23).

(2) Tautochrones - this method uses temperature and depth as co-ordinates and plots the line at a given time (e.g., Figs. 11 and 43).

(3) Time/Temperature Graph - using time as abscissa and temperature as ordinate, this method shows the march of temperature at selected depths (Figs. 10, 14, 41).

(4) Polar Co-ordinate Diagram - by dividing a circle into twelve segments for the months, and using concentric rings for temperature, a circular path of temperature changes is portrayed (Figs. 9, 29).

A discussion of the individual merits of these methods for specific purposes will be given later.

It should be noted that the data used in this chapter was acquired as follows:

(a) At 1400 hours - that is at the maximum temperature epoch. (Lack of observers made the observation of a minimum soil temperature epoch impossible.) Therefore, results are daily maxima, not daily means.

(b) During the winter when soil temperature conditions are known to be relatively stable readings were taken about once every two days.

(c) During the summer readings were taken on almost every day.

The monthly averages of daily maxima, and of all temperatures recorded in control plot A*, are given in full in Appendix III. The original daily field sheets showing the individual readings have been filed with the Department for reference. Macro-climatic air temperature, rainfall and snow cover statistics have been drawn from the Monthly Meteorological Summary issued by Hamilton Weather Office.

On the largest scale, the soil temperature rises and falls in a periodic fashion, during the course of a year. This rise and fall is of course entirely governed by the seasonal variation of the external factors which cause the summer and winter climatic extremes, especially the variation of insolation. During the summer months the input is greater than the losses incurred in the energy budget of the soil. As a result, considerable amounts of radiation are converted into heat at the soil surface and conducted downwards

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* Hereinafter to be referred to as "total profile average".

into the underlying subsoil, because at this time of the year temperature decreases with depth, and a gradient downwards exists. During the winter this situation is reversed. The summer heat surplus is now stored at depth and comprises a reservoir supplying heat to the overlying colder layer. At this time of the year temperature increases with depth and the gradient is obviously upwards. The transition time between these two extremes is known as the "overturn" and occurs during the spring and autumn.

Figs. 8 and 9 show the results obtained using the monthly total profile averages. (These figures represent the average of the 14 depths in the control plot.) These monthly total profile averages can be assumed to reflect, in a general manner, the energy budget of the ground as it varies throughout the year. The wave-like appearance of this curve becomes immediately evident in Fig. 8, the summer maximum being attained in July and the winter minimum in February. The relative flatness of the curve during the months of January, February and March, may be attributed to the insulating effect of the snow cover. The spring heating beginning in April, after the snow has disappeared, is seen to be very rapid, and continues until the maximum point in July when cooling sets in again. For comparison the average radiation curve for the nearest station (Toronto) is included. There is a close relation between the two. However, the times of maximum and minimum are delayed in the soil for two reasons (i) these points are reached when incoming <u>and outgoing</u> radiation

FIG. 8 MONTHLY TOTAL PROFILE AVERAGES

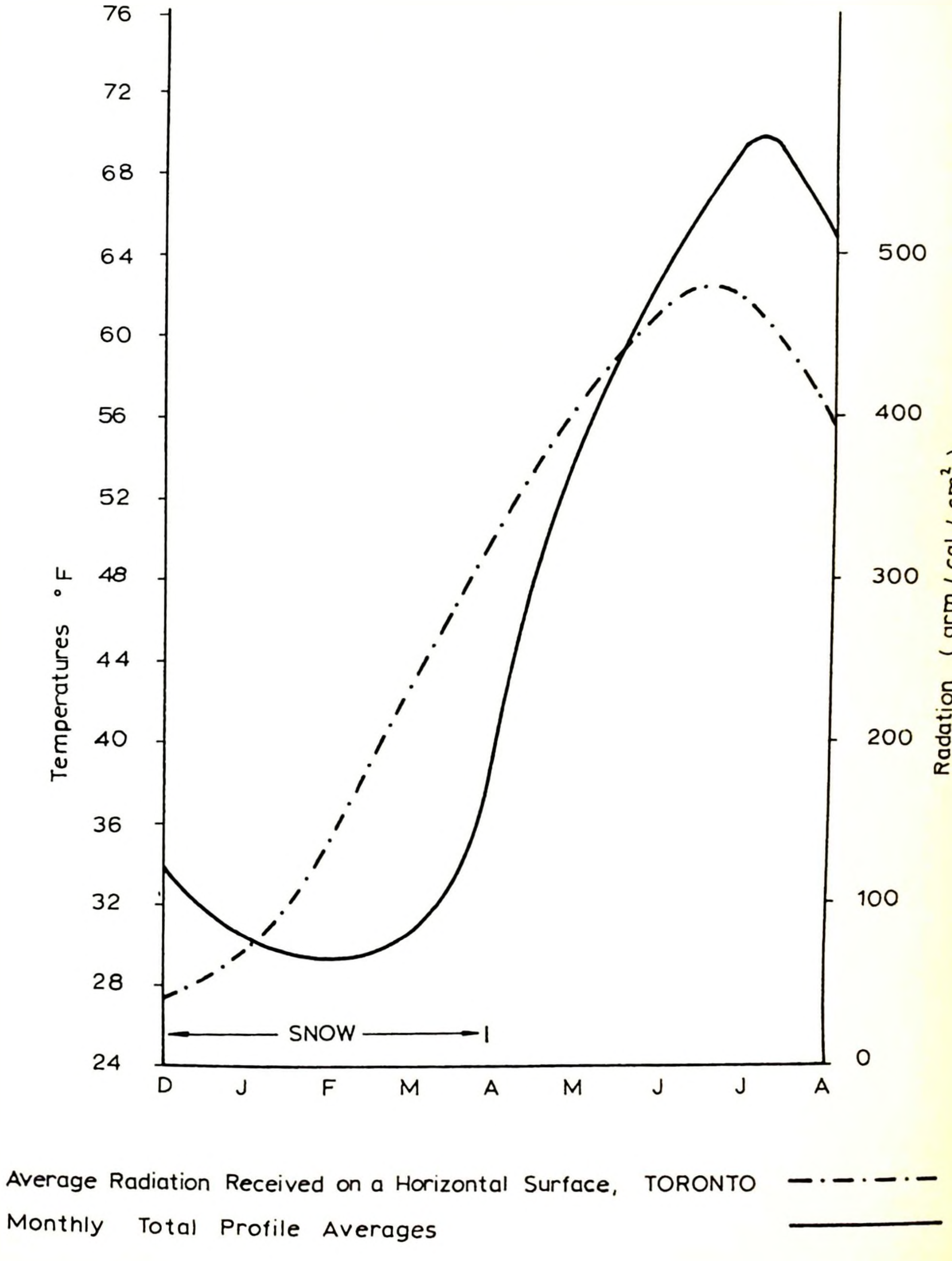
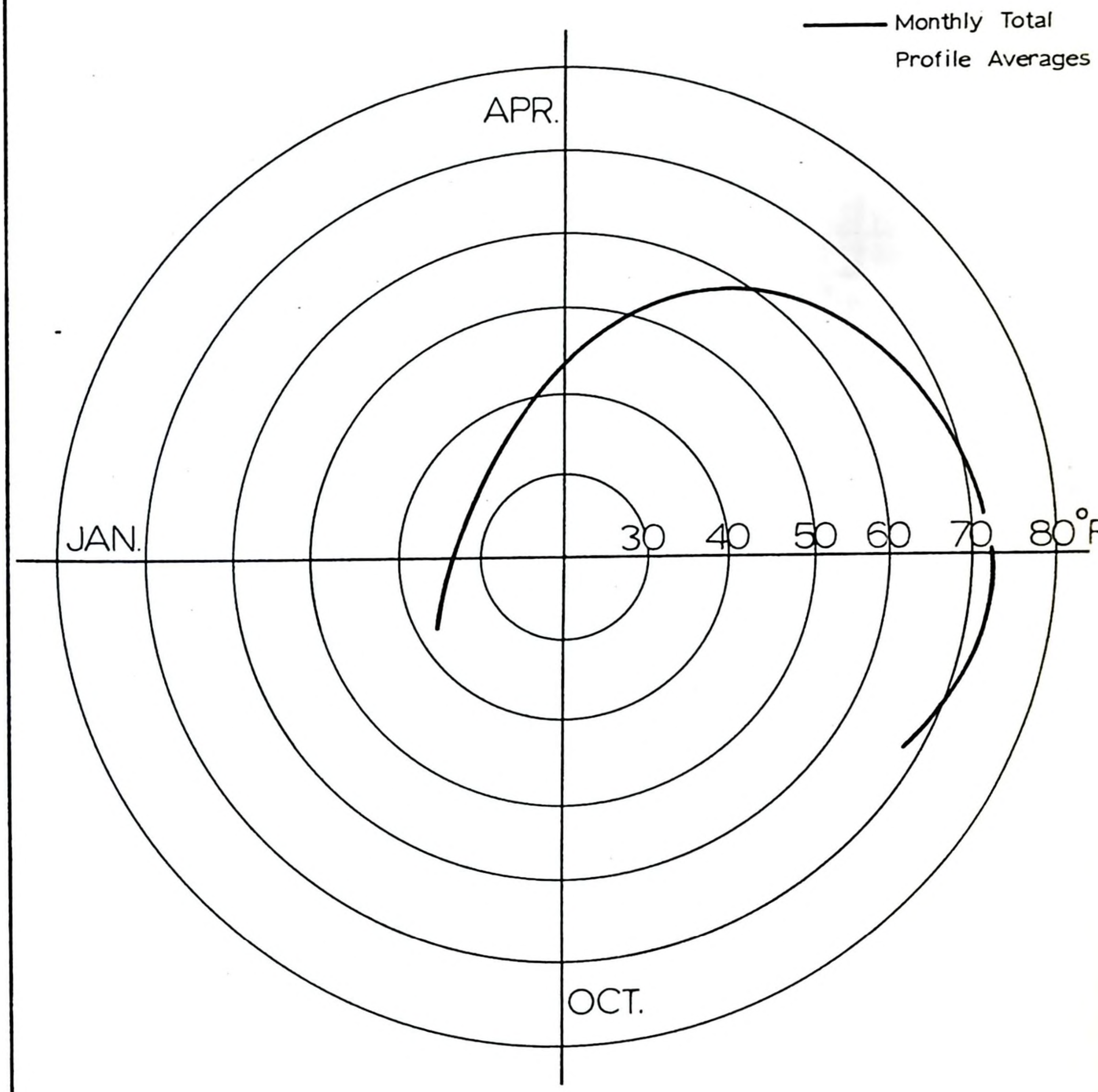


FIG. 9 MONTHLY TOTAL PROFILE AVERAGES



Method : Polar - Co-ordinates

attain a balance.[1 and 2] (ii) the winter snow delays heating.

Having presented the most general heat budget of the soil down to 225 cm, the individual depths may now be considered (Figs. 10, 11, 12 and 13). These four graphs of monthly soil temperature averages at selected depths illustrate well the various features of the annual soil temperature regime. Discussion of the features will be restricted to Figs. 10 and 11 because they exhibit best the main points to be considered.

Geiger[3] presents data acquired by Schmidt and Leyst at Königsberg and remarks "The extraordinary regularity with which the heat movement in the soil proceeds is so great that the curves appear to have been plotted theoretically". The same may be said of the curves representing average monthly soil temperatures at selected depths (Fig. 10) made in this study. Indeed the only apparent irregularity concerns the 1, 2.5 and 5 cm depths during January and February. However, these abnormalities are immediately attributable to the effect of a snow cover during these months; a feature not encountered on the artificially cleared plot of Schmidt and Leyst. Both Figs. 10 and 11 illustrate very clearly a number of salient points regarding the annual soil temperature regime:

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[1] See BRUNT, "Weather Study" 1956, p. 33. and

[2] G. T. TREWARTHA, "An Introduction to Climate", McGraw-Hill, 1954, p. 26-27.

[3] R. GEIGER, Op. cit. 1959, p. 32.

FIG. 10 Monthly Averages at Selected Depths

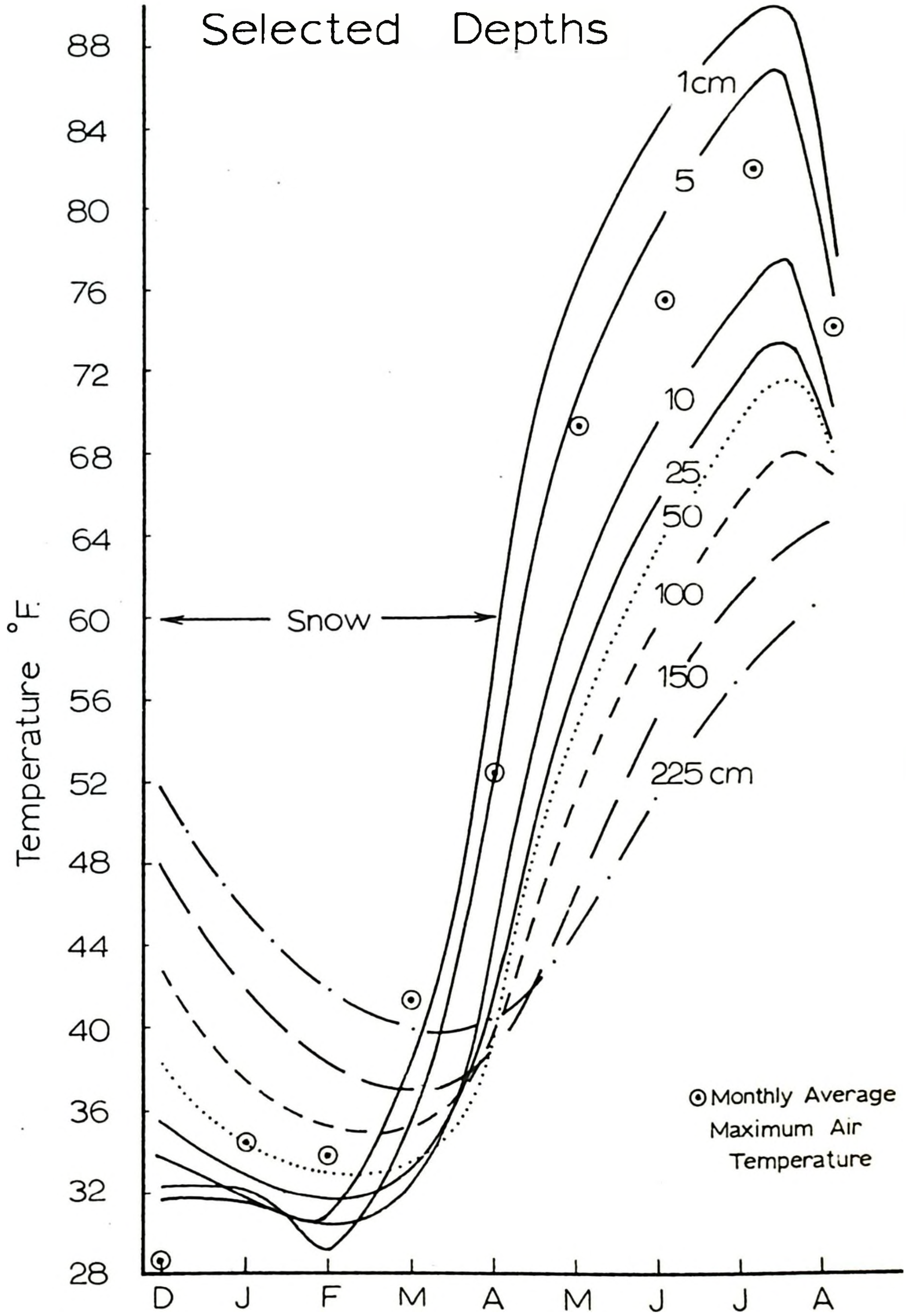


FIG. 11 TAUTOCHRONES OF MONTHLY AVERAGES AT ALL DEPTHS

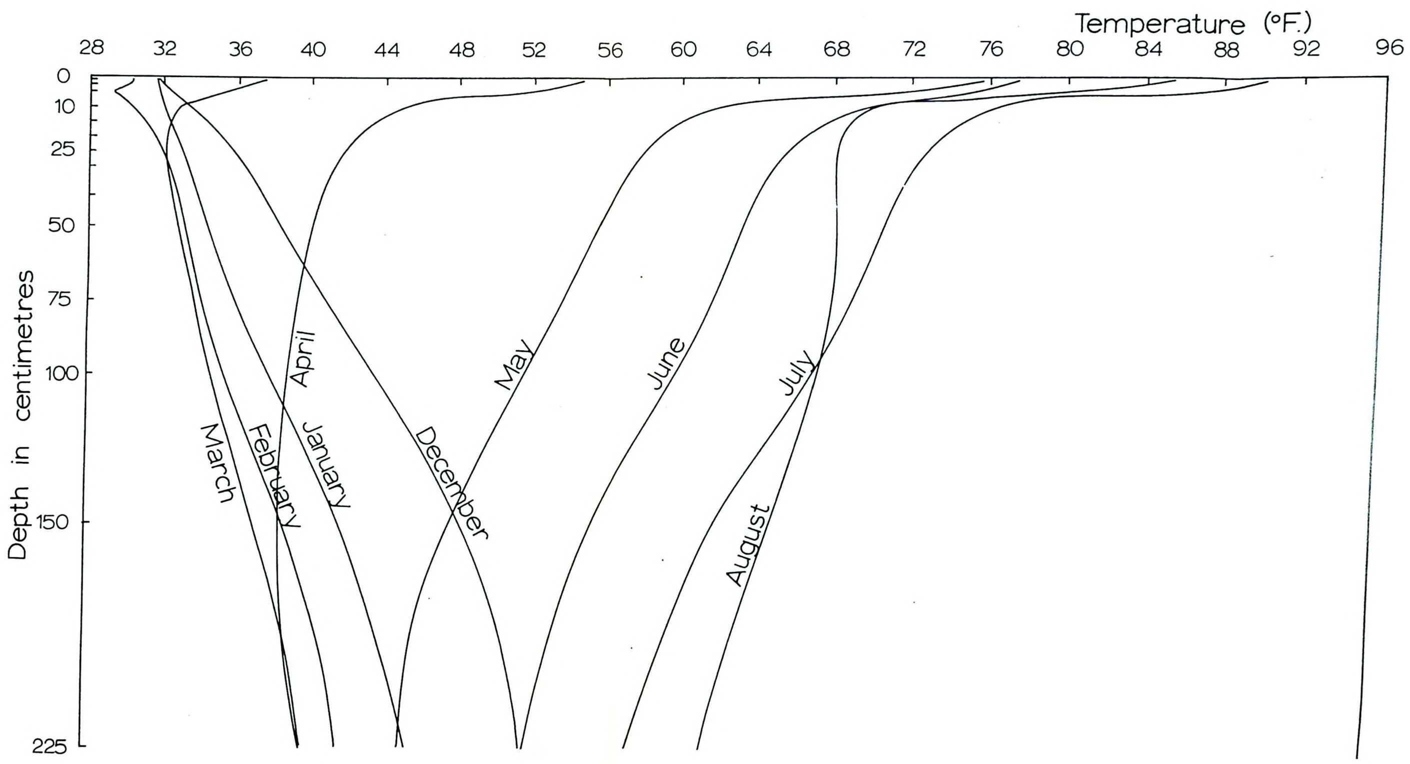


FIG. 12 Monthly Averages at Selected Depths

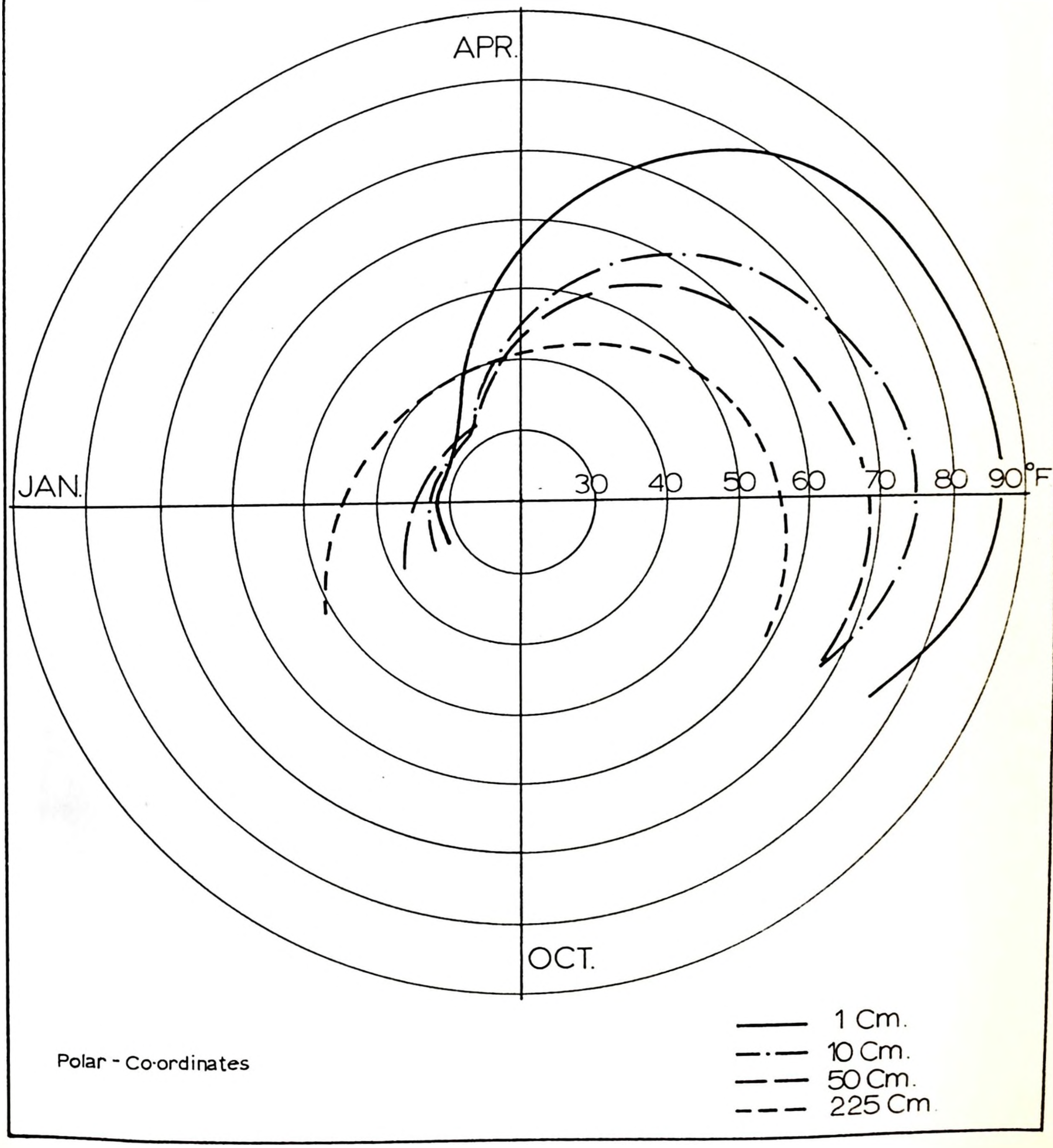
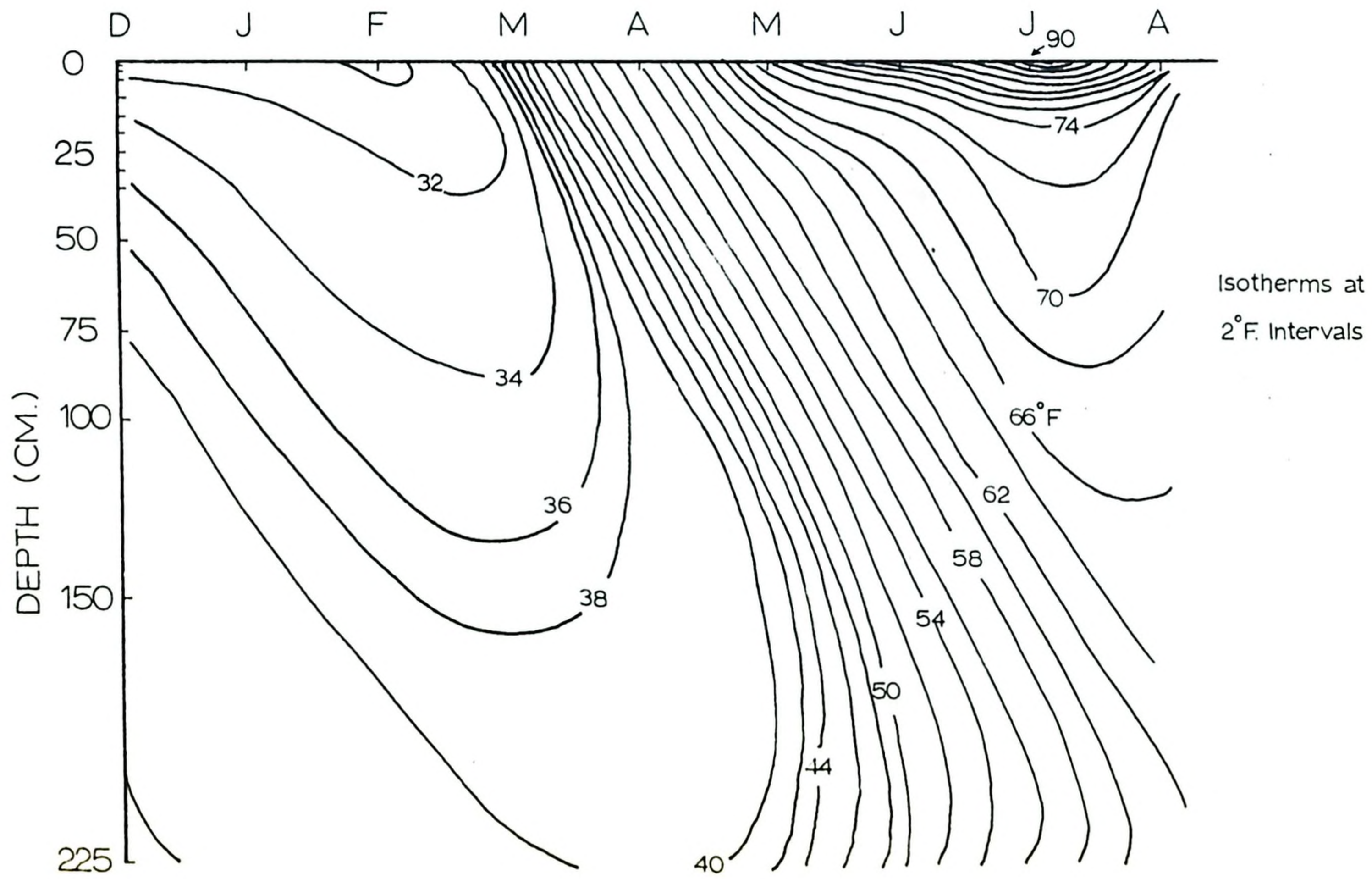


FIG. 13 Isopleth of Monthly Averages



(1) Dynamic situation - The soil is in a constant, complex state of flux, containing annual, diurnal and hourly members. The simplest pattern is the largest - the annual harmonic wave as indicated in Figs. 8 and 9 above. When a number of depths are also added to the parameters of time and temperature two points become clear:
(a) at any depth, temperature varies with time. As an example of this the course of any depth line should be traced in Fig. 10.
(b) at any time, temperature changes with depth. For instance note the gradients on the monthly tautochrones of Fig. 11, or selecting one month in Fig. 10, consider the temperature values at different depths.

(2) Diminution of wave amplitude with depth - When the ground surface is heated or cooled a temperature gradient exists between it and the underlying layers. In this manner a heat wave is propagated which travels away from the active layer. As the wave progresses its effects are dampened until finally it can no longer be discerned as a variation. These waves may be propagated on a diurnal or annual scale. The diurnal wave will be dealt with later. Here only the damping of the annual wave is to be considered. Fig. 10 clearly shows the tremendous spread of temperature at the 1 cm level during the course of the year, the minimum being 30.4° F in February, the maximum being 89.8° F in July, an annual range of 59.4° F. Although the maximum temperature has not been observed for the 225 cm level, it can clearly be seen that the annual range is much diminished, probably in the region of 20° F. Fig. 10 immediately shows the difference in amplitude between these two

waves, and also indicates the intermediary levels and amplitudes between these two extremes. It should be noted that the 25 cm depth has an annual range about midway between the two extremes, but it by no means occurs midway between them on the depth scale. This indicates a further point, that the amplitude of the annual wave decreases rapidly with depth, for by the time it has reached 25 cm it is already only about two-thirds the value at 1 cm.

(3) Time lag with depth. Just as the wave amplitude is decreased with depth, so the time at which deeper levels register these temperature changes is delayed with depth. Thus a surface temperature change is not reflected lower down until sometime later - there is a time "lag". This phenomenon also occurs on both the diurnal and annual scales. In this context Fig. 10 shows that the 1 cm depth records its annual minimum in February, the 100 cm level reaches its low in March but it is not until April that 225 cm reaches its lowest temperature of the year. Had observations been continued longer a similar lag in the achievement of the maxima would have been noticed. The lag in minima also shows in Fig. 11. In March down to 25 cm the soil is beginning to show signs of springtime warming; below this the winter up-flux of heat continues and all depths show cooling from the previous month. The April tautochrone indicates the warming process to be much intensified in all layers down to 200 cm, but due to the lag in time needed to conduct this heat downward the levels below 200 cm still indicate winter cooling.

(4) Winter - temperature increases with depth. The winter period in between the autumn and spring turnover periods is characterized

by a net heat loss consequent upon the greatly reduced incoming insolation. The soil heats up little by day, but cools greatly by night, resulting in a cold surface and warmer subsoil. An "up-flux" gradient exists allowing the stored up summer's heat to be expended from the lower strata. Thus the surface is cold and temperatures increase with depth, until the zone of constant temperature is reached. In Fig. 11 the tautochrones for December, January, February and March have a definite slope to the left indicating an up-flux from below. Fig. 10 also shows the lowest level to be the warmest from the time observations were begun, until the spring "overturn" in April.

(5) Summer - temperature decreases with depth. Following the spring overturn, heat income begins to exceed losses and continues to do so throughout the summer period. The active surface is now in receipt of considerable heat which is propagated downwards, as a "down-flux". In consequence the temperature decreases with movement downwards away from its source. As a result the lowest level in Fig. 10 is now the coolest in the profile, and in Fig. 11 the inclination of the tautochrones is to the right.

(6) Turnover. During the transition periods of spring and autumn between the conditions of summer and winter the reversal of temperature gradients takes place. This is a complex time and a most critical one. Fig. 10 shows very well these conditions, with characters very similar to those of Cook[4]. The lines representing depths

[4] F. A. COOK, "Near Surface Soil temperature Measurements at Resolute Bay, Northwest Territories", Arctic, Vol. 8, No. 4, 1955, p. 243.

all bunch together and cross over, so that in effect their temperature values are completely reversed the warmest now being the coldest and vice versa. This is also a good time to watch the time "lag" phenomenon, the lowest depth always changing its trend last of the profile. After the turnover the lines diverge again as the temperature gradient builds itself up. The turnover is less easily seen in Fig. 11, but in Fig. 13 it is evidenced by the isotherms running in a vertical, isothermal position at the beginning of April.

(7) Fluctuations during the seasons. Both the daily and monthly fluctuations in soil temperature during the winter months are slight, especially with the presence of an insulating snow cover. During the summer months of intensive solar radiation and no snow cover these fluctuations are much more marked, and their associated temperature waves have greater amplitudes. Consequently the winter months are characterized on Fig. 10 by a flattened curve, and on Fig. 11 by a close bunching of the tautochrones around 32° F. In contrast the summer exhibits a steep gradient curve, and widely spaced tautochrones respectively.

(8) Relation soil:air temperature. Since the air temperature is determined largely by the temperature of the soil surface it should show some relationship with lower soil depths. Fig. 10 shows a very good over-all relation between air and soil temperatures in the summer, but a less distinct correlation during the winter, due to the introduction of a snow cover. Keen and Russell[5] noted a relation

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[5] B. A. KEEN and E. J. RUSSELL, Op. cit., 1921, p. 218.

between the 6 in. (10 cm) soil temperature and that of the air in a thermometer screen. A less distinct relation has been achieved in this study but the following may be concluded: (a) Winter - air temperatures are usually warmer than those of the soil down to a depth of 50 cm. (b) Summer - during the months of April, June, July and August the air temperature corresponds to a depth in the soil somewhere between 5 and 10 cm.

Moving from the general to the more specific, Figs. 14 and 15 represent the individual daily readings taken at 1400 hours from November, 1963 until August, 1964. These are the individual daily observations which have been averaged to produce the monthly means represented in the previous soil temperature diagrams. Of the four methods of presentation, only those involving Time/Temperature, and Isopleths are of practical use for presenting such detail. In this chapter the data for meteorological elements during the study period, presented in Chapter 3, is expanded and analyzed with reference to its effect on the daily soil temperature patterns. The study period is divided, for convenience, into seasons and discussed by the month following this breakdown:

(A) Winter (including November, December, January, February and March).

(B) Spring, using only April.

(C) Summer (including May, June, July and August).

Over-all Trends

On the broadest scale Figs. 14 and 15 show the general patterns exhibited in Figs. 8 and 9, namely the sharp cooling in early winter, followed by a steady period associated with snow cover until the spring turnover when all depths run together and finally diverge in the summer heating cycle. However, the monthly means impart a distorted picture of the actual conditions from day to day. As in many climatological and especially micro-climatological investigations the mean values are much less important than the individual readings from which they are derived. It is seen that although the winter readings show a steady pattern similar to the monthly means, the summer results contain most complex heating and cooling elements which are not revealed by these averages. Two other points of a general nature which are somewhat concealed by the monthly means are:

(1) The tremendous contrast in conditions between the steady course of the 225 cm depth and the highly erratic 1 cm level shown in Fig. 14.

(2) The very marked lag of the minimum temperature with depth is shown clearly on Fig. 15 during March and April, along with the continued cold penetration during these months.

(A) Winter

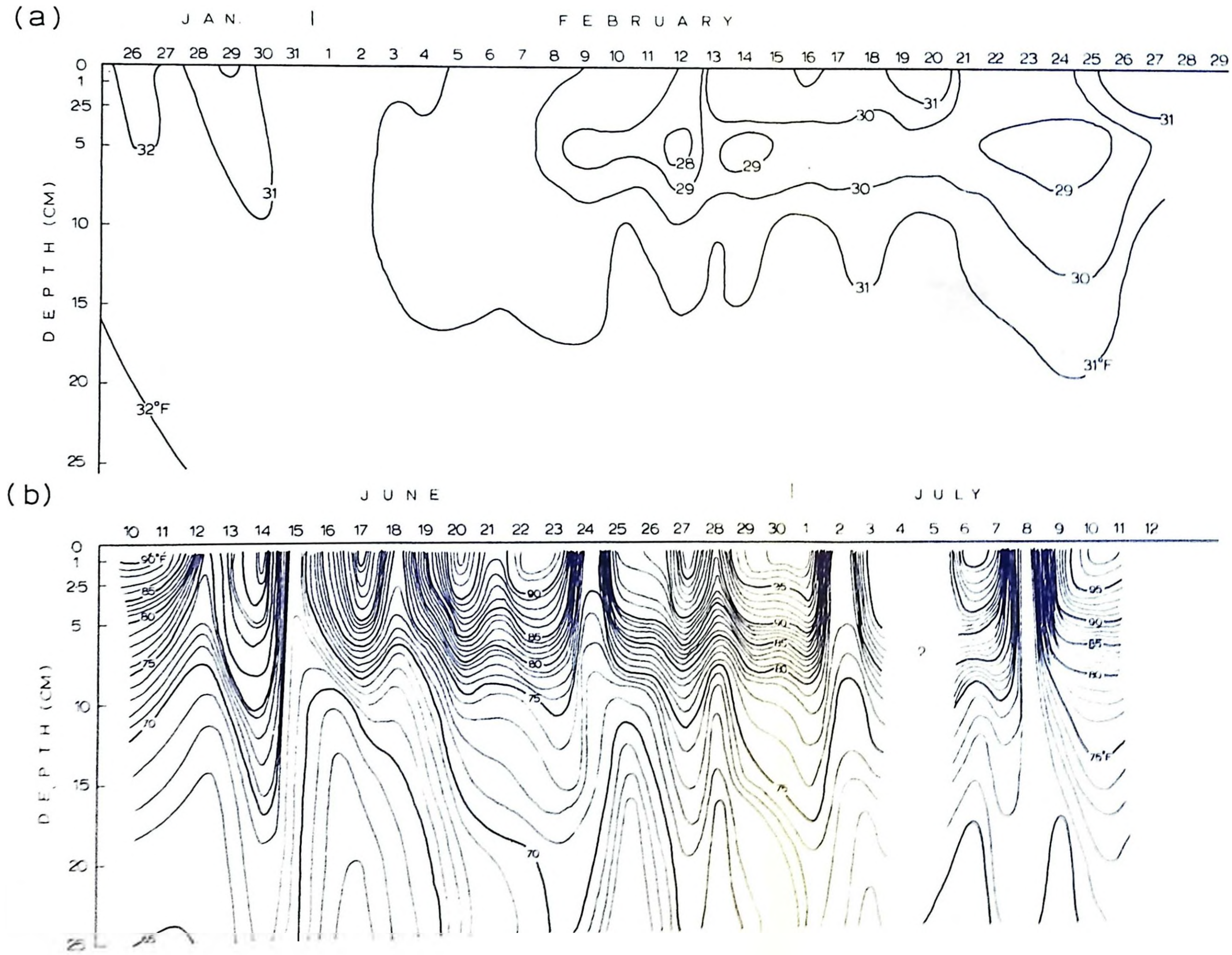
The winter months are characterized in the diagrams by a steady fall in temperature at all depths with the warmest level in the profile being the deepest, and conditions becoming progressively colder as the surface is approached. Rain seems to have very little effect on soil temperatures during these months owing to the frozen state of the ground, but the snow cover does show a marked insulating influence. The 32° F frost isotherm entered the ground in earnest around December 11, but due to the thick snow cover it made little impression below 5 cm. A sudden thaw on January 9 brought the 32° F isotherm back to the surface but the ensuing cold mid-January temperatures without a snow cover saw this time quickly penetrate to 30 cm. The deepest depth of frost (40 cm) was recorded on March 3, and after this it abated quickly to finally leave the ground on March 26, at the 25 cm depth. There is an obvious "low" core in mid-February, as illustrated in Fig. 15.

Fig. 16a represents daily conditions encountered during most of February, and serves to illustrate the relatively steady state of soil temperatures existing during the winter under a snow cover, even when air temperatures may fluctuate wildly. Indeed during this period maximum air temperatures fluctuated 25° (20-45° F), and the difference between maximum and minimum was 40° (5-45° F); and yet during the same period soil temperatures at 1 cm depth varied only 2.95° F! (28.75-31.7° F), and at 25 cm only 1.55° F (30.95-32.5° F) Obviously at this stage in the year the correlation between air and soil temperatures is low.

(1) <u>November</u>

From the weather records it would appear that this was one of the warmest Novembers ever in this locality and no frost was found in the ground at all. Soil moisture remained low after near drought conditions. Due to the lack of moisture the Specific Heat of the

FIG. 16 WINTER / SUMMER CONTRAST IN DAILY CONDITIONS



ground remained low and diurnal fluctuations of soil temperature were greater than would normally be expected. From the limited observations made in this month it would appear that temperatures remained at a high level, and failed to fall as expected.

(2) December

In contrast to November, this month proved rather cold, with an air temperature average much below normal. Following the mild months of October and November this radical change in conditions is immediately reflected in the snow-free soil. Fig. 14 shows well this sudden drop in soil temperatures at the beginning of the month, associated with much reduced air maximum and minimum temperatures. Small pockets of frost appear at shallow depths. Between December 7 and 9 the light snow cleared and temperatures rose. Depths down to 10 cm show a warming, and on Fig. 14 the 25 cm level shows a small warming "hump".

On December 12 nearly 4 inches of snow fell, and from this time until the end of the month snowfall was above average and lay as a continuous cover. At the same time there was a dramatic drop in air temperature with one night of -10° F and only 3 days with daytime temperatures just above freezing. Yet significantly the fall in soil temperature is relatively slight compared with that during the earlier and warmer part of the month. This must be attributed to the effect of the snow cover "blanketing" the soil from outside air fluctuations due to its peculiar thermal properties. During this time frost did enter the ground on December 11 and remained throughout the month, but at a steady level of only 5 cm.

(3) January

Air temperatures during January were slightly above normal and snowfall was only 75% of the average. This snowfall mostly fell early in the month and melted away gradually. During the time when this snow lay, night minimums fell to -1, 4 and -2° F, but due to this cover they are not reflected in the course of soil temperatures. However, a quick thaw on January 9 caused the control box to be flooded and a potentiometer to be damaged. This mishap caused a two-week gap in the records during which time air temperatures fell sharply, and without a snow cover ground temperatures may also be assumed to show a penetration of the frost depth. Throughout this time temperatures at most depths declined at the normally expected rate. Near the end of the month a warm spell brought all depths down to 10 cm just up to the freezing level, and partially halted the cooling of lower layers (Fig. 14).

An interesting comparison of conditions between December 7 - 9, and January 3 - 8, may be made. During both these periods air temperatures were mild for the season, around 45° F, naturally causing a warming of the topmost layers. But a comparison of the magnitude of this warming is most revealing.

TABLE 1 Comparison of Soil Warming, With and Without A Snow Cover

Depth (cm)	December 7 - 9, 1963		January 3 - 8, 1964	
1	2.75° F	(32.15-34.9)	0.30	(31.85-32.15)
2.5	2.55	(32.3-34.85)	0.25	(31.85-32.1)
5	1.95	(32.6-34.55)	0.25	(31.85-32.1)
10	0.30	(34.3-34.6)	0.55	(32.55-33.1)

These figures demonstrate that in December, a two-day rise in air temperatures results in a considerable measure of soil warming. However, in January a five-day period of higher air temperatures has comparatively little effect except to raise soil temperatures, at all depths down to 5 cm, slightly above freezing. The only element which differs is that of snow cover; in January there was 3 inches of snow; December was without a cover.

(4) February

February this year was relatively mild, with many afternoon temperatures above freezing. However, because sunny, clear skies prevailed conditions were at an optimum for night radiational cooling, and as a result night minimum temperatures were often between 5 and 10° F. Snowfall totalled 11 inches which is close to normal, and the snow cover remained continuous for almost the complete month.

In general soil temperatures at lower depths show cooling, but the over-all tendency is towards a marked flattening of this fall. Both Figs. 14 and 15 show this slackening off in the cooling wave below 50 cm. In this respect the following table of fluctuations and over-all tendencies shows a number of interesting points:

TABLE 2. February Tendencies and Ranges of Soil Temperature

Depth (cm)	Monthly range of daily readings at 1400 hours	Difference between beginning and end of month
1	4.6° F	Rise of 1.65° F
2.5	4.4	" " 1.3
5	3.2	" " 1.0
10	1.75	0.0

Continued

25	1.25	Fall of 0.4
50	0.85	" " 0.2
75	0.75	" " 0.25
100	1.15	" " 0.75
150	1.2	" " 1.2
225	1.45	" " 1.45

Points to note:

(a) Levels down to 10 cm show an over-all rise in temperature at the end of the month. This means that these depths have reached their minima at the base of the annual cooling curve. This is in fact the case: The temperature at 1 cm depth reached its annual minimum of 28.75° F on February 12. On the same day the 2.5 cm level reached its minimum of 28.6° F, while the 5 cm level attained a minimum of 27.65° F. The 10 cm level reached its minimum of 29.5° F on February 25. Fig. 15 clearly shows both the extent in time and depth of this mid-February "cold pocket" of annual minima. The coldest depth of all during the year is seen to be the 5 cm level, and this is thought to be due to the weak penetration of daytime heat to only about 2.5 cm. This being so, night cooling would be likely to penetrate deeper and continue to cool the 5 cm depth without allowing daytime warming to restore the deficit. The 1, 2.5 and 5 cm minima of the 12th, may be attributed to the lowest air maximum for February of 20° F which occurred on February 10, augmented by a 6° F minimum on the night of the 11th.

(b) Below 10 cm all depths are still cooling, because the times of annual minima show a lag in time with depth.

(c) Ranges are greatest near the surface and decrease with depth down to 75 cm. This is the normal pattern of diminution of wave amplitude with depth.

(d) The 75 cm level shows a maximum fluctuation between its highest and lowest points for the month of only 0.75° F, amazingly steady. This is partly due to the snow cover, and partly to the fact that this depth is reaching the low point of its cooling curve and is preparing to rise towards the spring turnover (Fig. 14).

(e) Below 75 cm the range becomes larger and at the 150 and 225 cm levels is equal to the over-all difference. This is because these lower depths are cooling: (i) Steadily, thus there is little or no fluctuation, (ii) Rapidly, (these depths are the furthest away from their minimum position due to the lag of cooling with depth).

(f) The stable conditions for this month under snow cover have already been discussed (Fig. 16a).

(5) March

A low temperature of 13° F on March 11, and a high of 63° F on the 24th show the erratic nature of temperatures during this month which however was relatively milder than normal. Precipitation was high with 9 inches of snow and 3.5 inches rain.

The soil temperatures in March were characterized by a number of shallow penetrating thaws associated with these erratic air temperature highs. These thaws heralded and hastened the spring turnover time. Three marked warming periods occurred during the month:

(a) March 4-5 - the air temperature hit maximum of 52-57° F and the 1 cm soil temperature left the freezing zone for the first time since early December, and rocketed to 43.35° F. This short thaw was followed by rain and cool air and soil temperatures subsided again.

(b) March 15-16 - air temperatures rose again to about 50° F and those at 1 cm climbed to 46.1° F. Again this rise was followed by cool air with clear skies and temperatures in the low 30's.

(c) March 24 - the final of 3 increasing steps upward comprised two peaks. A high of 63° F was recorded on 24th carrying temperatures at the 1 cm level to 55.2° F. This was followed by some snow and 1.61 inches of rain in two days which cooled the ground to 37.2° F on the 26th. The second peak came on the 28th with a 1 cm soil temperature of 40.1° F.

After these three thaws, the air temperatures again plummeted at the end of the month. But the damage had been done. All levels down to 225 cm showed some rise due to this final double-headed heat attack. In fact each of the three waves is reflected in at least a small way to lower depths, but often the lag is so great that at depth they occur at the time of the intervening minimum (Fig. 14).

In the general picture, all depths down to 100 cm show a flattening during this month, and due to the final heat wave an eventual rise. The flatness of the curves for lower depths is so marked that had the thaw of the last few days not penetrated, the ranges would have been even smaller than those of February.

TABLE 3. March tendencies and ranges of soil temperature

Depth (cm)	Monthly range of daily readings at 1400 hours	Difference between beginning and end of month (°F)
1	23.75° F	Rise erratic
2.5	21.55	" "
5	18.45	" "
10	5.15	" of 1.8
25	2.2	" " 2.1
50	1.5	" " 1.25
75	1.25	" " 0.75
100	0.85	" " 0.4
150	1.1	Fall of 0.75
225	1.5	" " 1.2

There are a number of points to note:

(a) Unlike February, there is a tremendous fluctuation in temperatures near the surface, but as can be seen, this only really extends to 10 cm.

(b) The temperature range decreases progressively down to 100 cm (25 cm lower than in February) indicating the decreasing wave amplitude with depth.

(c) Below 100 cm the range increases with depth due to the continued cooling of these depths.

(d) All depths down to 100 cm are rising over-all, indicating that their annual minima have been achieved during this month. The dating of the minima indicates the time lag necessary for deeper depths to attain their lowest temperatures:

TABLE 4 Lag of annual minima

Depth (cm)	Minimum (°F)	Date achieved
20	31.05	March 3
25	31.10	" "
30	31.55	" "
40	32.00	" "
50	32.40	" 9
75	33.20	" 16
100	33.95	" "
150	36.30	" 24

The 150 cm level achieved a minimum of March 24, then rose and continued to fall again until the end of the month, but never attained such a low value again.

(B) Spring

The general characters of the "turnover" period have been summarized in the section discussing monthly mean temperatures. Briefly it may be said that in winter the surface is colder than the subsoil, while in summer the reverse is true. The transition time between the two is the spring "turnover" period. This is a most significant time not only climatologically but ecologically because these changing conditions signal various faunal movements in the soil. For instance McColloch and Hayes[6] have indicated that white grubs move upwards at this time.

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[6] McCOLLOCH and HAYES, Op. cit. 1923.

The overturn of soil temperature takes place in this locality in April, and so this phenomenon will be considered in this context. Air temperatures during this month were slightly below normal and very variable, there being a low of 15° F on April 4 and a high of 79° F on the 17th. Temperatures at the end of the month were unseasonably cool, and plant development was slow. Precipitation was high, including 5 inches of snow early in the month, and 3.8 inches of rain, mainly at the end.

The turnover period occurred in early April, and as has been mentioned, was heralded by frequent and increasingly severe thaws in March. There were continually rising maximum air temperatures from April 4 - 7 when the value reached 68° F and this caused the turnover. In Fig. 14 all the depth lines are seen to bunch together, and the temperature range for the whole group showed one minimum on April 6. This range was 5.75° F (33.75° F - 39.5° F) and covered all depths from 1 to 225 cm. This date of the "group overturn" compares favourably with that of Harrington[7] in Saskatoon who quotes April 16, and Thompson[8] in Winnipeg whose date was April 27. Both these stations being more northerly than Southern Ontario, and with a 5° F lower April air mean temperature, would be expected to record a later occurrence of the turnover. In Fig. 15 the same date exhibits vertical isotherms evidencing the changing role of the soil from being

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[7] E. L. HARRINGTON, Op. cit. 1928, p. 189.

[8] W. A. THOMPSON, Op. cit. 1934, p. 212.

an energy supplier to becoming a heat sink. Depths closest to the surface (1 - 10 cm) experienced various small overturns as far back as February under diurnal heating, but if these are neglected the complete period required for all depths to turn over was just short of three weeks (March 3 - 23) - an amazingly short time.

The times of turnover at each depth are of course subject to the normal lag in time required for the heat wave to penetrate. A graph of these times is shown in Fig. 17 and an increasing lag is evident as deeper depths are penetrated. Thus between 25 and 50 cm 1 day elapses; but between 200 and 225 cm $4\frac{1}{2}$ days would be required for the same distance to be covered. The time of the group turnover is seen to coincide with that at 75 cm.

An even more drawn out time lag series is completed at about the same time: The last of the annual minima at each depth is attained at 225 cm on April 9 with a low of 38.65° F. These minima also exhibit a time lag sequence which may be presented graphically, as in Fig. 18. The minima above 25 cm show that a complex state of affairs exists, probably due to intermittent snow cover and erratic diurnal variations Below this depth the line again assumes an exponential form. However, it should be noted that due to the extreme flatness of the lines for the deepest depths at their minima, a spread of possible values results, and are plotted on Fig. 18 with the curve drawn through their mean positions.

Immediately following the turnover time more warm air conditions prevailed and the normal summer characters of soil temperatures become abruptly evident. For instance in Fig. 14 large temperature

FIG. 17 Spring Turnover - Time Lag with Depth

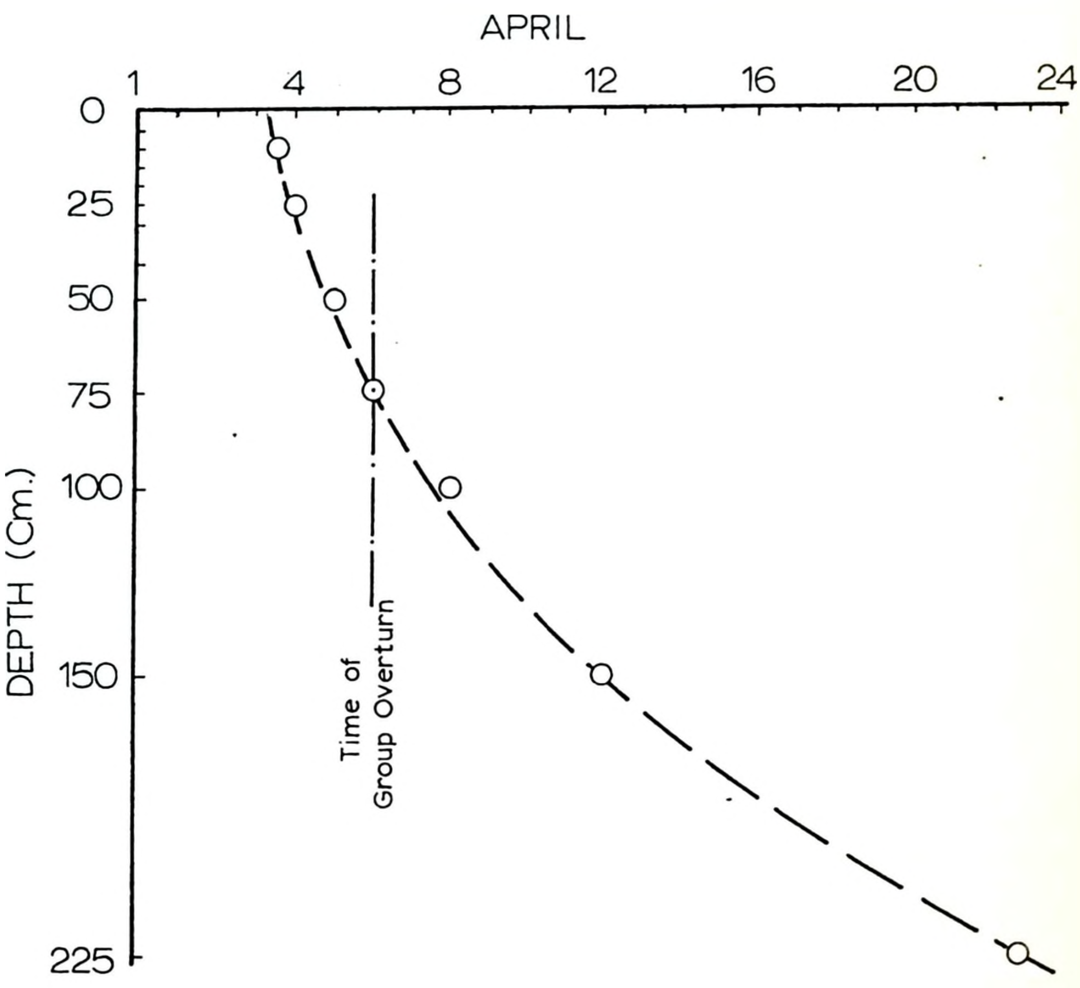
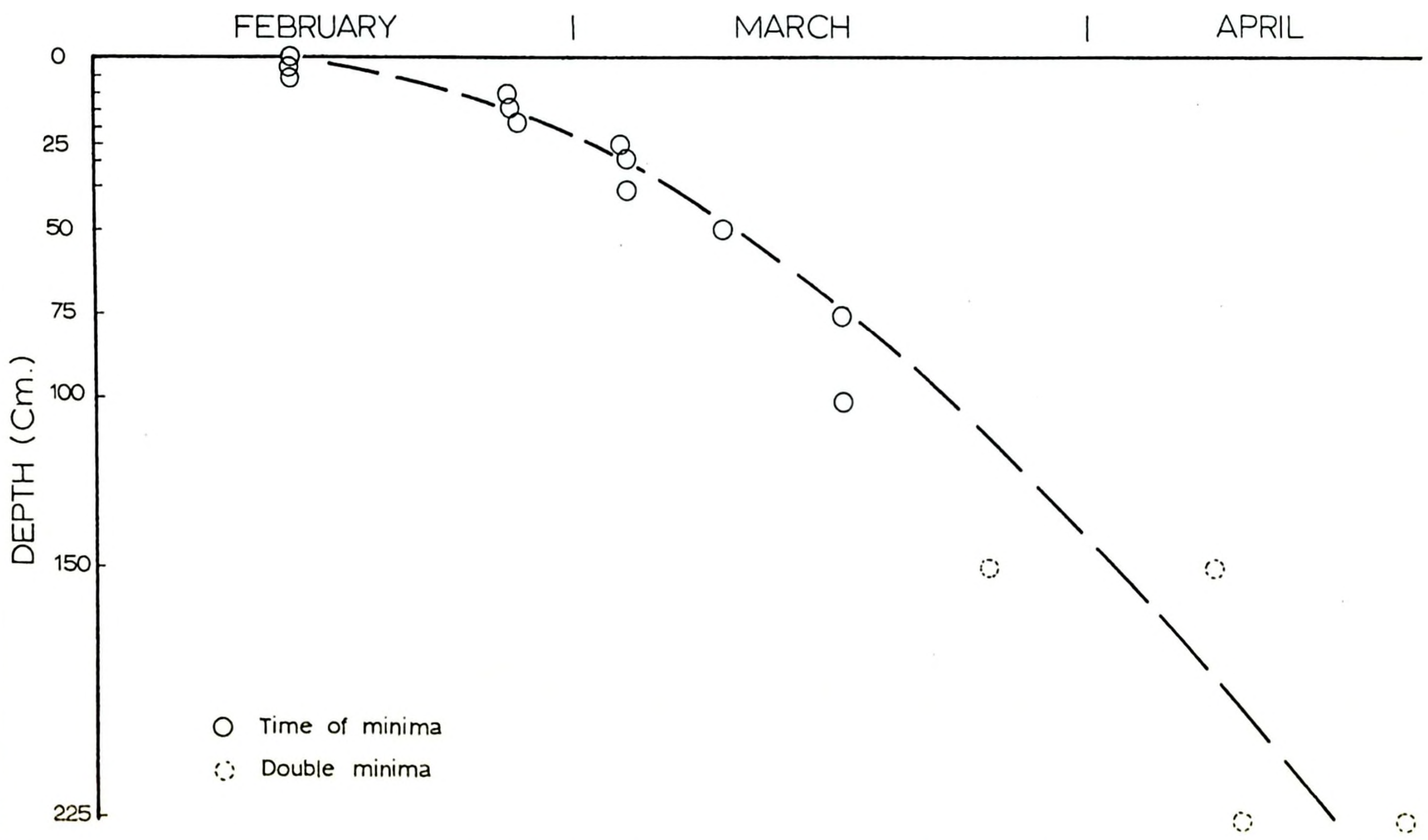


FIG. 18 Lag of Annual Minima at all Depths



amplitudes are common, the steadiness of winter conditions is notably absent. The lag in time for a warm or cold wave to penetrate the soil becomes longer, and the depth lines diverge to provide a considerable range of temperature within the profile. For instance, on the 6th the range was 5.75° F while 8 days later, on the 14th, the range is 24.5° F (37.5° F - 62.0° F). During mid-April a series of warming and cooling waves sets in associated with alternating warm days (c. 60° F), and cooler rainy days. Lower depths continue their marked warming trend but reflect these conditions as a series of steps along their paths, as in Fig. 14.

At the end of April cool 50° F maximum daily conditions set in, and 2.05 ins. of rain in the last 4 days resulted in considerable cooling felt at all depths. It is very noticeable that both the wave amplitude, and the time lag for conditions to be felt, are affected by depth.

(C) Summer

The summer months of May, June, July and August show the very considerable steep rise in soil temperature values associated with the increased insolation of this season. From the time of the spring turnover, Fig. 14 shows diverging depth lines associated with greater heat penetration; considerably greater depths of influence; build-up of temperature wave lags; and most obviously the infinitely greater complexity of fluctuation in soil temperatures from day to day. Just as striking is the increased complexity of the isotherm graph (Fig. 15).

In contrast to Fig. 16a depicting the stable characteristics of February, Fig. 16b represents daily conditions during the end of June and the beginning of July. The dissimilarities of the two periods are self-evident, and highlight the conditions of the two extreme seasons.

(1) May

The macro-climatic air temperatures during May were much above normal with one low of 36° F and a high of 89° F on the 23rd, while rainfall fell below the seasonal average. These air temperatures followed a pattern of 3 "lows" and 2 "highs" and the soil temperatures follow the same pattern with an amazingly good correlation: The month started with the cool conditions of the end of April, but the air warmed up steadily to a high of 83° F on the 7th; correspondingly soil temperatures climb into the upper 70's and definite rises are noted at all depths. A sub-high of 70° F is also reflected in the soil temperature results. These two peaks can be traced down through the depths in Fig. 14 as the amplitude becomes reduced and the time lag increases. At 73 cm the two peaks merge into one hump and continue on down to 225 cm. These two highs were followed by cool conditions with temperatures about 58° F, and as a result the curves plunge again, with reduced amplitude and increased lag as they penetrate into the subsoil. This sequence of two highs separated by a low present the best possible examples of lag and wave diminution with depth.

Again air temperatures soared to 88 - 89° F between May 19 and 23 as a result of which soil curves rise steeply and further heat waves are propagated downwards with the same characters as those above. On the 28th the air cooled to 58° and 1.25 ins. of rain fell in 4 days with cloudy, thundery conditions. The dive taken by soil temperatures on this occasion is so dramatic that a "reverse turnover" is effected down to 50 cm on May 29 and 30. This is in effect a miniature autumn turnover, but the situation returns to normal again by the beginning of June.

(2) <u>June</u>

Air temperatures during June were officially about normal, but this result is composed of two separate portions - a cool beginning to the month with some rural frost, followed by decidedly warm conditions at the end with temperatures in the upper 80's and 90's. Rainfall was well above normal and fell chiefly during the six thunderstorms which occurred. One storm of particular note on June 23 precipitated 1.43 inches of rain with violent winds estimated up to 105 m.p.h., all within half an hour.

Figs. 14 and 15 both show that the soil temperatures follow the pattern for the summer which started in May. Thus the complexity of temperature fluctuations increases and penetration is greater. As Fig. 16b shows, the intensity of activity in the topmost 10 cm becomes extreme, and the temperature gradient becomes steep.

As the month progresses a good correlation between air and soil temperatures is again observed. All depths down to 100 cm show cooling associated with the low temperatures at the end of May and beginning of June. The rise of the 58° F isotherm in Fig. 15 is especially noticeable. These cool conditions were followed first by a steady, steep rise until the 10th, then a fall on the 11th and 12th, then another steep rise on the 14th when the 1 cm level reached 91.85° F. A rainfall of 0.5 ins. on the morning of the 15th, combined with cooler air caused soil temperatures to plunge steeply, which is evidenced by the familiar lag at all depths.

The second half of the month demonstrated fluctuating high temperatures between the mid 70's and 90° F. Soil temperatures faithfully follow this pattern ending up with a 1 cm reading of 98.2° F, and a 94° F air temperature maximum on June 30. The extreme storm of the 23rd, which included 1.43 ins. of rain, caused considerable cooling on the ensuing days and this effect shows a time lag of several days until it reached the lowest depth. Immediately subsequent to the storm, readings were made every 5 minutes for 2 hours, but it was found impossible to separate the effects of the percolating water from the normal nocturnal cooling pattern.

In general June was a month showing an intensification of those summer activities which began in May.

(3) <u>July</u>

Air temperatures in July were more than 2° F warmer than normal, including a maximum of 94° F on July 28 and 18 days with their maximums greater than 80° F. The last week of July became so hot and humid as to be physically uncomfortable. Rainfall was also well above normal, mainly due to heavy thunderstorm rain in the middle of the month, which produced 4 ins. of rain in a 3 day period.

Soil temperatures show considerable variation, but in general also exhibit a good correlation with the macro-climate air temperature.

At lower depths where the small-scale variations do not appear, the steady over-all rise of temperatures continues.

During the first few days of July, very high soil temperatures were recorded. The highest temperature for any depth throughout the year, of 99.0° F, was recorded at the 1 cm level on July 1. Following this initial hot period temperatures in general show a definite halt in the upward rise. In the middle of the month this halt becomes a positive decline with very marked cooling at all depths due to the 4 ins. of rain which fell on July 12, 13 and 14. Thereafter, and until the end of the month, soil temperatures show a steep and rapid rise at all depths. At the end of the month a number of depths reach their annual maxima positions. The 1, 2.5 and 5 cm levels reached maxima of 99.0, 97.15 and 93.45° F, on July 1 during a short period of hot weather. Lower depths required the more prolonged heat wave at the end of the month to achieve their maximum positions. On the 28th the 10 cm level reached its maximum of 80.95° F. On the following day the 25 and 50 cm depths attained maxima of 77.8 and 75.55° F respectively. The 75 cm depth reached its highest temperature for the year of 73.0° F on July 30.

(4) <u>August</u>

August this year proved exceptional in many ways. It was considerably cooler than average and notably very wet. Rainfall totalled 7.02 ins., twice the normal amount, and fell on 12 days during the month. Daily minimum temperatures fell as low as 46° F and daily maxima remained as low as 62° F on one occasion.

The result to soil temperatures is both dramatic and obvious. At the beginning of the month with air temperature maxima around 70° F, soil temperatures at all depths down to 150 cm are seen to fall steeply from their July peaks. The rate of fall is very rapid, and is hastened by a 1.65 ins. fall of rain on the 3rd. This process continues until the middle of the month. From the 12th to the 14th night minima and day maxima were low, and there was rain on each of the four days from the 11th to the 14th. This final cooling causes a premature autumn overturn at all depths down to 100 cm, and the complete profile reaches its lowest range since the spring. Around the 26th temperatures begin to rise, and again temperature decreases with depth, in the normal summer pattern.

The summer's peak has obviously been surpassed by the end of August and the succeeding months of September and October may be expected to witness a gradual cooling, followed by the autumn overturn and a return to the winter conditions seen at the start of this programme.

CHAPTER 5

WINTER EXPERIMENTS

During the winter months more intensive observations than those indicated in Chapter 4 were carried out for two purposes:

(a) To examine the amount by which the normal soil temperature regime could be modified by the application of simple treatments.

(b) To augment the more general daily readings by enabling an hour-by-hour diurnal fluctuation curve to be constructed.

The results of both these investigations are recorded and analyzed in this Chapter.

(A) Surface Treatments

The methods by which subsurface temperatures may be artificially modified are discussed at full length in Chapter 6, but briefly it may be said that they involve altering the influencing factors, either external or intrinsic. Methods involving varying the external factors include insulating, or heating the ground, changing the absorptivity or altering the air temperature by shelter-belts or wind machines. The intrinsic factors may be manipulated by such procedures as wetting or draining the land, changing the rate of evaporation, changing the conductivity by farming practices or altering the absorptivity. Thus by the former practices the energy balance is altered, whereas by the latter methods the thermal properties of the soil are changed at least temporarily.

During the winter, daytime heating is weak and nighttime cooling strong. To keep the soil warm without adding artificial heat, the best practice is to attempt to conserve as much of the summer-acquired heat at depth as possible. Conversely, to promote the penetration of cold, procedures should be used which will allow this stored up heat to dissipate easily. In this study an example of both was attempted. One plot (B) was covered with a 6 inch cover mulch of wheat straw, the aim being to provide over the ground a "blanket" of poorly insulating material which would both keep out cold, and keep in the acquired warmth. Plot E, on the other hand, was not allowed to accumulate any snowfall at all (Plate 11). As soon as snow fell it was brushed off. In this way the ground was deprived of its natural insulating blanket of poorly conducting snow, and cold could get into the ground and warmth escape. The procedures and results of these experiments are presented in the following section.

1. Procedures

Before any treatments were applied it was necessary to ascertain that in the three plots (A, C and E) temperatures at corresponding depths were similar, so that a valid unit of comparison between plots could be established. To this end observations were taken every day for two weeks, and the temperatures at each depth compared. Small constant discrepancies were noted. To make all plots similar at the start of the experiments, quantitative corrections

Plate 11. Winter view of experimental site. Note straw mulch, and snow cleared plots, and thermocouple ladder.

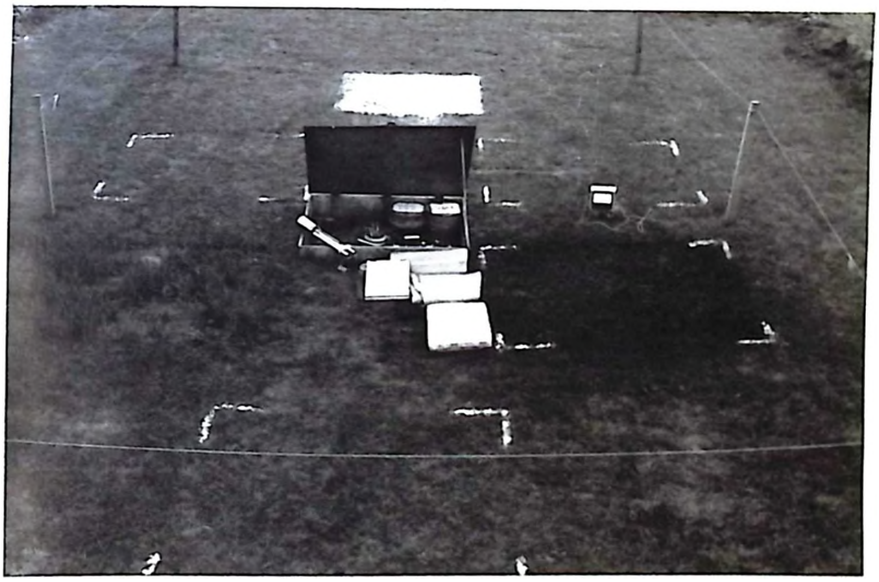


Plate 12. Summer view of experimental site. Note Talc covered, Carbon-Black and Oats plots.

were applied to the recorded readings. These corrections never amounted to greater than 0.9° F and were usually much less. The application of small corrections was deemed justifiable under the steady winter conditions when the soil temperature gradient is slight. During the last weeks of the experiments warming became strong and at this time small errors may result, but this was only after the treatments were removed and conditions in all plots allowed to re-settle. During the summer experiments further corrections had to be applied, but a more elaborate scheme was employed, under those more unstable conditions.

Plot "A", used in all the work concerning the annual march of temperature under natural conditions, was selected to provide the control against which plots C and E would be compared. Observations were made on most days at 1400 hours and averaged into 18 weekly means between January 2 and May 6, arranged as follows:

Week 1 (Jan 2 - 8)	Weeks 2 and 3 (No observations - instrument damage)
Week 4 (January 24 - 30)	Week 5 (Jan 31 - Feb 6)
Week 6 (Feb 7 - 13)	Week 7 (Feb 14 - 20)
Week 8 (Feb 21 - 27)	Week 9 (Feb 28 - Mar 5)
Week 10 (Mar 6 - 12)	Week 11 (Mar 13 - 19)
Week 12 (Mar 20 - 26)	Week 13 (Mar 27 - Apr 2)
Week 14 (Apr 3 - 9)	Week 15 (Apr 10 - 16)
Week 16 (Apr 17 - 23)	Week 17 (Apr 24 - 30)
Week 18 (May 1 - 6)	

These results are shown in Figs. 19, 20, 21 and 22 and discussed under the following headings:

(a) Weekly total profile averages.

(b) Weekly averages at all depths.

(c) Course of the 32^{o} F isotherm.

2. Results

(a) Weekly total profile averages.

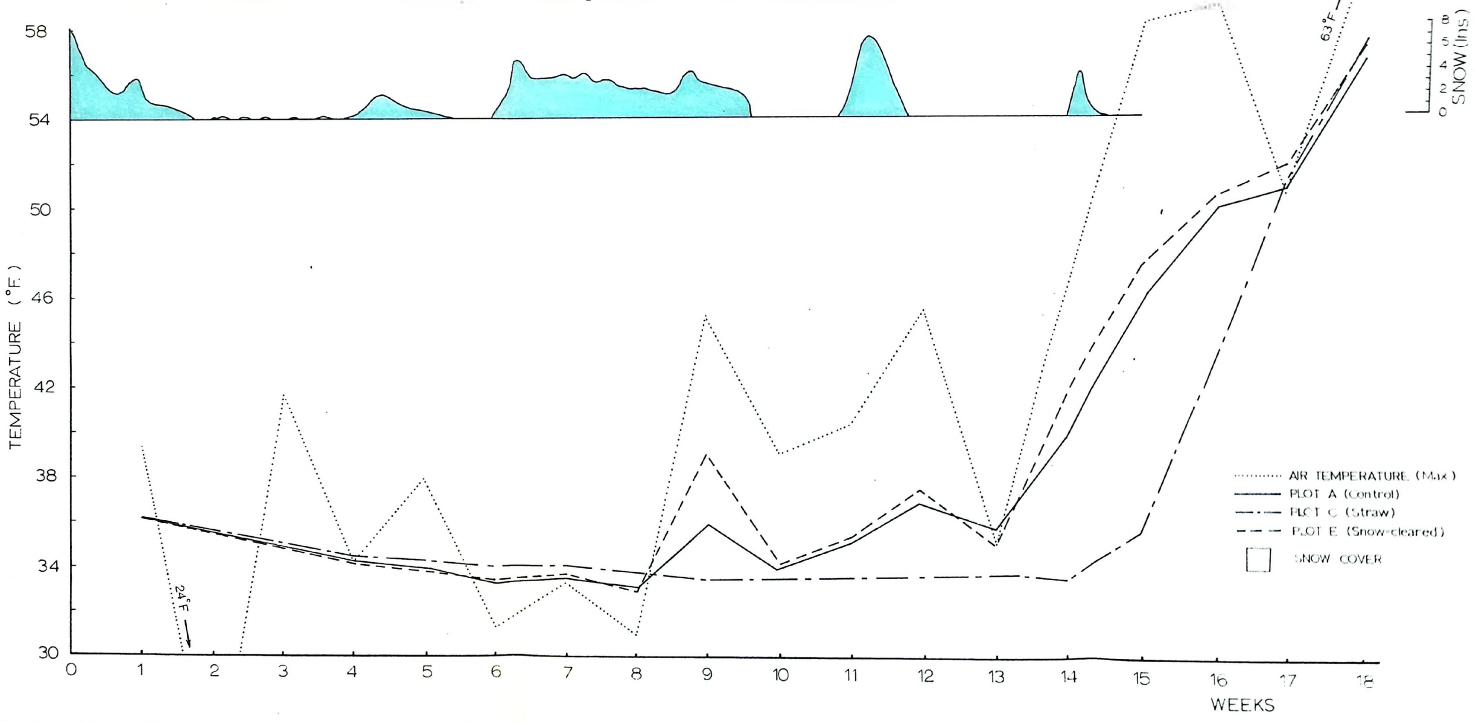
As in the similar section of Chapter 4 dealing with total profile averages, these results are presented to depict the general temperature balances between plots, each value representing an average of all depths within the week. By this method small fluctuations at any one depth will not be seen, but long term trends become more apparent than they would in a diagram containing more elements. Detailed conclusions should not be drawn from Fig. 19 as this indicates nothing more than a broad framework. Macro-air temperature maxima are given, because soil temperatures are also maxima.

Fig. 19 shows that all plots start together in Week 1, all all depths being at comparable temperatures. As time proceeds the lines diverge, the difference between them representing the magnitude of the effects induced by the application of the treatment. After the treatments were removed in Week 16, the lines are again seen to converge within 2 weeks.

Plot A (Control)

As with all plots, Plot A starts in Week 1 with an average of 36^{o} F, it continues a steady fall until Week 8 associated with a stabilizing snow cover of between 3 and 4 ins. During Weeks 2 and 3 the equipment was damaged by flooding and so no records are available,

FIG. 19 WINTER TREATMENTS - Weekly Total Profile Averages



but since air temperatures fell and there was no snow cover, soil temperatures may be assumed to have fallen, returning to a steady position by Week 4. The gradual fall until Week 8 may be attributed to the normal declining temperature conditions of this time of year. Week 4 shows an arresting of the tendency to fall associated with a short-lived cover of snow. The week following shows a further drop as air temperatures fall. Weeks 6, 7 and 8 are characterized by a 3-4 inch cover of snow and low air temperatures. Soil temperatures under such conditions exhibit a small range of only 0.4° F, and the line reaches its minimum for the period of 33.0° F.

The minimum having been achieved, soil temperatures start rising again, and are given a considerable boost in Week 9. This week was characterized by a thin 2 in. cover of old snow and this was further decreased by air temperatures rising to 57° F. The weekly average of daily maximum temperatures rose 12.1° F including 2 days with 46° F and one each of 52 and 57° F. Soil temperatures show a reduced amplitude rise of 2.75° F during the week. In the following week, air and soil temperatures fell with no snow cover. Similarly in Weeks 11 and 12 both rose, to be followed in turn by another fall in Week 13. From this time until the end of the period under observation there was a continual rise in both air and soil temperatures, until the soil average reaches 56° F in Week 18.

During periods with little snowfall, soil temperatures show a positive correlation with changes in air temperature, especially in the period from Week 8 to Week 15, every jump and fall in air conditions is reflected with smaller amplitude by the soil.

Plot C (Straw mulch)

The treatment of 6 ins. of straw laid on Plot C proved the most striking application of all. As explained, the effect is to reduce all outside fluctuations and to conserve the exuding terrestrial up-flux. The result is temperature stability. This becomes immediately evident from Fig. 19. Plot C remains amazingly steady, showing only a gradual slight fall for 14 weeks. The total range during this period is only 2.8° F in 100 days, in which time air temperatures fluctuated 23.0° F. Indeed during weeks 9 to 14 the range varied a mere 0.25° F - a very notable example of insulation. It seems that no matter what the magnitude of change in other plots, Plot C remains steady with only very gradual cooling. It is interesting to note that the time of maximum activity in Plots A and E is the steadiest in C.

After Week 14, Plot C exhibits rising temperatures, but the rise is both delayed and reduced in magnitude compared with the two uncovered plots. Even this rise would probably not have been so great, had the straw not compacted down during the course of the winter under the weight of snow, and become wet with the thawing snow. These two conditions raised the thermal conductivity of the straw, thus degrading its value as an insulator. Following the removal of the straw in Week 16 the soil temperatures soared, taking only 1 week to reach the value of control Plot A, and in Week 18 to surpass it. The fact that C overtakes A may be attributed to the poor cover of grass revealed by the uncovering of C, thus decreasing its resistance to heat penetration.

It is obvious then that an application of a 6 ins. straw mulch radically alters the underlying soil temperature conditions. The question to be answered is - is it beneficial? In answering this question, Week 8 is critical. Up to this time, Plot C is the warmest, whereas after Week 8 it is the coldest. Weeks 8 and 9 occur at the time of the annual "turnover"; obviously the straw mulch delays these conditions. Thus it may be said that in winter such an application is of value in maintaining soil heat, but if continued beyond the spring "turnover" time its effect can only be detrimental except in its ability to retain stability.

Plot E (Snow-cleared)

The only time Plot E, kept clear of snow, may be expected to show a difference from the conditions of A, is when the latter is covered with snow to any reasonable depth, or for any period of time. During the mild January of 1964 Plot E was unable to take any such advantage over the control. February was again relatively mild but had a good snow cover. Temperatures, however, were only about freezing during Weeks 6, 7 and 8 and A and E still kept together. Week 9 was very mild, with the average air temperature rising to 45° F. Bare Plot E took immediate advantage and rose steeply; Plot A covered with 2 ins. of old snow mirrors this rise in a reduced manner. From this time on until Week 13 Plot E's average remains above that of Plot A, under warm conditions. During Week 13 air temperatures fell and so did soil temperatures. Plot E fell more than Plot A, yet both were free of snow. The only possible reasons for this are:

(a) Plot A may have been wetter due to snow melt, and so its specific heat would be higher thus rendering it less liable to violent temperature changes.

(b) Being uncovered the grass of Plot E was attacked by night-frost and so the surface was barer, possibly encouraging cold penetration.

(c) The grass cover was to some extent damaged by the constant brushing-off of the snow.

In general it may be said that the mild conditions of the winter of 1963-64 did not allow the effect of clearing the ground of snow to be manifested. It seemed that when there was snow the weather was mild, and when it was cold the control plot was similarly bare; no advantage could accrue. However, it will later be shown that even if the numerical value of the cooling in E was not great, the depth of penetration still manifested itself under such conditions.

(b) Weekly averages at all depths

Figs. 20(a-c) and 21(a-c) show on isopleth and time/temperature graphs respectively, the weekly average results at various depths. These results illustrate the smaller variations which constitute the larger framework presented in Fig. 19.

Plot A (Control)

The trends shown in Fig. 20b and 21b are the same in the previous chapter. Weeks 5, 6 and 7 represent the "cold-core" of early and mid-February, while Weeks 10, 11 and 12 show the erratic conditions of the March thaws leading up to the spring turnover in Week 14, followed by summer heating. These then are the natural unmodified conditions against which those of Plots C and E should be compared.

Plot C (Straw)

In discussion of Fig. 19 the striking stability of conditions under the straw mulch was emphasized. In greater detail Figs. 20a and 21a again illustrate this important fact, especially during the first 14 weeks of the experiment. A glance at the course of the 1 cm level in Fig. 21a serves to verify this. Daigo and Maruyama[1] found the same conditions under an 18 cm thick layer of straw during December and January. During the period 1913-15 Oskamp[2] conducted similar experiments in both winter and summer, and he concluded that such a mulch equalized both extreme diurnal and annual fluctuations, and that differences were especially small during the winter. Similar results were also obtained by Bushnell and Welton[3] during the summer period.

A close look at Fig. 20a reveals the lack of both cooling in Weeks 5, 6 and 7, and heating in Weeks 10, 11 and 12, as experienced in Plot A. The 32° F isotherm runs a steady course at about 20 cm and remains in the ground 3 weeks longer than in Plot A. In Fig. 21a all the topmost depths are seen to hug the 32° F level seemingly without regard for external factors. No matter what the fluctuation in air temperature, conditions beneath the surface remain steady, and

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[1] Y. DAIGO and E. MARUYAMA, Op. cit. 1952.

[2] J. OSKAMP, Op. cit. 1915-16.

[3] J. BUSHNELL and F. WELTON, Op. cit. 1939.

it would appear that the insulation provided is fully sufficient because the addition of snow seems to have no further influence.

In addition to maintaining temperatures at a steady level, the straw mulch seems to delay the time of turnover, especially for depths close to the surface:

TABLE 5. Times of turnover in Plots A, C and E

Depth	Time of Turnover (Week) A	C	E
10 cm crosses 20 cm	10	12 and 15 1/2	9 3/4
20 cm crosses 50 cm	13	15 1/2	10
50 cm crosses 100 cm	14	15	13 1/2
100 cm crosses 225 cm	15 1/2	16	15 1/2

Because the shallower depths are delayed longer, the period of "turnover" is much shorter than normal. Viz., A - 5 1/2 weeks; C - 4 weeks, and in fact mostly in 1 week. The annual minimum range covering all depths at this time is also much smaller in the case of C - about 2° F compared with the 5.5° F of Plot A.

Following the "turnover", temperatures rise and in Week 16 treatments were removed. Between Weeks 16 and 17 both Plots A and E show a step in their rise associated with a fall in air temperature. A similar step in C is not discernible because this plot has a considerable leeway to make up over other plots.

Plot E (Snow-cleared)

Figures 20c and 21c which relate to Plot E show it to be the most variable of all plots, as may be expected. However, due to the relative mildness of the winter it is not markedly different from the control. The cold period of Weeks 6, 7 and 8 is noticeably accentuated, as are the periods of warmth of Weeks 9 and 12. The "cold core" is best shown because it was accompanied by low air temperatures and a cover of snow on Plot A. Table 5 shows that the times of "turnover" for Plot E are somewhat earlier than either of the other two, indicating the ease of penetration. The 32° F isotherm line in Fig. 20c is seen to run deeper than in A and this will be discussed in the following section.

(c) <u>Course of the 32° F isotherm</u>

Fig. 22 attempts to study the course of the 32° F freezing isotherm through the ground during the winter months in each of the three plots. It is realized that the depth of freezing is not synonomous with the depth of the 32° F isotherm. As Bouyoucos[4] pointed out, soil moisture does not freeze at 32° F but rather the moisture remains in a super-cooled state until at least 1.8° F below its true freezing point, and even then it requires agitation to cause freezing. As supercooling is continued, a point is reached where freezing occurs automatically. Bouyoucos[5] believes this point to be about 24.5° F for all soils if the soil is kept undisturbed and moisture is at saturation . This raises three important points:

a) In mild winters the soil may not freeze even though its temperature is cooled below the freezing point.

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[4] G. J. BOUYOUCOS, "Degree of temperature to which soils can be cooled without freezing", Journal of Agricultural Research, Vol. 20 1920-21, p. 267-9.

[5] G. J. BOUYOUCOS, Ibid.

b) A sub-freezing point temperature does not automatically mean the soil is frozen.

c) As long as the moisture remains unfrozen temperature fluctuations will be smaller, because liquid water has twice the Specific Heat of ice.

Point number 2 is of immediate importance here. This leaves a certain amount of indecision as to the actual depth of frost penetration. However, present knowledge does not allow us to predict frost depth by temperatures alone. As Haley[6] says, "Information on the freezing point of moisture in soils is required, because of the influence of this factor on the theoretical prediction of depth of frost penetration". Therefore under present conditions one must assume that soils freeze at 32° F or at some constant temperature below 32° F. In either case theresult is tied to the freezing point of water and so this value is used in this study.

The depth of freezing is controlled by two main factors:

(a) Air temperature conditions.

(b) Depth and duration of snow cover.

Thus in Fig. 22 both these elements are presented. Following the programme of Fuller[7], air temperature is shown as an accumulated temperature deficiency below 32° F. This value can be found by sub-

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6 J. F. HALEY, "Cold Room studies of frost action in Soils. A Progress Report", Highway Research Board Bulletin 71, 1953, p. 13.

7 H. U. FULLER, "Frost penetration as affected by weather and snow conditions", Journal New England Water Works Association, Vol. 50, 1936, p. 299 and, "Studies of frost Penetration", Journal New England Water Works Association, Vol. 54, 1940, p. 275.

tracting the mean temperature for the day from 32° F, and adding these "deficiencies" to that of the day before, starting on December 1. Thus a rising line indicates colder conditions, and a falling line warming tendencies. The depth of snowfall is plotted for each day from personal observations and from Monthly Meteorological Summaries for the Hamilton area.

Plot A (Control)

In Plot A (Fig. 22) the 32° F isotherm really enters the ground on December 11 as the temperature deficiency line rises sharply; temperatures remain cold for the rest of the month but a 3 ins. continuous snow cover prevents penetration deeper than 5 cm. The "frost" line leaves the ground on January 9 due to the quick thaw. This date was followed by two weeks of no observations when cold conditions prevailed without a snow cover. Thus when readings were resumed on January 26 the 32° F isotherm is found to have penetrated to about the 20 cm depth. This penetration continues down to 30 cm by February 1. At this time there is a period of slight warming, evidenced by the halt in the temperature deficiency rise with no snow cover, which causes the "freezing line" to rise to 25 cm. At this depth the line levels out with the return of the snow cover though temperatures continue to fall below 32° F, showing the "blanketing" influence of the snow. The maximum temperature deficiency below 32° F is attained on February 29, with a value of 630 accumulated degrees. It is interesting to note that on the map by Linell[8], showing

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[8] K. LINELL, "Frost design criteria for pavements", Highway Research Board Bulletin No. 71, National Research Council Publication No. 262, 1953, p. 22.

Freezing Index contours for North America, the study area lies between the 500 and 750 isopleths indicating accumulated degrees below 32° F. Thus one may assume this winter to have been fairly normal in this respect. However, as has already been stated, the coincidence of cold temperatures and snow-free ground suitable for frost penetration, was not regularly experienced this winter.

At about the time of the deficiency maximum, the snow clears and the 32° F line in "A" falls to nearly 50 cm; its lowest depth for the year. When the deficiency line falls again, indicating warming, the "freezing line" returns to 25 cm where it is held steady by new snowfall. Just as with other soil temperatures there is a lag in the penetration of the cooling waves. For instance, around March 4, when the surface 10 cm is thawing, the frost line reaches down to 50 cm; a similar pattern is shown on March 16. In both cases the surface warming is due to the prevailing macro-climatic conditions, and the cooling penetration may be attributed to a cold spell immediately preceding.

The final thaw which eliminates the 32° F isotherm from the ground consists of two elements: warming from (a) above; (b) below.

The first sigrsof the final thaw are seen on March 19 at the surface, and the depth of the thawed layer deepens with time, depending on the receipt of heat from the atmosphere. On March 24 the 32° isotherm moves upwards from 30 cm drawing its heat supply from the now almost expended heat of the previous summer. This phenomenon of thawing from both above and below is an established fact as shown by Atkinson and Bay[9] and Keränen[10]. In fact Keränen in Finland has given values to the importance of these two elements; he considers 71% of the thaw is effected from above, 23% from both directions, and 6% from below. Spring rain is known to be effective in causing the final thaw, but in this case the initial movement was primarily due to a series of warm air temperatures from the 19th to the 26th viz: 35, 34, 40, 46, 38, 63, 57 and 40° F, probably augmented by 1.5 ins. of rain on March 25 and 26. The "freezing" line finally left Plot A on March 26 at the 25 cm epth.

The over-all pattern of events fits in well with similar observations made by other workers. The complete diagram of frost penetration and temperature deficiency is comparable with that of Fuller[11] in many respects. For instance, there is a good relation between frost depth and temperature deficiency when the frost is penetrating - in fact the one almost mirrors the other. Also when the air above, and the soil beneath, are both warming, the relation is less good, and the frost leaves the ground well before the temperature deficiency returns to zero. The dates when the maximum penetration was achieved, and when the final thaw occurred, both compare very favourably with those of Fuller[12], and of Legget and Crawford[13].

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9 H. B. ATKINSON and C. E. BAY, Op. cit. 1940, p. 947.

10 J. KERÄNEN, "Über den Bodenfrost in Finnland", Mitteilungen der Meteorologischen Zentralanstalt des finnischen Staates, Helsingfor, No. 12, 1923.

11 H. U. FULLER, Op. cit. 1936 and 1940.

12 H. U. FULLER, Ibid.

13 R. F. LEGGET and C. B. CRAWFORD, "Soil Temperatures in Water Works Practice", Journal American Water Works Association, Vol. 44, 1952, p. 926.

Plot C (Straw)

The application of a 6 in. layer of straw over Plot C was made on January 2. It is seen that throughout December all plots show similar conditions with respect to the depth of the 32° F isotherm; however, immediately following this date the depth of "freezing" is seen to be influenced by this straw mulch.

From January 2 until 9 a thaw gradually sets in as evidenced by the declining temperature deficiency curve during this period. The "frost" lines of both Plots A and E rise gradually to the surface, but the insulated Plot C remains steady at 10 cm. It takes the flooding conditions of January 9 to raise the "freezing" level to the surface. This condition represents the slow response of the straw covered plot to an outside warming influence when the frost is already in the ground.

The 32° F isotherm having left the ground shows a similar unwillingness to re-enter during the cold spell when no observations were made. The depth to which the cooling has penetrated in the same period of time, is 22 cm in control Plot A, but only 15 cm in the straw covered "C" plot. From this time, at the end of January, until the thaw begins on April 11, (a period of eleven weeks) the 32° F isotherm varies generally about 5 cm either side of this value of 15 cm - an amazingly constant performance when considering the course of the temperature deficiency line during the same period. Its maximum penetration was 25 cm on March 17.

From the line representing the course of the 32° F isotherm in Plot C, five very important conclusions emerge:

a) Stability - Throughout the period, fluctuations seen in the other two plots are either much reduced in "C" or non-existent. The insulation provided by the straw mulch provides an almost complete screen against air temperature variations.

b) Duration - The 32° F isotherm remains in Plot C until April 16, 21 days longer than in control Plot A! The insulation now prevents the penetration of heat rather than its loss.

c) Thaw - The first signs of thawing are witnessed from below rather than from above, which shows that the "blanket" is still working and the warmth is emanating from the lower depths of the soil itself.

d) Snow - the addition of a snow cover over the straw mulch seems to have no extra insulating properties. One may therefore assume that a six inch cover of straw is sufficient to provide complete insulation. This is in agreement with the 18 cm straw mat used by Daigo and Maruyama[14].

e) Depth - Throughout the period the "freezing" line in Plot C always remains at a lesser depth than both Plots A and B. In fact on March 3 the straw cover diminishes the depth of its value in control plot A; and diminishes the depth of penetration throughout the period January 26 to March 26, by an average of 41%. This latter figure compares very favourably with the 40% diminution recorded by McKinney[15] under a litter cover in a forest, although close comparisons

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[14] Y. DAIGO and E. MARUYAMA, Op. cit. 1952, p. 75.

[15] A. L. McKINNEY, "Effects of forest litter on soil temperatures and soil freezing in autumn and winter", Ecology, Vol. 10, 1929, p. 319.

should not be drawn.

Thus, in summary, one may conclude that the effect of a straw mulch on the depth of freezing is to stabilize the depth at a shallow level, but also to prolong its existence during the spring.

Plot E (Snow cleared)

At the time when the experiment was first started Plot A was covered with a considerable layer of snow. Thus the uncovered Plot E should show a loss of warmth and subsequent lowering of the "frost-line", and this is in fact the case. However, its development is arrested by the general thaw. The succeeding two weeks, when no observations were made, was characterized by low air temperatures and little or no snow cover. Considerable heat was lost from both Plots A and E whose surfaces were now in the same condition. Thus, when the deep continuous snow cover of February arrives, both plots exhibit the same depth of frost. However, from this date until the end of snow in mid-March, the "frost-line" in "E" is always deeper than that in "A".

The line representing the 32° F isotherm in Plot E provides a mirror-image of the temperature deficiency curve, especially when the frost-line is penetrating. The isotherm dips steeply in mid-February when the temperature deficiency rises, and it reaches its 50 cm maximum depth at the time of the deficiency peak at the beginning of March. The better correlation of "E" with the freezing index by contrast with "A" is to be expected because the former, being uncovered, is always open to atmospheric influences without the interruption of the impeding snow. After the peak the correlation, as Fuller[16] commented, is not so good.

The mild conditions caused the thawing of the topmost 10 cm in Plot E in early March, and again in mid-March. In the first instance Plot A was also uncovered and so shows a similar period of thawing, but on March 12 "A" was snow covered and so the penetration of heat is less noticeable in this plot. The final thaw in "E" starts on March 21 with a 40° F air temperature. The 32° F isotherm leaves this plot on March 24 at the 30 cm depth with a 63° F air maximum. Three general conclusions may be drawn:

a) Depth - The level of the "frost-line" in an uncovered plot is generally lower than than in a plot from which the snow is not cleared. In the period January 26 to March 26 the bare Plot E had on average a 21% lower "frost-line" than control Plot A. If the winter had been colder the over-all depths would probably have been deeper, for as Atkinson and Bay[17] state "Atmospheric temperature influences the depth to which frost will penetrate". However, there is no reason to believe that the figure of 21% will radically change.

b) Susceptibility - Being open to the air, an uncovered plot is more likely to thaw more quickly as well as freeze more quickly.

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[16] H. U. FULLER, Op. cit. 1940.

[17] H. B. ATKINSON and C. E. BAY, Op. cit. 1940, p. 947.

c) Effect of snow - Many workers have noticed the effect of snow on keeping the frost out of the ground, notably Croxton and Nicholson[18], Atkinson and Bay[19], and Crawford[20], and the last three authorities also relate the depth of snow to the depth of freezing. In this study, the period between January 26 and March 26 was characterized by an average snow depth of 7 cm. During the same period the average depth of the "freezing" level in Plot A was 30 cm, and in Plot E 38 cm, a difference of 8 cm. Thus it would seem that a cover of 7 cm reduces the depth of frost penetration by a similar amount. This result is in exact accord with the results of Atkinson and Bay[21], who report that snow reduces frost penetration by an amount equal to its depth, and also with Legget and Crawford[22], who state that snow reduces penetration "by an amount equal to or greater than itself".

(B) Diurnal Wave

On a number of occasions throughout the winter intensive daily observations were made, during which readings were taken once an hour

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[18] W. C. CROXTON and P. NICHOLSON, "Extent to which the snow blanket influences the temperatures beneath it", Minnesota Academy of Science, Proceedings, Vol. 5, 1937, p. 46-49.

[19] H. B. ATKINSON and C. E. BAY, Op. cit. 1940.

[20] C. B. CRAWFORD, Highway Research Board, Bull. 71, 1953, p. 48.

[21] H. B. ATKINSON and C. E. BAY, Op. cit. 1940.

[22] R. F. LEGGET and C. B. CRAWFORD, Op. cit. 1952, p. 938.

for 24 hours. The results could therefore be shown as a diurnal curve similar to the annual curves already presented. In fact, the similarity between these two curves, or waves, is quite striking, both having the character of an ebb and flow of heat. During the night period for the diurnal wave, and the autumn and winter for the annual wave, the soil surface is cooling, and there is a flow of heat from the interior outwards. Similarly by day, and in spring and summer the soil surface is warming and there is a propagation of heat downwards. Thus the daily wave is analogous to the annual wave but on a reduced scale; the depth affected being only 30 to 60 cm and the time period being 24 hours instead of one year.

The results of two such daily runs are presented here as they are representative of the conditions obtained, and show these features to best effect. The dates chosen are first, February 26/27, and secondly, March 10/11; on both occasions all three plots were observed. During the summer period a similar 24-hour run was made and a comparison is available between this and the winter diurnal waves, in the control Plot A.

1. <u>February 26/27, 1964</u>

When considering readings as closely spaced as one hour apart, the influence of prevailing weather conditions throughout the period of observation becomes of prime importance. For this reason a complete outline of the weather situation is given:

On February 26 a belt of snow and rain extended right down the East coast of America. By mid-day on the 27th this system had moved north-eastwards and was centered over Newfoundland. As a result of this situation Hamilton experienced the typical onset of a frontal system and its associated snow and cloud condition. This sequence is plain to see from the following hourly observations made:

TABLE 6. Passage of snow storm, February 26

E.S.T.	1200	1300	14000	1500	1600	1700	1800
Cloud (oktas)	1 Cu	2	3	3 Cu	4 Cu	7 Cu N	7
E.S.T.	1900	2015	2130	2230	2330	0030	0130
Cloud (oktas)	8 Str Cu	6	7	7	6	1	0
E.S.T.	0230 - 0430		0530 - 0730		0830 - 1630		
Cloud (oktas)	0		7		0		

Cu - Cumulus; Cu N - Cumulo-nimbus; Str Cu - Strato-culului

This shows the gradual build-up of cloud from noon until 1900 hours, terminated by a snow storm between 1830 and 2015 hours, which was followed by decreasing cloud and intermittent snow until midnight. After midnight until 0530 hours clear skies conducive to good radiational cooling prevailed.

TABLE 7. Course of nocturnal air cooling, February 26/27

E.S.T.	2330	0030	0130	0230	0330	0430	0530	0630
Temperature* (° F)	20.4	16.9	15.1	12.4	11.6	9.4	9.3	11.7

The time of the night minimum at 0530 hours is coincidental with the last hour of clear skies during the night. The maximum temperature on

* As obtained by means of an Assmann psychrometer.

the 26th was 29.3° F; the overnight minimum 9.3° F, and the high for the 27th 21.4° F.

The snow cover over the plots had been continuous since a 3.5 ins. fall on February 6. During this period the cover varied between 2.25 ins. and 4 ins. Snow fell on the evening of the 26th such that there was a 2.25 ins. base of old snow, underlying 1.75 ins. of fresh snow. Winds were light or calm with slight drifting.

Experiments

(a) Plot A (Control)

The results of hourly observations are shown in Fig. 23 including both snow and soil temperature measurements, and a trace of air temperature readings.

(i) Snow temperatures - snow temperatures were obtained by use of the thermocouple ladder already described (Ch. 2).

At the maximum temperature epoch, around 1400 hours, the snow surface reaches its maximum of 32.0° F. Following this the surface begins to cool steadily and reaches 24° F by 1730 hours. The arrival of the warm sector and its associated snowfall brought the 26° F isotherm back to the surface. From 2015 onwards the cooling, of course, begins to take place at the new snow surface. Cooling continues under clear skies, ideal for nocturnal outgoing long wave radiation, until the minimum temperature is attained at the snow surface at 0430 hours, almost coincident with the air temperature minimum. After 0430 hours the snow surface warmed quite quickly reaching 30° F by 1100 hours.

Three important points emerge:

a) The minima of the snow surface and air are both achieved at approximately the same time.

b) Most of the extreme cooling occurs in the newest snow. Thus the isotherms bunch in the topmost 1 inch up to 1800 hours and in the new 2 ins. of snow after this. This is almost certainly due to the reduced thermal conductivity of new snow consequent upon its reduced density as shown by Beskow[23]. Old snow has a conductivity of about 0.0004 - 0.0008 cal/cm/sec but fresh snow has a much lower value of about 0.0015 grm/cal/sec, due to its air content and low density. By night, according to Ångström[24] snow has a very high emissivity, near unity, and therefore cooling is very great at its surface. However, being a poor conductor, this lost heat is not replenished from below and so the snow surface becomes excessively cold. Thus, in this case, it would seem that the newest and poorest conducting layers become the coldest. Some allowance must of course be made for the normal steepening of gradient as the surface is approached.

c) At the time of the minimum snow surface temperature at 0430, and as a result of the processes described in b), there is a very steep temperature lapse rate of 16° F in the topmost 2 ins. of snow.

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23 G. BESKOW, "Soil freezing and frost heaving, with special reference to highways and railroads", Northwestern University Bookstore, 1942, 242 p.

24 A. ÅNGSTRÖM, "On the radiation and temperatures of snow and the convection of air at its surface", Arkiv för Matematik och Fysik, Band 13, No. 21, p. 1-18.

(ii) Soil temperatures

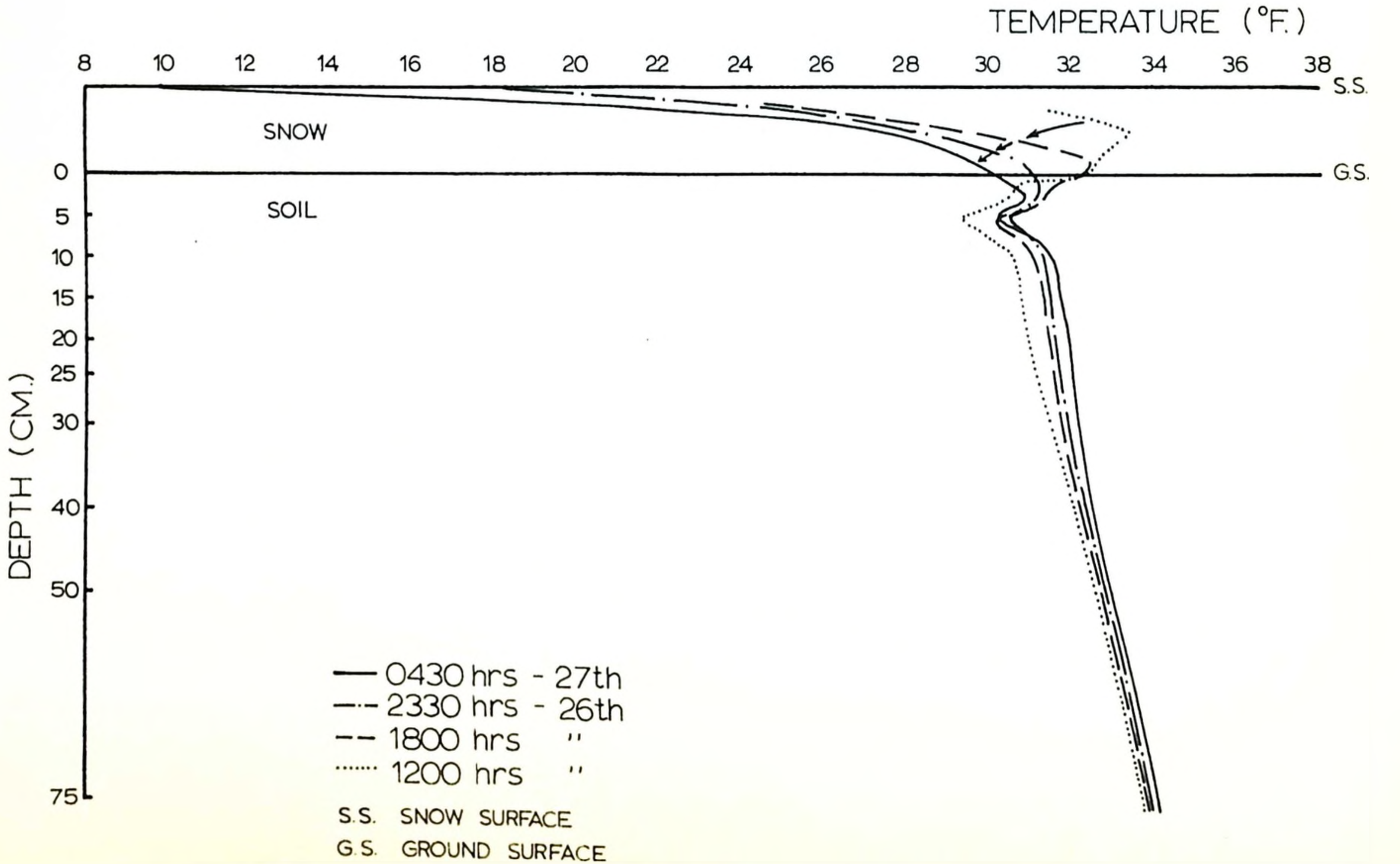
Soil temperatures are only shown down to a depth 15 cm because below this depth conditions are virtually stable. Indeed the most striking point about the temperature conditions of the soil in Plot A is the complete lack of any semblance of a diurnal wave pattern. There seems to be no reflection in the soil of the tremendous cooling process which is operative at the snow surface, only 4 ins. above (Fig. 24). This is a good example of the insulating value of a snow cover. The loss of heat is confined to the snow, and the upward passage of heat from the interior is held up at the boundary between the two.

In addition to being an example of the general insulating value of snow, it is also an example of the greater insulation provided by a cover of even poorer conducting new snow. In the period 1200 to 1830 hours when the cover is of old snow, the soil temperature gradient is considerably steeper than later when the new snow fell, in spite of the fact that air temperatures are much colder. In addition to the poorer conductivity, the snow cover is of course also deeper, thus providing a more effective "blanket".

(b) Plot C (Straw)

The 6 ins. of straw applied on January 2 had, by February 26, settled and compacted to a 4 in. layer under the weight of snow. On the diurnal scale presented in Fig. 25 the influence of this cover seems to be completely analogous to the 4 ins. of snow shown in Fig. 23. The temperature gradient within the soil is very, very

FIG. 24 Progressive Tautochrones, Feb. 26/27th, Plot A



shallow - about 1° F in 20 cm, and there is absolutely no evidence of any wave patterns.

Further comparisons of Plot C with Plot A reveal that the steady soil temperatures are repeated with similar patterns in the two plots, but the values of Plot A are on average 1° F lower. Similarly the 32° F isotherm is slightly closer to the surface in Plot C, probably because this plot has received continuous protection whereas the cover of Plot A, varying with snowfall, has sometimes been non-existent, allowing heat to be lost. In Plot A, as mentioned, there are signs of cooling between 1200 and 1830 hours but not after the fall of new snow. Plot C shows no such cooling at any time, suggesting that the properties of straw are more like those of new snow, than old snow.

The diurnal ranges in the two plots, which represent the wave amplitude, or difference between the maximum and the minimum, are both very much the same, both plots having a small range:

TABLE 8. Diurnal ranges in Plots A and C, February 26/27

	Plot A			Plot C		
Depth (cm)	Max.	Min.	Range (° F)	Max.	Min.	Range
1	31.55	30.2	1.35	32.0	30.95	1.05
2.5	31.55	30.4	1.15	32.0	30.65	1.35
5	30.4	29.25	1.15	31.7	30.9	0.8
10	31.55	30.55	1.0	31.9	30.65	1.25
15	31.8	30.9	0.9			
20	31.95	31.45	0.5	32.3	31.85	0.45
50	32.9	32.85	0.05	33.35	33.1	0.25

(c) Plot E (Snow cleared)

Plot E was kept clear of any snow up to the date of February 26 and the snow of this day was also brushed away. This plot was the only one of the three to be open to the atmosphere and having no intermediary layer of snow or straw to impede the incoming and more especially the outgoing radiative processes. The result is an excellent example of the winter-type diurnal wave, involving a small receipt of heat by day, and a considerable loss of warmth by night. The curve is so obvious that it lends itself to representation by the four well known methods, as in Figs. 26, 27, 28 and 29.

Fig. 26 clearly shows most of the salient features of the diurnal pattern; the cycle is a complete one because the right-hand side is a mirror image of the left-hand side. The 1 cm level achieves its maximum at about 1830 hours and thereafter begins to cool. At the same time as this maximum at the surface, the 20 cm depth is still receiving the cooling effects of the previous night. The air temperature begins to drop at 2030 hours and the 1 cm soil level shows its first cooling at 2300 hours, 1 1/2 hours later. Cooling continues until the night minimum of 19° F is attained at 0600 hours, again 1 1/2 hours later than the air minimum. After 0600 hours the layers nearest the surface begin to warm but very noticeably the cooling continues at depth as the waves penetrate with a lag in time. This lagging wave penetration is very well shown by the bulge of the curves downward, and to the right. The curve of the isotherms indicates that the diurnal effects are felt at least down to 40 cm and probably deeper.

FIG. 27 Progressive Tautochrones, Feb. 26/27th, Plot E

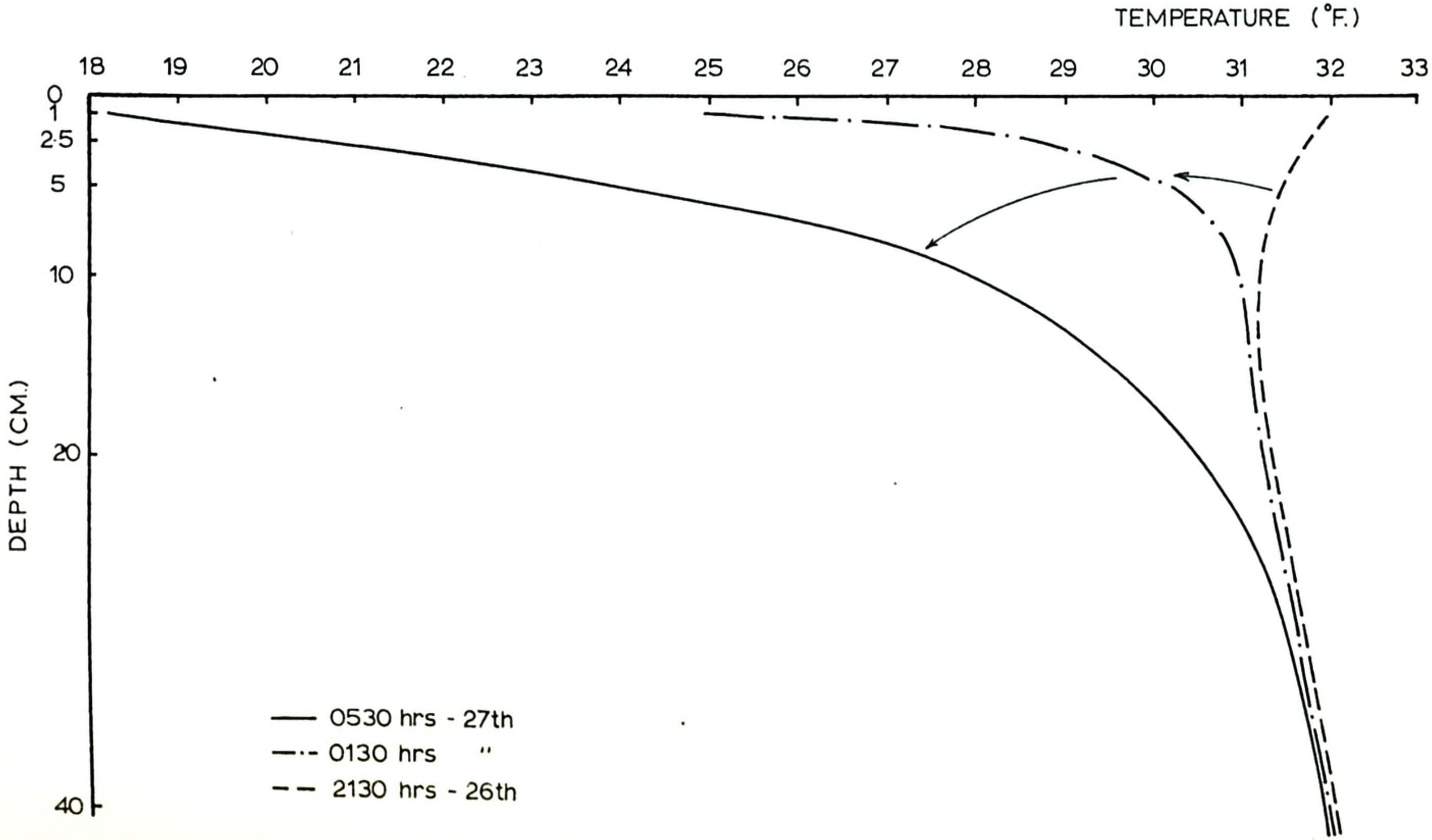


FIG. 28 Graph of Hourly Readings, February 26/27th, Plot E

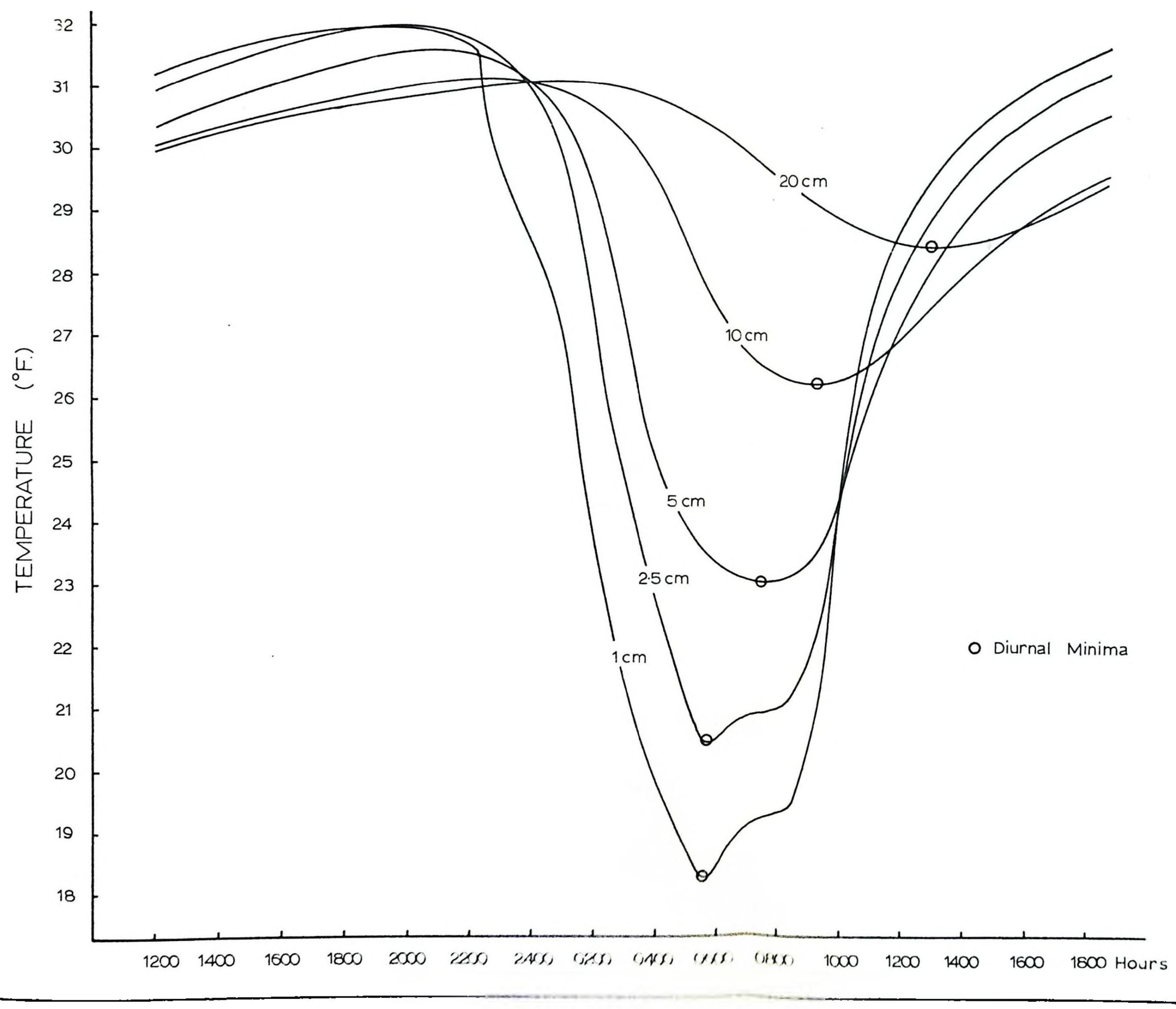
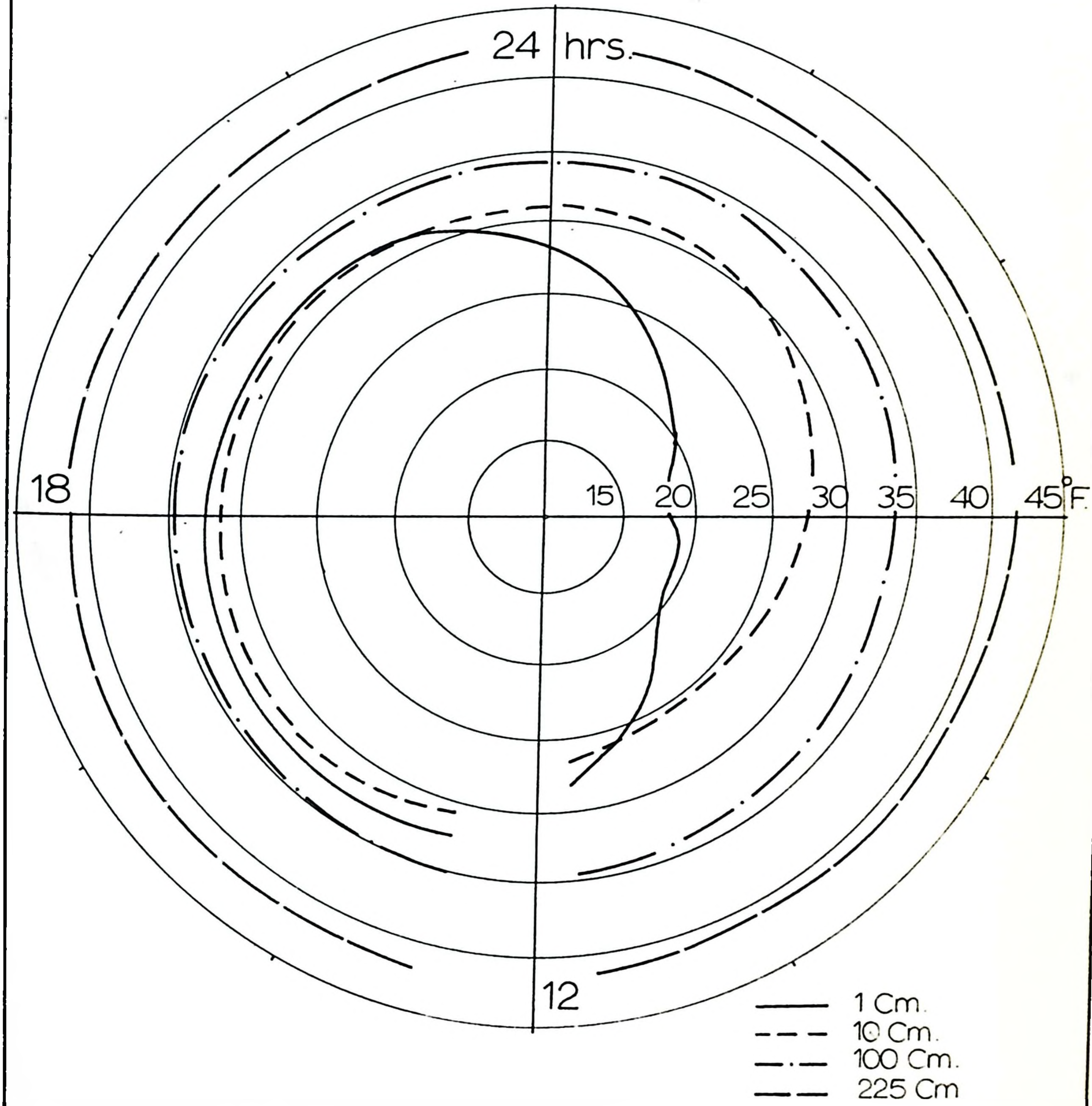


FIG. 29 Diurnal Course of Temperature in Plot E February 26/27th.



A simplified and easily understood picture of the nocturnal cooling pattern in Plot E is shown in Fig. 27. Here each tautochrone represents a time, and the progression of cooling is clearly shown. The curve for 0530 hours appears so perfect that it might have been theoretically plotted. However, this is not the case: it is in fact the result of 5 hours of perfect radiation cooling under clear skies.

The same results are plotted on a Time/Temperature graph in Fig. 28 at depths down to 20 cm. This shows the diurnal "turnover" (analogous to the autumn "turnover" of the annual curve (Fig. 10)) to occur at about 2400 hours. From this time onwards temperature increases with depth, and the amplitude of the cooling wave decreases with depth. At the time of the 1 cm minimum at 0600 hours there is a steep temperature gradient, the steepest of the day. During the summer the steepest gradient is at the maximum epoch around mid-day giving the contrast between the dominant night radiation of the winter, as against the all-important daytime heating of the summer. There is a definite lag in time with the depth at which the minimum is attained. The times of these minima when plotted on a Time/Depth graph (Fig. 30) approximate very closely to a straight line, indicating a constant rate of penetration of the cooling wave. This relationship is in very good agreement with the findings of McKenzie Taylor[25] who found a similar relation between the time of the minimum and depth. This figure, together with Fig. 18, also

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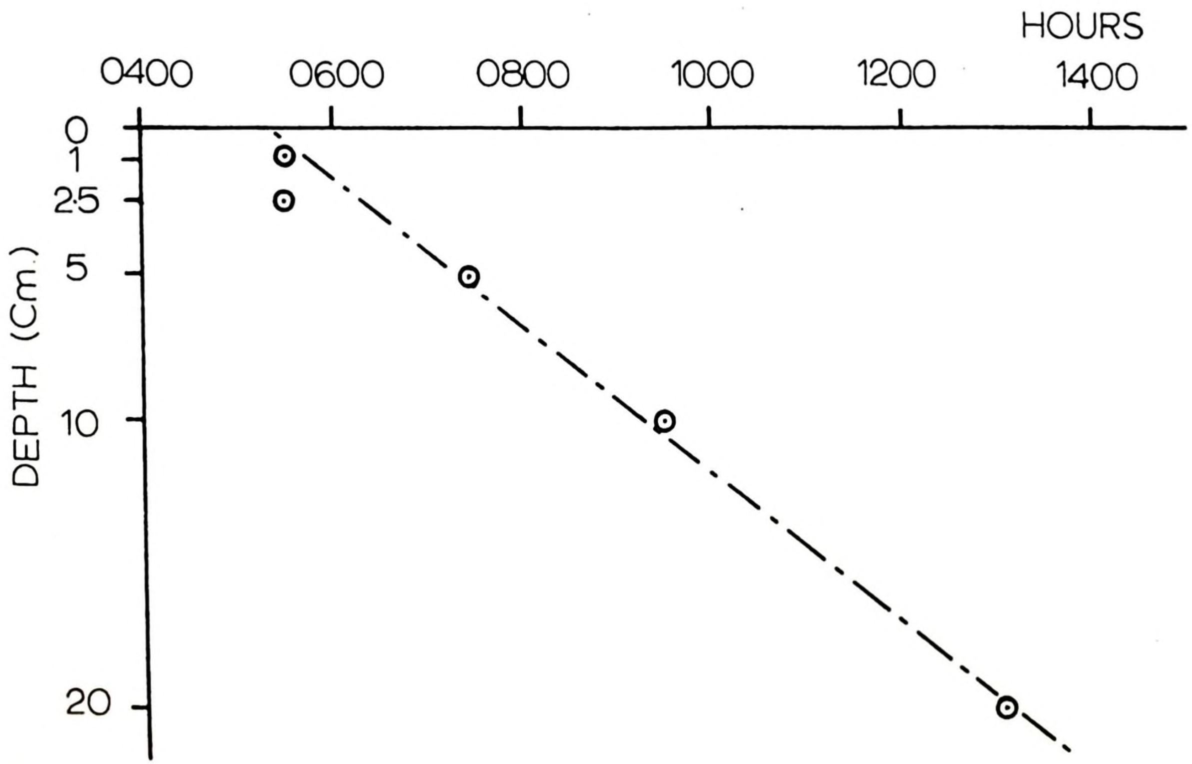
15 McKENZIE TAYLOR, <u>Op. cit.</u> p. 105.

FIG. 30 Lag of Diurnal Minima with Depth



—·— Line of minima, Plot 'E', February 26/27th.

provides another comparison between the diurnal and annual curves, by resembling closely the time lag in the achievement of annual minima. After the minima have been passed, the depths begin to warm up successively and a "turnover" similar to the spring "turnover" of the annual curve (Fig. 10) is seen, after which temperature decreases with depth again.

Making a comparison between control Plot A (Fig. 23) and bare Plot E (Fig. 26), a striking contrast is seen. Compare diurnal ranges in the two plots:

TABLE 9. Diurnal ranges in Plots A and E, February 26/27

	Plot A			Plot E		
Depth (cm)	Max.	Min.	Range (° F)	Max.	Min.	Range
1	31.55	30.2	1.35	32.1	18.25	13.85
2.5	31.55	30.4	1.15	31.95	20.55	11.4
5	30.4	29.25	1.15	31.55	23.2	8.35
10	31.55	30.55	1.0	31.15	26.1	5.05
20	31.95	31.45	0.5	31.05	28.55	2.5
50	32.9	32.85	0.05	32.0	31.45	0.55

Thus the ranges in E are seen to decrease with depth, showing the diminution of the wave amplitude with depth, and are of a much higher value. In the topmost 10 cm Plot E has a greater maximum, and a lower minimum than Plot A at every depth. A more striking example of the degree of insulation provided by a snow cover could not be desired.

(2) March 10/11, 1964

The general synoptic situation on March 9 showed a series of storms being spawned over Texas and extending up the eastern seaboard with considerable rain or snow. On this date the Hamilton area received 1.23 ins. of rain due to heavy thunderstorms. On March 10 a low pressure system was centered over Lake Ontario with associated strong winds and continuous snowfall from 0800 to 1800 hours, during which time nearly 7 ins. of snow was deposited. By March 11 the storm center had moved north-eastwards and left Southern Ontario and Quebec with a high pressure system and mainly sunny skies. Thus in the period of observation from 1800 hours on the 10th, to 1000 hours on March 11, cloud cleared after the snowstorm and gave an excellent cloud-free night:

TABLE 10. Cloud conditions March 10/11

E.S.T.	1800 - 2100	2400	0100	0200 - 0800	0900	1000
Cloud (oktas)	8	6	2	0	1	2

These clear night conditions, favouring heat loss allowed the air temperature to drop to 13.7° F, the lowest level in March:

TABLE 11. Course of nocturnal air cooling March 10/11

E.S.T.	1800	2100	2400	0100	0200	0300	0400	0500	0600
Temp. (° F)	26.4	25.6	24.6	22.6	21.3	19.3	18.3	15.7	13.7
E.S.T.	0700	0800	0900	1000					
Temp. (° F)	14.2	18.5	22.1	26.6					

The maximum temperature for the 10th was 33° F, the overnight minimum 13° F, and the maximum for the 11th 34° F. From March 3 until 10th there was no snow on the ground but following the heavy rain of the 9th, snow fell all day on the 10th, and after drifting the plots were covered with 4.5 - 5 ins. of fresh snow. Following the snow, winds were absolutely calm throughout the observation period.

Experiments

(a) Plot A (Control)

In this experiment readings were made every three hours in the period 1800 to 2400 hours, and thereafter once every hour until 1000 hours. Control Plot A was covered with a 4.75 in. layer of newly fallen snow throughout this period. The results are shown in Fig. 31 in conjunction with a trace of air temperature.

(i) Snow temperatures - Fig. 31 shows the snow to be continually cooling from the start of observations until the minimum is achieved at 0600 hours. Thus, as on February 26/27, the snow surface and air temperature minima both occur at the same time, showing a close interdependence between the two. After 0600 hours the snow warms quite rapidly to achieve a temperature of 28° F near the surface at 1000 hours.

Because all the snow is new the cooling takes place throughout the 4.75 in. layer. None of the very poorly conducting snow is able to obtain compensating heat from below, and so it cools excessively as described in the experiment of February 26/27. Due to these poor conducting qualities the lag of the cooling waves with depth, is also much reduced. At the time of the night minimum value of air temperature at 0600 hours, the snow surface falls to 0.85° F with an air temperature of 13.7° F. Yet on February 26/27 the snow only fell to 10° F with a 9.3° F air minimum. The reasons for this difference are twofold: (a) It is a reflection of the near perfect radiation conditions of this night in March. Ångström has pointed out that the snow surface often falls far below the air temperature, and that this is best seen "during calm and clear nights"[26] because the radiation to sky and space is unimpeded.

(b) The snow in question is all new and therefore first, its albedo will be high (at least 70%) thus reducing daytime absorption of insolation. Secondly its emissivity will be very high, and replacement from below of this heat loss will be negligible due to the poor conductivity of the less dense new snow. The result of these qualities is to produce an extremely pronounced cooling power.

This condition, in which the temperature of the snow surface is below that of the air, is quoted by Ångström[27] as being a well recorded fact, according to such authors as Hjeltström, Westman, Sarke, Süring, Polis and Müller. Actual values are not quoted but from Fig. 31 it can be seen that at 0400 hours the temperature of the snow surface has fallen to 16.7° F below that of the air. Similarly Table 12 shows the progression of this fall of snow surface temperature below that of the air:

TABLE 12. Fall of snow surface temperature below air temperature

E.S.T.	1800	2100	2400	0100	0200	0300	0400
Snow surface below air (°F)	-3.65	-3.7	-3.7	-6.1	-11.95	-12.9	-16.7
Cloud (oktas)	8	8	6	2	0	0	0
E.S.T.	0500	0600	0700	0800	0900	1000	
Snow surface below air (°F)	-14.5	-12.85	-10.5	-6.1	-1.65	+1.5	
Cloud (oktas)	0	0	0	0	1	2	

A definite pattern of cooling is in evidence. During the period of heavy cloud between 1800 and 2400 hours the temperature of the snow surface remains steady compared with that of the air. However, after 0100 hours the sky clears and the snow surface temperature falls fast. After sunrise the snow begins to be heated and with the arrival of more cloud the temperature of its surface eventually rises about that of the air.

At the minimum temperature epoch at 0600 hours there is a very steep temperature gradient in the snow of 30.1° F in 4.5 ins. and in fact 17° F in the topmost 2 ins. It is interesting to note two things: a) The gradient throughout the complete cover of snow is much steeper than on the 26th/27th of February, seemingly because old snow is accounted for in that result.

b) The temperature gradient in the new snow of the February run, and that in the corresponding new snow of this run have an almost identical value of 8° F for each inch.

(ii) Soil temperatures

The course of soil temperatures in the topmost 50 cm during this run is really quite astounding. As can be seen the 32° F isotherm runs horizontally at a depth of 30 cm. Throughout the period of observations, depths down to 30 cm showed no variation from the range 31.95 - 32.0° F, giving a temperature gradient in this layer of virtually nil. There is no reflection in soil temperatures of the turmoil occurring above in the snow. In fact, the insulation appears perfect. Franklin states that "as little as 4 ins. (of snow) provides a complete protection for the ground surface from very large variations of temperature above the snow surface".[28]

In this case soil temperatures are much higher than snow temperatures, showing beneficial conditions. The reasons for this stabilized warmth are as follows:

a) Poor conductivity - as already pointed out the thermal conductivity of new snow is so low that heat is only transported through it with the greatest difficulty - it is a good insulator. Indeed Atkinson and Bay consider "if sufficient insulation is provided by snow or other materials, frost may be drawn from the soil by the warmth of the Earth".[29] In other words, it is driven out by the upward heat flux.

b) Latent heat of fusion of water - when soil moisture freezes latent heat is released at the rate of 79.77 gram calories for 1 gram of ice. Thus as soon as water freezes the release of latent heat pushes

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[28] T. B. FRANKLIN, Op. cit. 1919, p. 72.

[29] H. B. ATKINSON and C. E. BAY, Loc. cit. 1940, p. 947.

the temperature back up to 32.0° F. Any excess latent heat will travel upwards to the zone of cold above and be trapped there, unable to escape, because of the snow cover. Thus in this way also soil temperatures are stabilized.

c) Rain - as Franklin[30] has pointed out, rain is an equalizer of temperature between the surface and lower soil layers. The 1.23 ins. rainfall of March 9 fell on snow-free ground and obviously would do much to promote thawing in the topmost layers. Similarly the addition of rain to the soil raises the heat capacity (or Volumetric Specific Heat) of the soil. Thus, for any given input of heat, the temperature of the soil will change less readily, and this will again provide a stabilizing effect.

(b) Plot C (Straw)

The effect of the cover of straw (Fig. 32) is almost exactly the same as that of the 4 1/2 ins. of snow in Plot A. Plot C shows a slight lag over Plot A in achieving 32.0° F isothermal conditions but this may be explained by: (1) Straw would slow up and to some extent prevent the percolation of the previous day's rain; (2) Plot C had been continuously covered, and, as shown in the previous experiments on this plot, all variations are recorded very slowly, in a gradual manner.

Thus one may say that the insulation of the two plots was similar, but the effect of snow was more immediate. From about 2300 hours onward the temperatures in Plots A and C were identical.

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[30] T. B. FRANKLIN, Op. cit. 1919, p. 63.

(c) Plot E (Snow-cleared)

Fig. 33 shows that the air temperature and that at a depth of 1 cm starts to fall at about 2400 hours. Cooling continues until 0700 hours when the minimum is achieved, about 1 hour later than the air, as in February. Comparing Plot E for March 10/11, with the same plot on February 26/27 (Fig. 26) a number of points emerge. The most interesting concern the recorded intensity of the cooling on March 10/11 even though conditions were ideal. The depth of cooling changes from 40 cm in February to 5 cm in March. The temperature gradient in the topmost 10 cm is halved, and there is a correspondingly much reduced development of wave lags causing isotherms to bulge to the right.

The reasons for this reduced extent, and intensity, depend on the following 3 factors:

a) Air temperature - the minimum of the night in February was 9.3° F, whereas the corresponding value in March was 13.7° F. However, this reason is regarded as being of only minor importance compared to the other two, which are dependent upon the increased soil moisture due to the heavy rainfall of March 9.

b) Conductivity - Patten[31] has shown conclusively that up to a certain limit, an addition of water to a soil will result in an increased thermal conductivity of that soil due to:

(i) increased thermal contact between soil particles;

(ii) replacement of poorly conducting soil air, by water.

This means that heat lost at the soil surface will be more easily

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[31] H. E. PATTEN, Op. cit. 1909.

replaced by heat flowing up from below, and this will prevent the soil surface from becoming too cold.

c) Heat capacity - a further effect of increasing soil moisture is to reduce the soil's ability to heat up or cool down, by increasing its Heat Capacity as has already been explained. Thus, although heat is more easily conducted, its influence upon the soil temperature for a given input is reduced.

Herein lies the reason for the reduced intensity of temperature cooling in March. In February, in the 20 days prior to the experiment, no rainfall fell at all, and snowfall amounted to only 0.9 ins. of water equivalent, most of which remained above the surface as a snow cover. In March, on the other hand, during the 4 days prior to the night run, as much as 1.54 ins. of rain fell on a snow-free, unfrozen surface, and so was totally available as soil moisture.

Evaluation of Methods of Presentation

As was stated at the beginning of Chapter 4, there are 4 methods of representing how heat movement takes place in the soil:

(a) Time/Temperature

(b) Isopleths

(c) Tautochrones

(d) Polar co-ordinates

Geiger[32] presents the first three of these methods, but as with other authors, fails to provide an answer as to which method is of the greatest value for showing any one, or any specific range of

143 R. GEIGER, Op. cit. 1959, p. 29.

features. It is felt that as all of these methods have been used in this thesis, up to this point a critical appraisal of the value of each method would provide an original contribution.

It was felt that a table would provide a less cumbersome and more handy reference (Table 13). The 13 most important parameters necessary for a soil temperature diagram to be of value were chosen, and placed at the heading of columns. Each of the 4 methods is grouped under each of the 4 headings used in this thesis, and example figures are given with their text number. The system of rating a particular diagram's value was based upon its ability to portray the parameter indicated, in the following manner.

Score 3 points - if portrayal is outstandingly clear
" 2 " - " " " good
" 1 point - " feature is discernible but poor
" 0 points - " presentation is bad, confusing or absent

A total possible score by any method is given to provide an absolute measure of the real value of each individual method. No method is seen to approach this ideal maximum, for if it did only that method would be used, and the present appraisal would not be required. By presenting this table, not only is the relative value of each method of presenting all the features analyzed, but also if any particular parameter needs to be emphasized the most efficient method is also evident.

1. Total Profile Averages

From Table 13 it becomes obvious that Isopleths and Tautochrones cannot be used because these methods both require a depth scale. The Time/Temperature method comes out best on every count, and the final result is the well-known harmonic curve. The circular path of Polar Co-ordinates is acceptable but less simple.

2. Monthly depth averages

Three methods are here all almost equally acceptable. Time/Temperature shows excellently the over-all pattern and wave diminution with depth, and the turnover period. For simplicity and appearance it deserves its number one position. Tautochrones score well on pattern, range, and gradient, but lack a correlation with the macro-climatic conditions. Isopleths are especially suited to showing the frost-line, and this is a recurring feature of this method, but as with Tautochrones they cannot show the turnover very easily. Polar Co-ordinates takes a poor last place on most counts.

3. Annual Curve

Tautochrones and Polar Co-ordinates are ruled out on the basis of clumsy complexity. The Tautochrone method in particular would be impossible to use, plotting one line for each day. A reduced number of days will reduce the complexity but also the accuracy. The Time/Temperature and Isopleth methods both score equally well, and may be considered complimentary rather than contrasting. Again, Isopleths show well the course of the frost line, whereas the turnover and wave diminution with depth are better shown on the Time/Temperature method. Both show an excellent correlation with macro-climatic conditions, a very important point in considering the annual march of temperature.

TABLE 13. EVALUATION OF METHODS OF PRESENTATION

Example Figure		Time Scale	Depth Scale	Temperature Scale	Correlation with macro-climate	Wave lag	Wave diminution	Temperature Gradient	Turnover	Quantitative Analysis	Over-all Pattern	Frost Line	Total Range	Ease of use	Total	Total Possible
	1. TOTAL PROFILE AVERAGES															18
8	Time/Temperature	2	N.A.	2	2	N.A.	N.A.	N.A.	N.A.	N.A.	3	N.A.	2	2	13	
N.A.	Isopleths		0											0	N.P.	
N.A.	Tautochrones		0											0	N.P.	
9	Polar Co-ordinates	1	N.A.	0	1	N.A.	N.A.	N.A.	N.A.	N.A.	2	N.A.	1	2	7	
	2. MONTHLY DEPTH AVERAGES															39
10	Time/Temperature	2	1	2	2	2	3	1	3	1	3	0	2	1	23	
13	Isopleths	2	2	1	2	2	1	2	1	1	2	3	1	1	21	
11	Tautochrones	1	2	2	0	2	2	3	1	1	3	0	3	2	22	
12	Polar-Coordinates	1	1	0	1	1	1	1	1	1	2	0	1	1	12	
	3. ANNUAL CURVE (Daily Readings)															39
14	Time/Temperature	2	1	2	3	3	3	1	3	2	2	0	2	1	25	
15	Isopleths	2	2	1	3	3	1	2	1	1	2	3	1	1	23	
N.A.	Tautochrones													0	N.P.	
N.A.	Polar Co-ordinates													0	N.P.	
	4. DIURNAL CURVE (Hourly Readings)															39
41	Time/Temperature	2	1	2	3	3	3	1	2	2	3	0	2	2	26	
26	Isopleths	2	2	2	3	3	1	3	0	1	3	2	1	1	24	
43	Tautochrones	0	2	2	0	2	3	3	1	1	2	0	3	1	20	
29	Polar Co-ordinates	1	1	0	1	1	2	1	2	1	2	0	1	1	14	

RANK: 0 - bad, or not present; 1 - poor; 2 - good; 3 - excellent

N.A. - Not applicable; N.P. - Not possible

4. Diurnal curve

For representation of hourly readings throughout a 24 hour period the Time/Temperature method scores 26 out of a possible 39 points. This method is outstandingly good in its portrayal of such important features as wave lag and wave diminution with depth, their correlation with outside climatic elements and the over-all wave pattern. Thus this method is simple and easy to both recognize and analyze. The Isopleth method also scores well, especially in representing the temperature gradient and frost line, but it fails to pin-point the times of turnover at selected depths. These two methods again appear to be complimentary rather than repetitive and their combination covers most points well. Tautochrones may be used to good effect if the number is restricted and the times shown clearly. If temperature variations are small this method becomes too cluttered with undistinguishable lines bunched closely together one upon another. Unfortunately too, a correlation with outside conditions on a time scale is lacking. The polar co-ordinates method is not a good one for representing any particular feature, as it scores low on most parameters. The biggest drawback with this method is the unequal representation of time due to the radial segments provided by the time scale. The line showing a fall of 5° F at a low temperature value is much shorter than a similar fall further up the temperature scale. Thus night cooling in winter (Fig. 29) is less well shown than day warming in summer, even though the magnitude of temperature variations involved may be of an equal value.

CHAPTER 6

SUMMER EXPERIMENTS

Chapter 5 illustrated the experimental work carried out during the winter months. Similarly during the summer more surface treatments were applied to the ground surface, and more intensive diurnal wave patterns observed. Again the results and analyses are presented under the two headings, Surface Treatments and Diurnal Wave, plus a section concerning Soil Moisture.

A. Surface Treatments

Considering the thermal balance at the ground surface, there are four main factors involved according to Ramdas[1]:

a) Radiation - the ground receives and absorbs radiation from the sun directly, and indirectly from water vapour, carbon dioxide and ozone in the atmosphere. The surface also emits radiation, according to the Stefan-Boltzmann constant, with an intensity approximately equal to the fourth power of its absolute temperature.

b) Convection - especially during the daytime heat is carried away by air flowing over the soil surface.

c) Conduction - small amounts of heat are conducted from the ground to the overlying atmosphere, but more important is the heat

[1] L. A. RAMDAS, "Phenomena controlling the thermal balance at the surface", UNESCO Arid Zone Research, Vol XI, Canberra Symposium, 1958

flux by conductance down into the soil by day, and upwards out of the soil by night.

d) Evaporation and Condensation - when water changes state to water vapour by evaporation, and conversely when vapour becomes liquid by condensation, considerable amounts of heat are involved. When vapour condenses this stored-up or "latent heat" is liberated causing a warming in the area immediately surrounding it. When evaporation occurs a similar amount of heat is taken up to effect the change of state, thus causing a cooling in the vicinity.

All these four factors are intimately inter-connected in controlling the thermal balance at the surface. Indeed they are so linked that changing any one causes adjustments to compensate by the other three. By applying treatments to the soil which will alter any one of these controls, the thermal balance may be consciously controlled, or at least modified. Thus when a straw mulch was applied during the winter the outgoing radiation was hindered, thus reducing upward conductance, convection and evaporation. The summer experiments were modelled along similar lines.

The main experiments concerned the effect of changing the colour of the ground's surface. Opposite ends of the colour scale were used, namely black (Carbon Black) and white (Talc). By changing the colour, Bouyoucos[2] has shown that the ability to absorb heat is radically changed. This as Ramdas[3] has shown is due to the different

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[2] G. J. BOUYOUCOS, Op. cit. Bull., No. 17, p. 31

[3] L. A. RAMDAS, Op. cit. 1958, p. 129.

"albedo" values or power of reflection, of the different colours. He assumed that French chalk (similar to Talc powder), has an albedo of 1.0, that is it absorbs no solar radiation at all. Conversely, he calculated powdered charcoal (similar to Carbon Black), to absorb 96% of all incident solar radiation, and therefore to have an extremely low albedo of 0.04. Thus we may expect temperatures under a black surface to be higher than under a white surface, due to increased absorption. This fact is well recognized and authenticated, but not much work has been conducted in temperate latitudes to ascertain the exact magnitude of these influences.

In addition to colouring the soil surface, a crop of oats was grown on one plot to ascertain the effect of a vegetation cover on soil temperatures. It was expected that incident insolation would be cut down and convective processes reduced.

1. Procedures

For the summer program, four plots were used in the following manner (Plates 12 and 13):

(a) Plot A - remained untouched as the control plot.

(b) Plot B - at the beginning of the period a crop of oats was sown. To sow the seeds the natural sod was first removed, and the soil worked into a tilth.

(c) Plot D - was covered with a layer of Carbon Black, just sufficient to change its colour.

(d) Plot E - was covered with a similar layer of white Talc powder. Both Plots D and E were periodically re-treated to maintain their artificial colours.

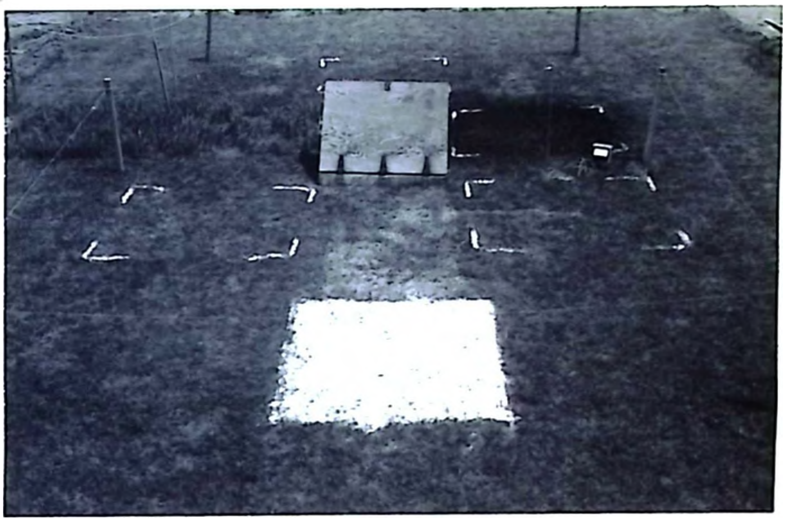


Plate 13. Summer view of site.

The experimental period for all plots covered the five weeks from June 16, 1964 until July 20, 1964 as follows:

Week 1 (June 16-22) Week 2 (June 23-29)

Week 3 (June 30-July 6) Week 4 (July 7-13)

Week 5 (July 14-20)

Throughout this period the temperatures in all plots were observed twice a day at 0600 and 1400 hours, to provide a daily mean. In Plots A and B readings were continued for a further four weeks, but at 1400 hours only:

Week 6 (July 21-27) Week 7 (July 28-August 3)

Week 8 (August 4-10) Week 9 (August 11-17)

Just as in the winter experiments, it was necessary to establish that all plots gave similar readings at corresponding depths, before treatments were applied. However, a check over a period of weeks revealed temperature differences at the same depth, in different plots. In addition it was noticed that these differences were:

(a) Greater at depths nearer the surface, and

(b) Greater when ambient temperatures were higher.

These two considerations suggested that the temperature gradient was the critical factor, because it is this gradient which is both greater near the surface, and greater under hot conditions. It became evident that under the extremely unstable conditions of the summer a simple quantitative correction would not suffice. Rather a correction tied to the temperature gradient was necessary. It was further realized that assuming the thermocouples to be recording accurately*, the only other factor which might cause such differences was an error in the depths at which they were emplaced. If a thermocouple placed near the surface was only 1 cm out in its positioning, the acute temperature gradient of summer could cause a temperature to be as much as 8° F in error. The method of emplacement using a steel welding rod could not guarantee such accuracy, and so a new method of correction was devised, taking into account the temperature gradient, and applying a correction for depth rather than temperature.

Readings were taken in all plots for a number of weeks. Plot A was again to be the control plot, and so its temperature profile was assumed to be correct, to provide a unit of comparison. The tautochrone for Plot A on each day was drawn using the depths originally chosen. At these same depths all the temperatures in the various plots were also plotted. Now assuming A to be correct, each was moved vertically either up or down until it coincided with the curve of A. At this point of intersection the depth was noted. This being done for a large number of days a "preferred" depth for each thermocouple was seen to emerge. All these preferred depths were averaged to give a calculated "real" depth for that junction. Appendix IV gives these values and the calculated real depths of emplacement in each plot. If each plot's temperatures were now plotted at these "real" depths a curve almost identical to that of A emerged. This fact was noted to hold under all conditions and at all times of day.

* This was later verified by re-calibration.

When the experiments began it was then necessary to correct each reading in the following way:

(a) Plot the temperatures at the real depths corrected as in Appendix IV, and draw the temperature profile. This curve was then the real temperature gradient in that plot.

(b) To provide the desired comparison at the same depths as those assumed in A, it was merely necessary to run up or down the curve to the original depth assumed in A, and read off a corrected temperature.

2. Results

(a) Weekly averages of daily means

Climatologists consider there are a number of ways of obtaining a daily mean from a set of given temperatures. Certainly the most accurate is to average all the hourly observations throughout the 24 hour period. However, one cannot expect to obtain such an abundance of data over an extended period, and be able to analyze it simply. To overcome this a simple relationship between the maximum temperature epoch (1400 hours) and the minimum temperature epoch (0600 hours) has often been used. To verify that such an average of the 0600 and 1400 hours readings would give a good approximation to the true daily mean, a check was carried out during July 16. A comparison of the daily mean as given by an average of maximum and minimum readings, and that given by an average of readings taken every 3 hours throughout the day, is presented in Table 14:

TABLE 14. Check of daily mean (July 16)

Depth (cm)	Average of 0600 and 1400 hr. readings	Average of readings taken every 3 hours	Differences
1	77.30° F	75.40	-1.90
2.5	76.70	76.00	-0.70
5	75.55	74.60	-0.95
10	70.95	71.85	+0.90
15	70.35	71.35	+1.00
20	69.55	70.25	+0.70
25	69.25	69.80	+0.55
30	69.30	69.45	+0.15
40	68.70	68.55	-0.15
50	67.55	67.65	+0.10
75	66.85	66.60	-0.25
100	65.25	65.10	+0.15
150	61.05	60.90	-0.15
225	56.55	56.60	+0.05

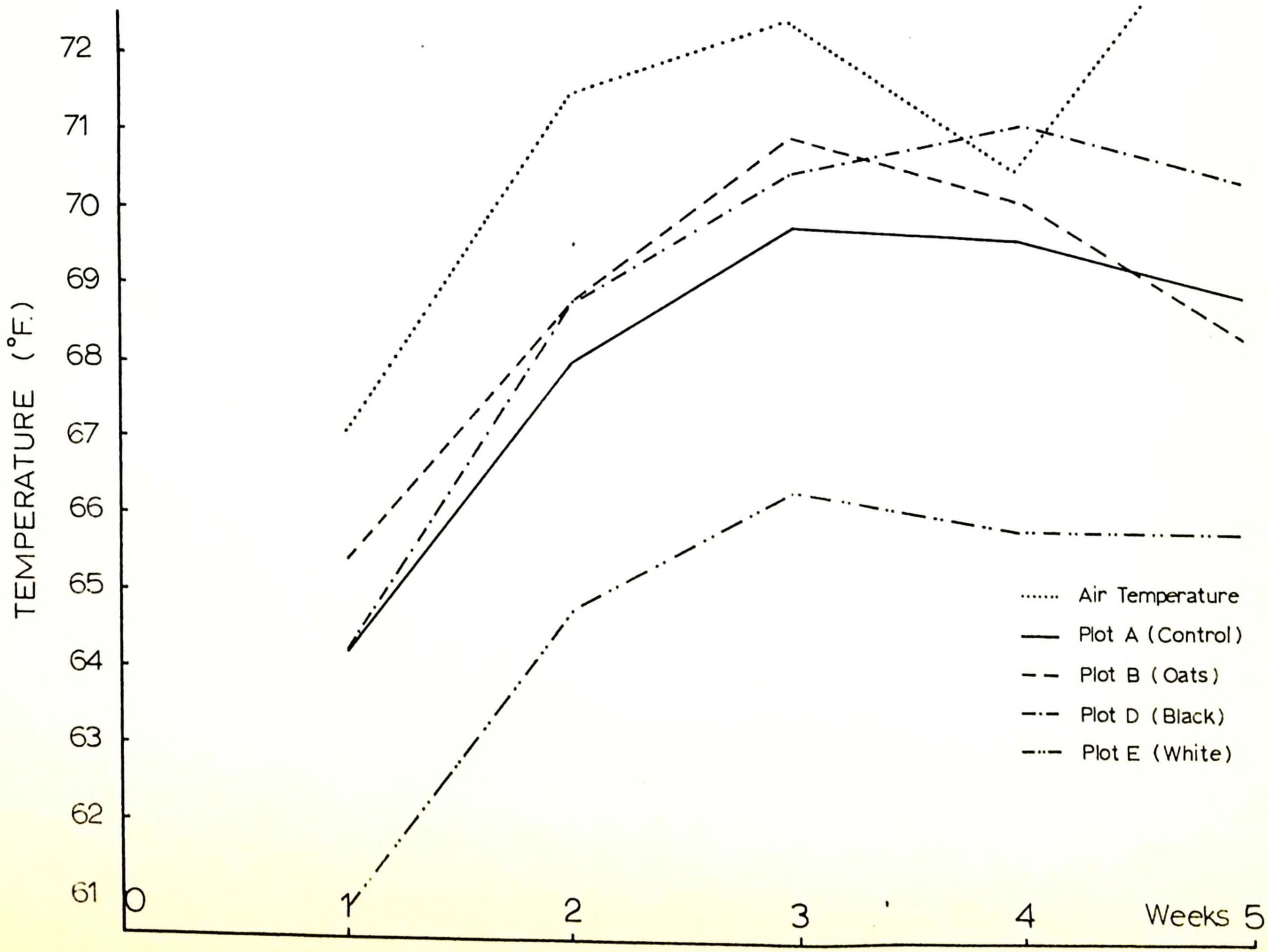
The biggest differences between the two averages are found nearest to the surface, and the disparity diminishes with depth as one might expect. Only the 1 cm depth approaches a difference greater than 1° F and this is on a day when the 1 cm depth had a diurnal range of nearly 30° F. Thus the very worst difference is only about 5% of the daily range, and all the others have very considerably better agreements. Thus it may be concluded that an average of the 0600 and 1400 hours readings does give a reasonable approximation to the true daily mean.

Such daily means have been gathered into the weeks already outlined and are presented here as weekly mean values. Fig. 34 presents the Weekly Total profile averages for all plots for the first five weeks of the experimental period. Plot A is seen to follow fairly closely the path of air temperature. This plot is again the control against which the treated plots should be compared.

By the end of the first week the temperatures in Plot B are seen to have risen above those in the control. This plot was cleared of its natural sod and planted with oats. By this time there was no vegetative cover and the plot was not only open to unhindered insolation, but also its albedo had been lowered, thus increasing its power to absorb. This state of affairs continues until Week 3. After this the cover of oats begins to become an effective interceptor of insolation and shades the underlying soil. By Week 5 the shading of the oats crop was sufficient to reduce the temperature in Plot B to bring it cooler than the natural control plot.

Plot D, covered with Carbon Black, remains at approximately the same temperature as Plot A at the end of Week 1. The fact that this treatment shows no effect at this time may be attributed to the low temperatures and cloudy skies of this period. Under such conditions, the extra absorption provided by the low-power reflecting surface, is not being utilized to its maximum advantage. However, in the succeeding weeks, with increasing air temperatures, this plot gradually becomes warmer and warmer than Plot A. By Week 5 the carbon plot is 1.5° F warmer than the control, and still showing a tendency to diverge from it.

FIG. 34 Weekly Total Profile Averages (Daily Means)



The most striking plot in Fig. 34 is Plot E, covered with white Talc. By Week 1 this plot has fallen 3° F below Plot A, and throughout the remainder of the 5 weeks it remains about 3.5° F cooler than the control, an example of reduced absorption consequent upon increasing the surface albedo.

However, in Fig. 34 the complete temperature scale only covers a span of 10° F and thus differences between plots are of a small magnitude. It became apparent that as Dravid[4] says "differences in temperatures (between plots) are relatively small in the morning but in the afternoon they show up very conspicuously." This is because, as Bouyoucos[5] showed, colour has no effect on radiation and thus all plots cool by radiation to the same temperature by night. But colour does have a very marked effect on absorption of insolation by day, causing very considerable temperature differences. To illustrate this fact Table 15 has been constructed. This table shows the 0600 and 1400 hours readings for all plots during the period June 30 until July 6. A glance at the two columns representing maximum differences between plots shows the great disparity in the afternoon as compared with the morning. Similarly Fig. 35 representing the maximum and minimum 1 cm soil temperatures in the period June 26 until July 1, shows how small the range of temperatures is at 0600 hours as compared with 1400 hours.

Thus by presenting weekly means, calculated from daily means,

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[4] R. K. DRAVID, Op. cit. 1940, p. 365.

[5] G. J. BOUYOUCOS, Op. cit., Bull. No. 17, p. 31.

as in Fig. 34, the contrasts under observation are greatly reduced. It was decided therefore to present only 1400 hours readings, as these highlight the differences under consideration, and will show the maximum effects.

(b) Weekly averages of daily maxima.

(i) Fig. 36 shows only the 1 cm depths in all plots at 1400 hours, averaged into weekly means. This figure illustrates simply, but effectively, the influences of the various treatments. Using the 1 cm level, the closest to the surface. The maximum differences between plots is brought out strongly.

The general trends of plots is exactly the same as in Fig. 34 but the much greater magnitude of the differences provides a clearer picture. All plots start together in Week 0 when no treatments were applied. From this point onwards each plot follows a path different from that of control Plot A and in a direction which is dependent upon the nature of the surface treatments.

Control - Plot A follows fairly closely the course of weekly maximum air temperatures.

Oats - as was previously pointed out, Plot B temperatures rose sharply in the beginning when it supported no cover crop or natural sod. With the appearance of the crop shoots above the surface in Week 2 temperatures begin to fall. By Week 4 the crop now at a height of 20 cm has reduced the temperature at the 1 cm level in Plot B to a lower value than that in the control. From Week 4 until the end of the experiments Plot B remained cooler than Plot A, and

TABLE 15. Comparison 0600 and 1400 hours - Week 3

0600 hours

Depth (cm)	Plot A	Plot B	Plot D	Plot E	Maximum Differences
1	66.60	65.80	65.85	64.20	2.40° F
2.5	67.10	66.55	66.15	64.60	2.50
5	67.60	67.90	66.70	65.35	2.55
10	70.90	71.45	70.50	67.75	3.70
20	71.50	72.05	71.75	68.60	3.45
50	68.50	70.45	69.30	67.60	2.85
100	63.70	65.50	63.75	63.00	2.50
150	58.20	58.65	58.40	58.25	0.45
225	54.10	53.90	54.30	54.05	0.40
Total Profile =	65.35° F	65.80° F	65.20° F	63.70° F	

1400 hours

Depth (cm)	Plot A	Plot B	Plot D	Plot E	Maximum Differences
1	91.40	94.80	95.10	79.20	15.9° F
2.5	90.10	93.35	9.355	79.05	14.5
5	87.20	90.50	89.65	76.85	13.65
10	76.40	77.65	77.35	70.95	6.7
20	71.85	74.00	73.40	68.50	5.5
50	68.90	69.50	69.45	66.20	3.3
100	64.35	65.05	64.25	62.50	2.55
150	58.70	58.60	58.85	58.40	0.45
225	54.40	54.20	54.40	54.40	0.2
Total Profile =	73.70° F	75.30° F	75.10° F	68.45° F	

FIG. 35 1cm. Maxima and Minima, June 26th.-July 1st.

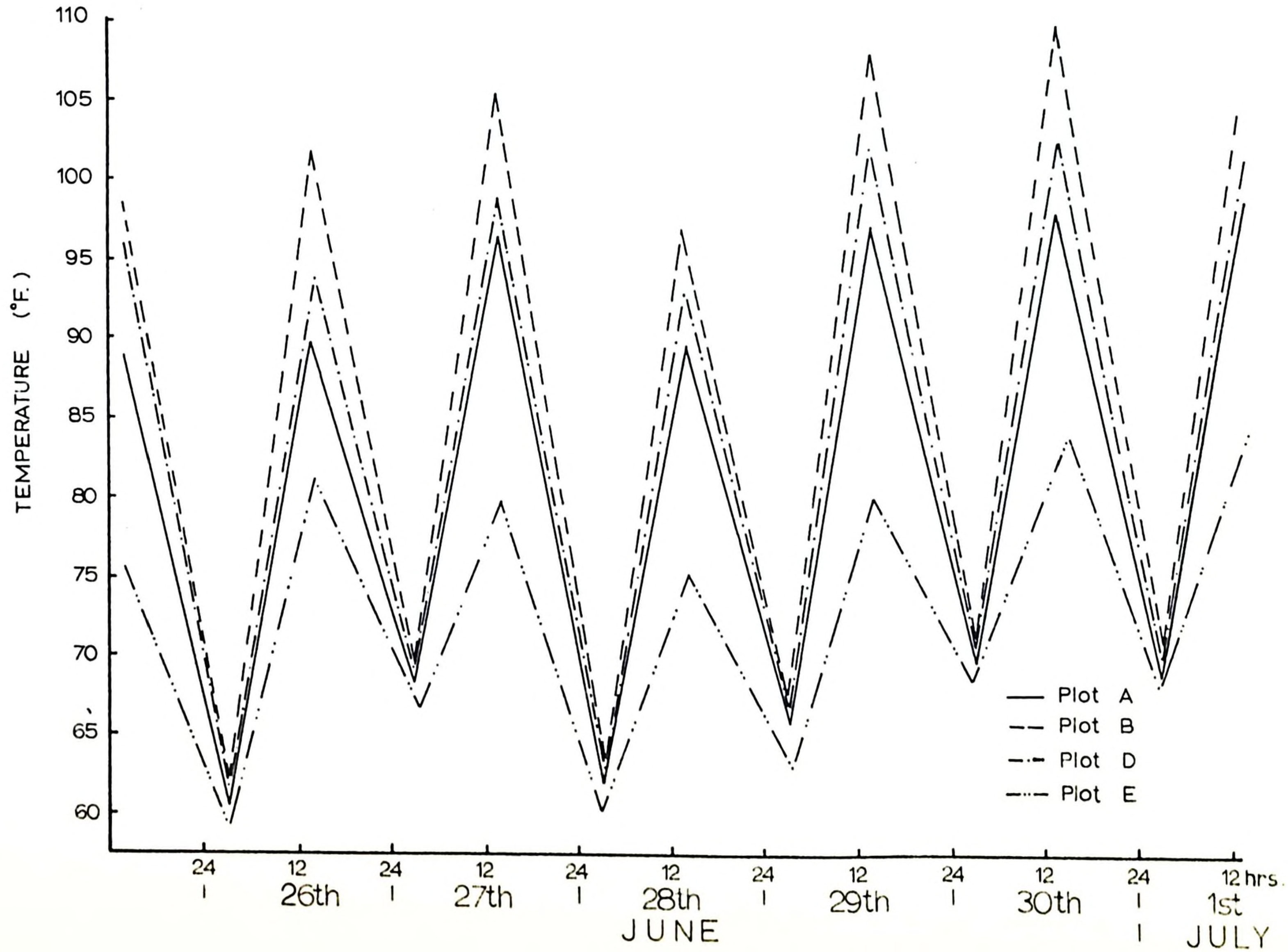
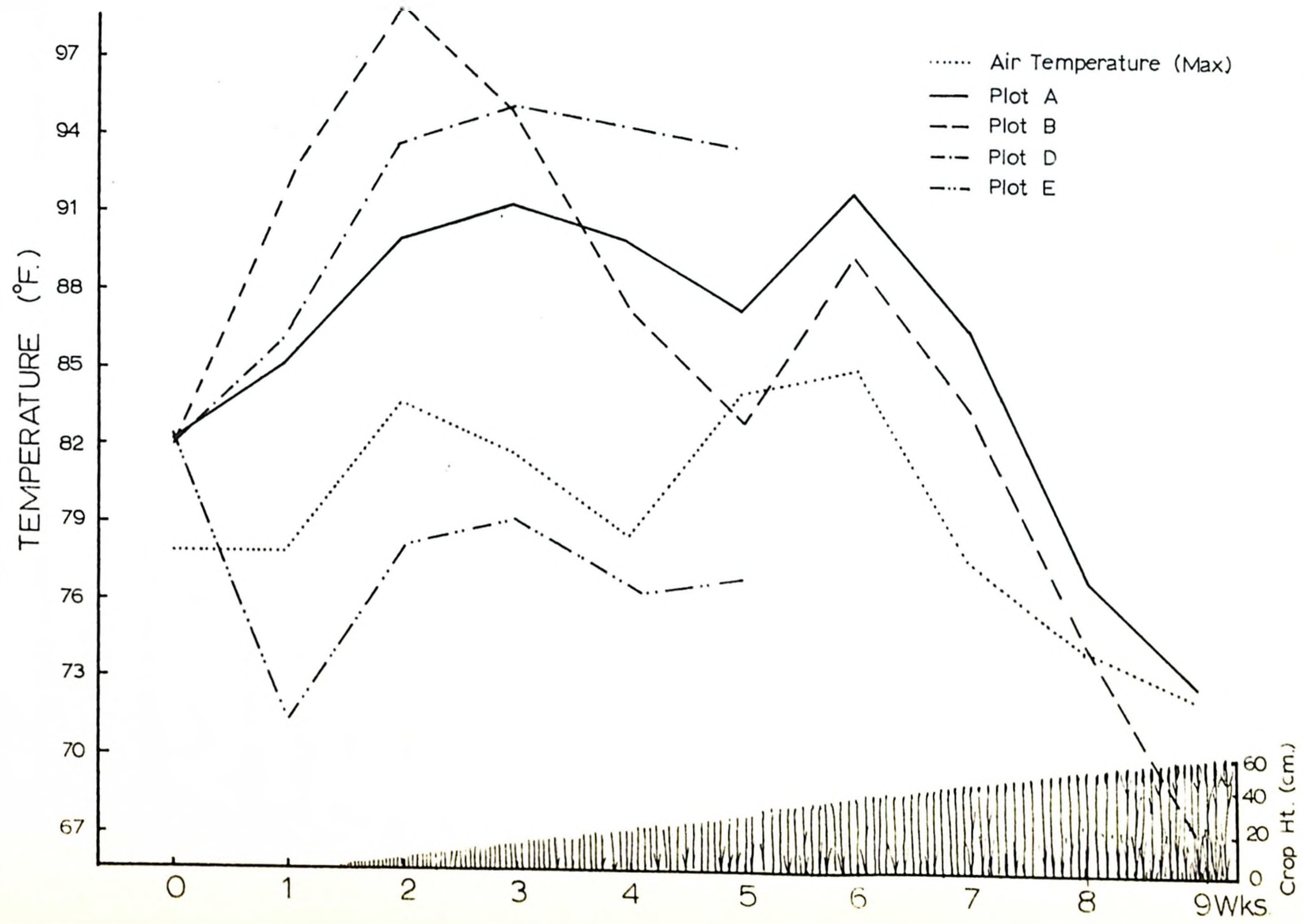


FIG. 36 Weekly Averages of 1cm. depth at 1400 hours



its isotherms roughly followed the course of those in the latter.

Carbon Black - the course of temperatures in Plot D follows closely that in the control. However, as time proceeds, Plot D becomes successively warmer than Plot A, and the two lines diverge. The treatment seems to build up gradually, for by Week 5 Plot D is warmer than Plot A by 6.5° F.

White Talc - during Week 1 Plot E shows a dramatic drop in temperature compared with the control plot. From this time onwards it seems to establish a close relationship with Plot A following its course, but remaining approximately 12° F cooler.

(ii) Fig. 37 (a, b, c, d) using the isopleth method, shows weekly means of daily maxima in all plots, down to a depth of 20 cm. The outstanding features of these results are as follows:

Control - this plot again shows the normal untreated course of soil temperatures. As can be seen in Fig. 37(a) Weeks 3 and 6 were exceptionally hot, and Weeks 4, 5, 7, 8 and 9 relatively cool.

Oat Crop - due to the removal of the grass sod cover this Plot (Fig. 37(b)) is much warmer than A up to Week 3. The isotherms dip steeply and penetrate rapidly in Weeks 1 and 2. In Week 2 the average temperature at the 1 cm level in A is 90° F, whereas in Plot B it is 98.4° F. However, as the cover crop grows the difference between the two diminishes, and the high peak of Plot A in Week 3 is not mirrored in Plot B. Following the cooling in Week 5 the 30 cm high crop of oats restricts the warming in Plot B, and during the succeeding weeks the isotherms rise steeply indicating progressive cooling. It is interesting to note that effects are only felt down to a depth of approximately 10 cm.

Carbon Black - during Weeks 1 and 2 the warming isotherms in Plot D penetrate more rapidly than those in the control plot (Fig. 37(c)). A similar "hot peak" is reached in both plots in Week 3, but the 1 cm maximum in the black plot is almost 5° F higher on average. All isotherms penetrate deeper in Plot D, and the effects of this surface treatment are easily visible at 20 cm. During Week 3 the 1, 2.5, 5, 10 and 20 cm depths have their maxima raised 6.2° F, 5.95° F, 5.55° F, 2.55° F, and 2.15° F respectively, above those of Plot A. This 1 cm rise represents a 7% increase in soil temperature as compared with the corresponding depth in the control.

White Talc - as already indicated the application of white Talc powder had the most striking effect of all treatments. In Fig. 31(d) the sudden upward swing of isotherms in Week 1 shows clearly the remarkable cooling this treatment induces. This feature is almost exactly analogous to that recorded by Dravid[6] in Poona using a thin cover of chalk powder. Especially noticeable is the rise of the 65° F isotherm, in this study, from 20 cm up to 10 cm within 1 week. The effects seem to be immediately recognizable to at least a depth of 20 cm and probably downwards towards the 50 cm level. Following this initial cooling, Plot E settles down into a pattern similar to that of Plot A but at least 10° F cooler at the 1 cm depth. During Week 4 the effect of the white Talc was to reduce temperatures in Plot E at the 1, 2.5, 5, 10 and 20 cm levels by 12.55° F, 12.05° F, 10.4° F, 4.9° F, and 2.2° F, respectively.

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6 R. K. DRAVID, Op. cit. 1940, p. 365.

The cooling at the 1 cm level represents a 14% decrease in temperature, in comparison with the same depth in Plot A.

All the results concerning a change in the colour of the ground surface emphasize that the effect of the white was much more striking than that of the black treatment. This result, however, is purely dependent upon the unit of comparison; in this case control Plot A. It is not unreasonable to assume that absorption and therefore the temperature of the soil varies directly with albedo. The carbon black covered ground with an albedo probably as low as 5%, and the Talc covered ground with a probable value of 90%, lie at opposite ends of the albedo scale. The albedo of grass-covered Plot A, however, is of the value 30%, and so lies closer to Plot D than Plot E on the albedo-scale. It is for this reason that Plot E provides the most marked effect. Similarly, Dravid[7] found that a black charcoal treatment to the already dark Poona soil had a relatively small effect.

(c) <u>1 cm Daily maxima (1400 hours)</u>

Fig. 38 representing 1 cm daily maxima readings for the period June 11 until July 19, shows the maximum treatment effects in each plot. A number of notable points emerge:

(i) All plots follow the same course until the treatments were applied on June 16.

(ii) From this date until July 1 Plot B (Oats) at the 1 cm depth is always considerably warmer than both the control and Plot D

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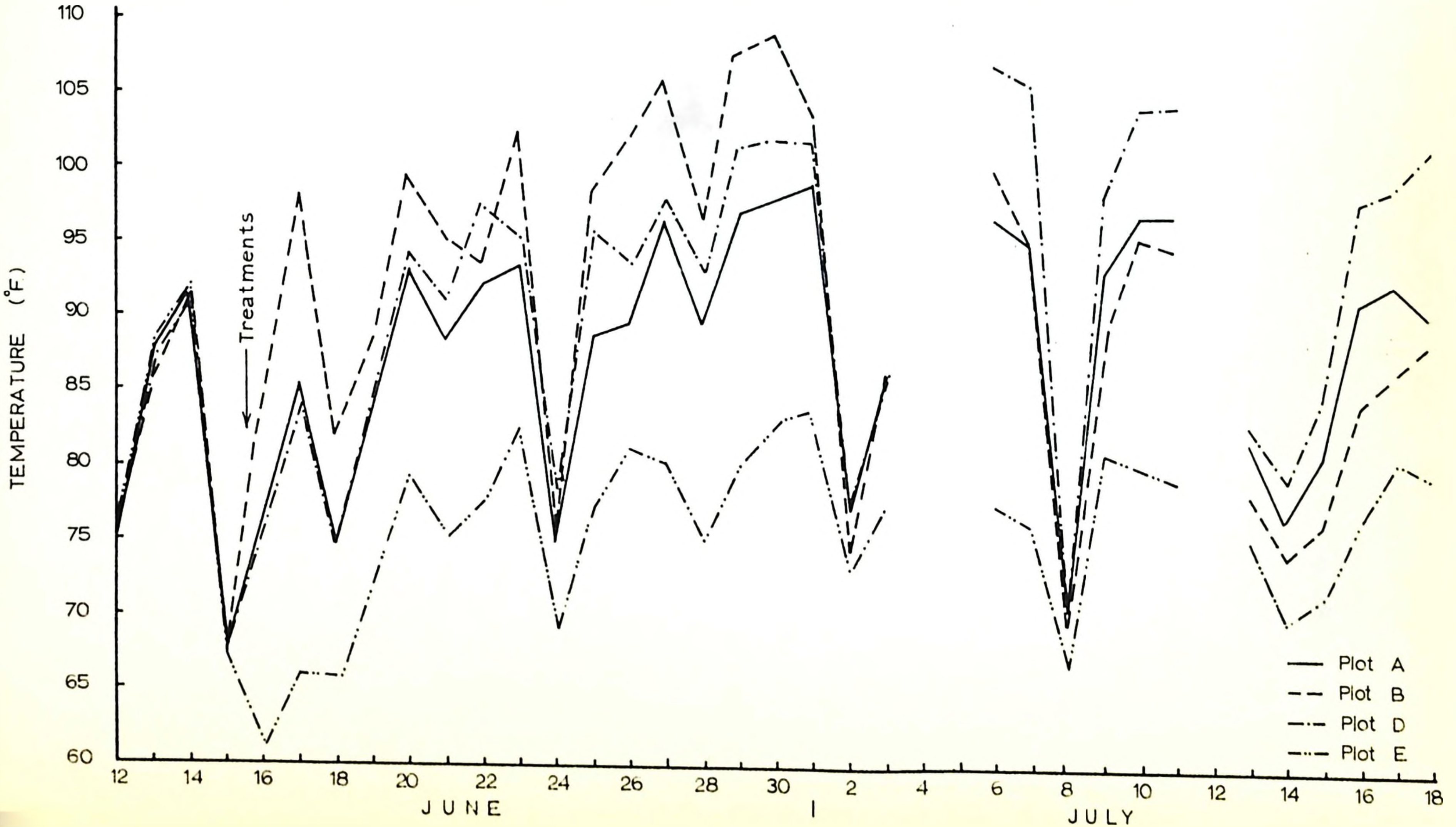
[7] R. K. DRAVID, <u>Op. cit</u>. 1940, p. 366.

FIG. 38 1cm. Daily Maxima (1400hours), in Plots A, B, D & E



(Black). Following this date B becomes cooler than D, and by July 9 cooler than control Plot A. As the crop continues to grow B cools successively, until by July 19 it begins to approach Plot E (Talc).

(iii) Plot D (Black) follows exactly the path of the 1 cm depth in A until June 20. After this date D diverges and remains constantly warmer than A.

(iv) The effect of the white Talc treatment on Plot E is immediate. The 1 cm depth in this plot remains 10-15° F cooler than Plot A throughout the experimental period.

(v) When over-all temperatures drop as on June 24, July 2 and 8, the differences between plots becomes much reduced; the range between the 1 cm readings in all plots diminishes. This is because due to the rainy and cloudy conditions associated with these periods, albedo differences have a much reduced effect because total absorption is drastically reduced.

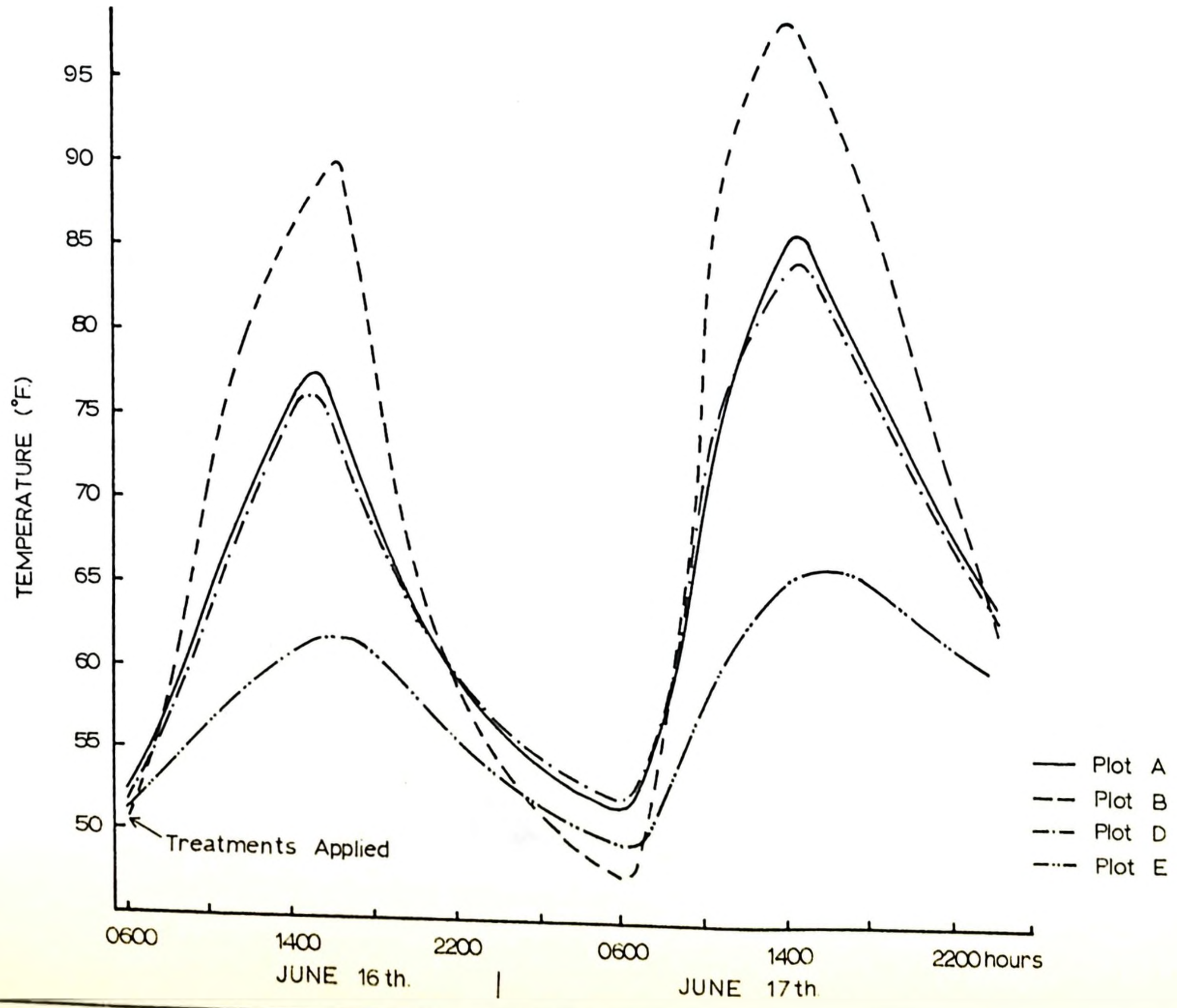
(d) <u>Speed of treatment effects</u>

Immediately following the application of surface treatments on June 16, observations were made at fairly close intervals for the next two days (Fig. 39). The object was to observe the speed with which each treatment effects became recognizable.

As can be seen, the temperatures at 1 cm depth in all plots started together at 0600 hours on the 16th. Thereafter the following effects are felt:

(i) <u>Plot B</u> - the effect of removing the grass sod cover is immediate. The range becomes more extreme, due to both a higher maximum and lower minimum temperature, than that in Plot A.

FIG. 39 Speed of Treatment Effects



(ii) Plot D - follows the path of the control throughout the first two days. The effect of applying a layer of Carbon Black is not therefore to immediately cause a rise in temperature at the 1 cm level. Rather, as has been shown, the warming is a more gradual, protracted process, over a period of at least a week from the time of application.

(iii) Plot E - as has been constantly stated, the effect of a white Talc treatment is immediately felt. Indeed, as Fig. 39 shows, at 1400 hours on June 16, (only 8 hours after the Talc was applied) the 1 cm depth in Plot E is 15.25° F cooler than the corresponding depth in control Plot A! At the same time on the 17th the cooling is of the order 19.55° F.

B. Soil Moisture

In the introduction to this chapter it was pointed out that all the four controlling factors (radiation, conduction, convection, evaporation and condensation) were closely linked and that a change in one causes adjustments in the others. In the experiments concerning modification of soil temperatures by changing the surface colour it has been shown that the radiation input factor is upset.

Ramdas[8] showed that, in particular by increasing or reducing the absorption of thermal radiation, the evaporation factor was considerably affected:

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[8] L. A. RAMDAS, "Natural and artificial modification of microclimate", *Weather*, Vol. 12, 1957, p. 237-40.

TABLE 16. Mean daily evaporation (inches), at Poona, India under varying colours

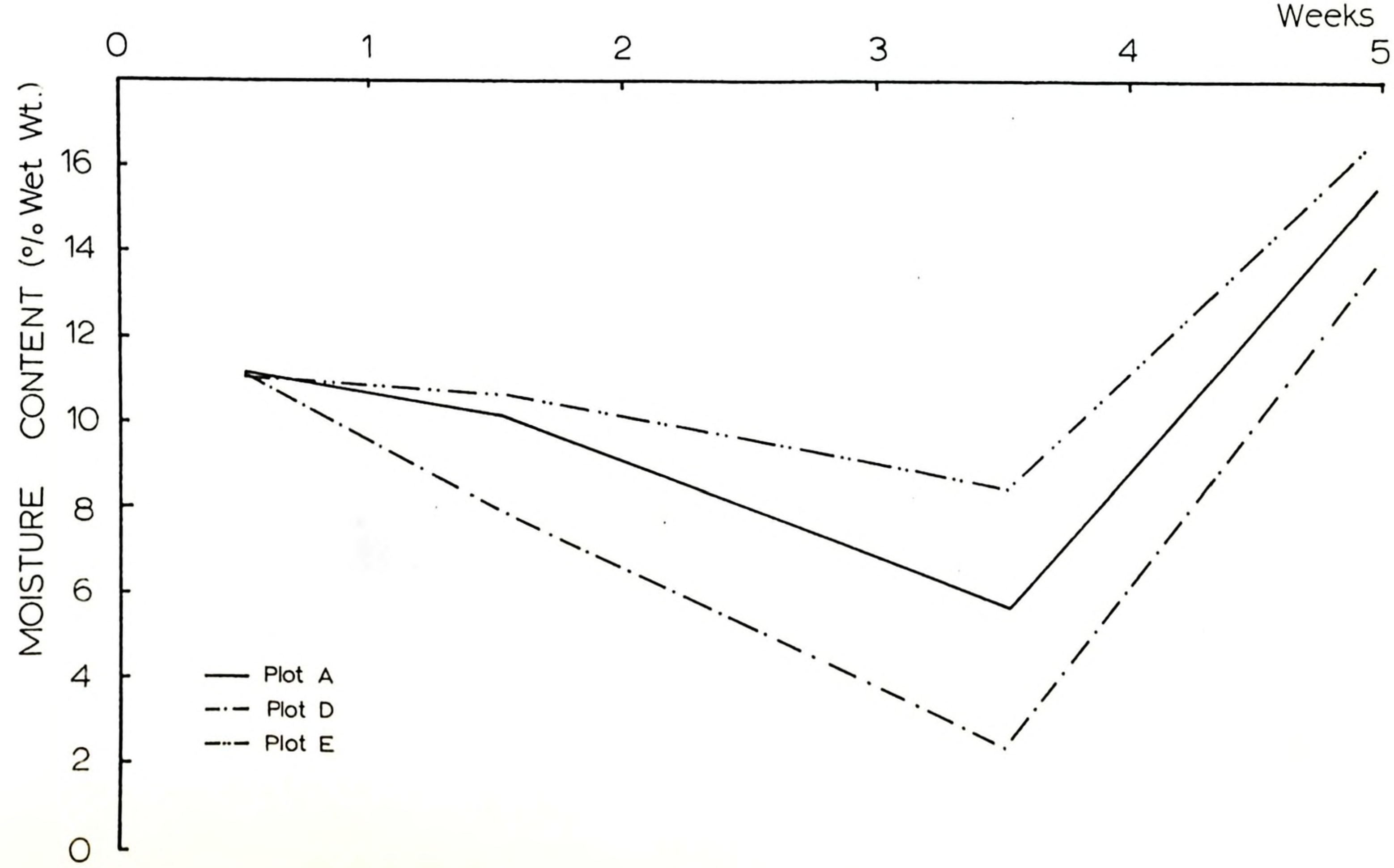
Poona soil untreated	Chalk treated	Charcoal treated
0.56	0.29	0.60

This shows the remarkable reduction in evaporation from a white-covered plot due to its lower temperature consequent upon reduced absorption of insolation. The charcoal plot shows a lesser difference because the Poona control plot is already a very dark colour.

In the experiments upon which this dissertation is based, the soil moisture content of a layer immediately beneath the surface was observed, using a "Speedy" soil moisture tester. The results are shown in Fig. 40. The number of observations is rather sparse, but definite general conclusions may be drawn.

The absolute values of soil moisture do not concern us here, as only the differences between plots is important. All plots (A - Control, D - Black, and E - White) begin together at the start of the experiments. Immediately after this point Plots D and E diverge either side of control Plot A. Plot D, covered with Carbon Black, always shows a lower moisture content in its upper layers than either of the other two plots. This may be attributed directly to the increased heat absorption of this plot encouraging evaporation, and therefore moisture losses. Conversely Plot E, covered with white Talc, always has a higher moisture content due to its reduced heat intake and therefore reduced evaporation losses. Thus, in this area, where there is a definite summer moisture deficit (Chapter 3), the application of

FIG. 40 SOIL MOISTURE



materials with a high albedo, such as horticultural lime, would definitely reduce the need for irrigation.

C. <u>Diurnal Wave</u>

Just as in the winter experiments a number of diurnal runs were made during the summer programme. One such diurnal pattern has been selected here as representative of the results obtained, and is presented in a similar manner to those of the winter programme (Chapter 5).

<u>July 16, 1964</u>

On both July 15 and 16 a high pressure system dominated the weather situation of the whole Eastern seaboard of North America. Associated with this ridge were the normal clockwise air movements of such an anticyclone, introducing warm, humid southerly air to the Hamilton area. Skies remained clear throughout the observation period except for a heat-haze which developed late in the afternoon of the 16th. Winds were typically light or calm. Under clear skies temperatures fell during the night of the 15th/16th to a low of about 60° F, and rose the next day to a high in the mid 80's.

<u>Experiments</u>

(a) <u>Plot A (Control)</u>

Soil temperatures for Plot A in the period from 2400 hours on July 15, until 2300 hours on the 16th, are shown in Figs. 41, 42, and 43. The analysis of this data is mainly confined to Fig. 41 which clearly shows all the main features.

The course of temperatures for Plot A shown in Fig. 41 represents an outstanding example of the summer diurnal soil temperature wave at various depths close to the surface. All the major features are well represented including:

1. <u>Sine curve</u> - the soil surface temperature is subject to rapid, irregular changes during the course of a day, but its normal regime approaches a sine curve, similar to that of the incoming radiation.

2. <u>Surface maximum and minimum temperatures</u> - the times of maximum and minimum temperatures at the surface do not, however, coincide with the corresponding points on the insolation curve, as might be expected. Rather the times of maximum and minimum occur when the incoming insolation and outgoing terrestrial radiation reach a balance, as described by Brunt[9] and by Trewartha[10]. These times are not then noon and midnight, but rather just after sunrise (at about 0630 hours), and around 1500 hours in the afternoon. On July 16 the 1 cm level reaches its minimum at 0600 hours, 1 hour after dawn; similarly the maximum is achieved at 1430 hours, 2½ hours after the sun was at its zenith.

3. <u>Heating and cooling</u> - it follows from the above that the daily wave of temperature in the ground is not a symmetrical sine curve. In the upper layers of the soil the day is divided into unequal periods of heating and cooling, because the time between the

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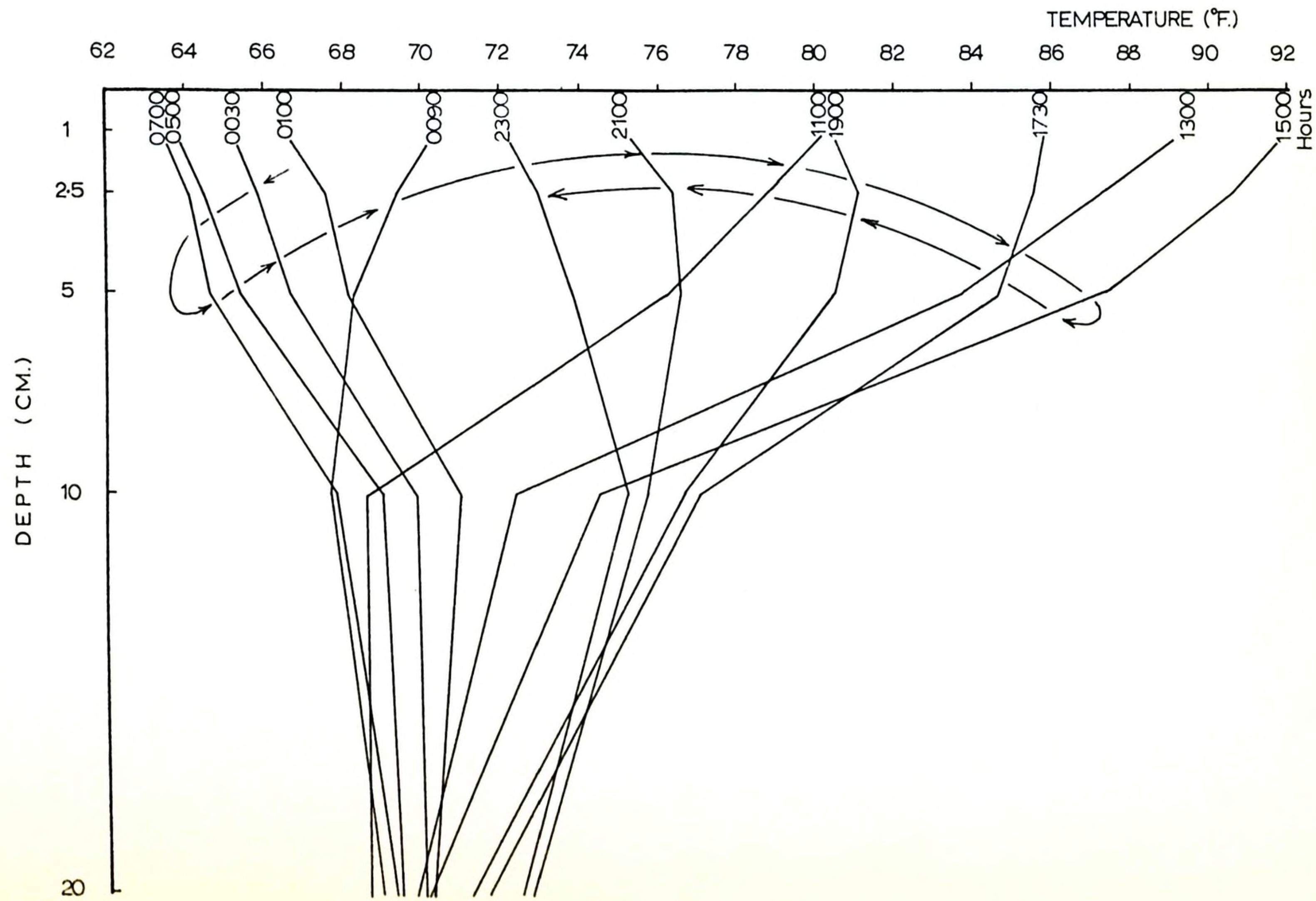
[9] BRUNT, <u>Op. cit</u>. 1956, p. 33.

[10] G. T. TREWARTHA, <u>Op. cit</u>. 1954, p. 26-27.

FIG. 43 Tautochrones for July 16th - Plot A



minimum and the maximum is shorter than the period between the maximum and the succeeding minimum. From Fig. 41 it is seen that the ground, at the 1 cm depth, is being heated for 8½ hours and cooled for 15½ hours. The disparity between the two periods diminishes with depth, for as Taylor[11] showed, and as has been verified here (Fig. 44), the lag in the maximum is much greater than the lag in the minimum. Thus on July 16 the disparity at the 20 cm depth is reduced by nearly one half of that at the 1 cm depth:

TABLE 17. Reduction of disparity between heating and cooling periods with depths

Depth (cm)	Ground heated (hours)	Cooled	Disparity
1	8½	15½	7
10	9	15	6
20	10	14	4

Thus, as greater depths are reached, the wave approaches closer and closer to the perfect sine curve.

4. Wave amplitude - two features of the wave amplitude become immediately obvious in Fig. 41:

(a) The wave amplitude is very great compared with the corresponding waves observed in the winter (Fig. 28). The increased range is attributed to the strong insolation of the summer, providing a 29.05° F difference between the maximum and minimum temperatures at

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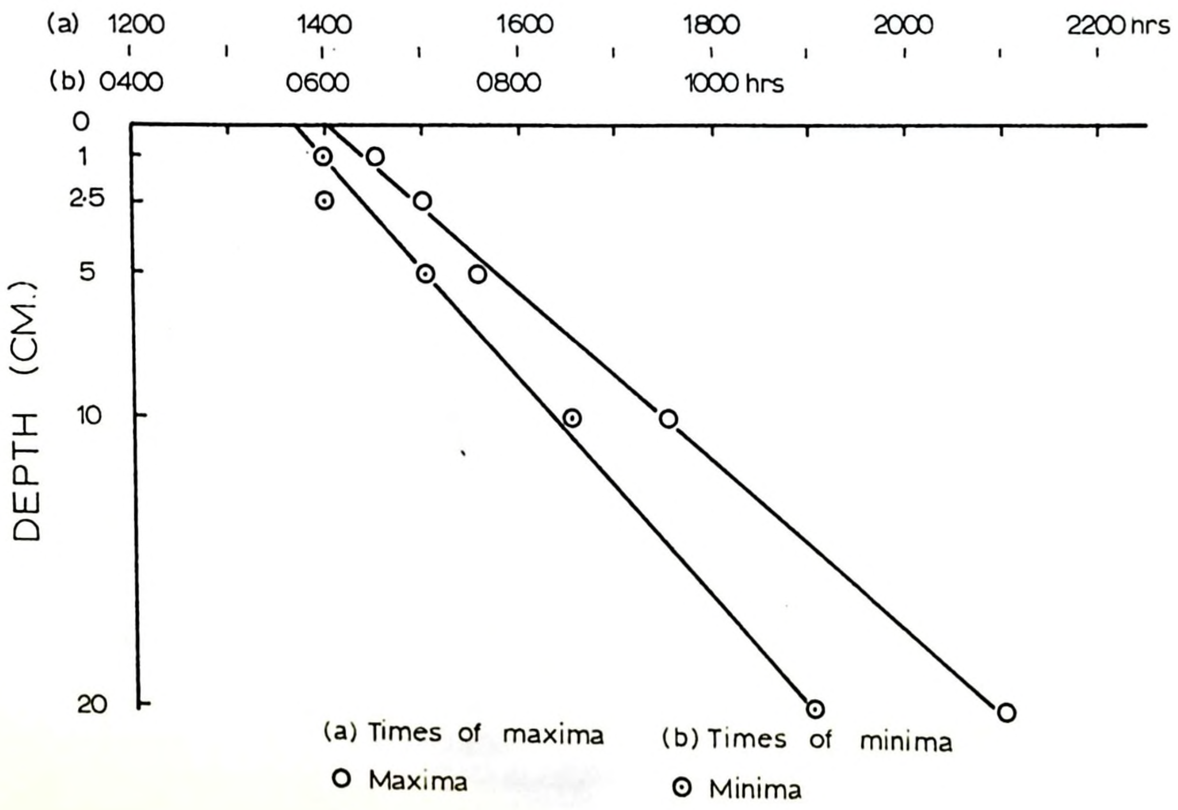
[11] McKENZIE TAYLOR, Op. cit. Vol. 18, p. 105.

FIG. 44 Times of Maxima and Minima



July 16th, Plot A

the 1 cm depth.

(b) The diminution of the wave amplitude with depth has been a constantly recurring feature of soil temperature waves on all scales, but nowhere can this phenomenon be better seen than in Fig. 41, and Fig. 43 for July 16.

TABLE 18. Diminution of wave amplitude with depth, July 16

Depth (cm)	1	2.5	5	10	20	50
Range (^{o} F)	29.05	26.75	22.95	9.3	7.5	1.4

The wave pattern at 20 cm is seen to be only a small image of that at the 1 cm level. It is also interesting to note that the air temperature wave is less responsive to insolation than all soil layers down to 5 cm.

5. Turnover - this period is again the transition between the night and day flows of heat. Because the morning curve is characterized by a sharp up-turn in the curves the period of turnover is a short one; in the evening under the slow cooling process this feature is of longer duration.

6. Lag of maximum and minimum temperatures with depth - the lag in time at which successive depths experience their extreme temperatures is well shown on Fig. 42 by the trend of the isotherms to the right. Similarly in Fig. 41 the peaks and troughs of the curves are offset at each depth. Fig. 44 presents graphically these results from Plot A. Both the times of the maxima and minima lie on straight lines, indicating constant rates of penetration. An almost identical

relationship was obtained during the winter (Fig. 30). The angle which the line of minima makes with the horizontal will vary with the diffusivity of the soil, and so no detailed comparisons should be drawn. However, it is interesting to note, as has already been pointed out, that the lag of the maxima is greater than the lag of minima (Fig. 44), as indicated by McKenzie Taylor[12] in Egypt.

(b) Plot D (Carbon Black covered)

The most striking feature of the temperature wave in Plot D (Fig. 45) is its increased amplitude over that of control Plot A. This increased diurnal range is due to two factors:

(i) Lower minima - but only by values which decline from approximately 2° F at the 1 cm level. Otherwise the minima are similar to those of Plot A, as was shown previously by the weekly averages at 0600 hours.

(ii) Higher maximum - this is the really outstanding feature of Plot D. The black treatment has raised the temperature at the 1 cm level in Plot D about 11° F higher than that at the corresponding level in Plot A.

Thus as was shown in the weekly averages the night-time cooling is similar in the two plots, but by day the effect of albedo differences causes extreme contrasts around the time of maximum insolation. The patterns of wave lag and diminution with depth are the same as those in Plot A; only the amplitude is increased. The treatment serves to raise maximum temperatures at the 1, 2.5, 5, 10 and 20 cm

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[12] McKENZIE TAYLOR, Op. cit. Vol. 18, p. 105.

This table shows the ranges in each plot, and a comparison of each of the two test plots with control Plot A. The table provides a fitting summary because it emerges from the foregoing that the temperature pattern in all plots is the same: only the differences in diurnal range, or wave amplitude pinpoint the treatment influences.

It emerges from Table 19 that Plot D is subject to an extreme range of 41° F during the day, caused mainly by a scorching high of 102.9° F at the 1 cm depth. At all depths down the profile to at least 20 cm this plot has a larger range than the control; in short a poor climate for plant growth. Conversely Plot E shows much reduced temperature ranges over-all, associated with a greater stability than either of the other two plots. The 1 cm amplitude of 12.0° F is amazingly small when compared with the air temperature range during the same period of 23° F. The soil at such a depth usually has a greater daily range than the air, being more responsive to insolation.

The foregoing results attest to considerable modification of sub-surface temperatures, by colouring the surface. However, not much work has been completed to date involving the lowering of soil temperatures by applying a white powder or irrigating the surface. Ramdas[13] and Dravid[14] appear to have been the only workers in this field. On the other hand the treatment with black was noticed long

[13] L. A. RAMDAS, Op. cit. 1957, p. 237-240, and "Soil temperatures in relation to other factors controlling the disposal of solar radiation at the Earth's surface", Proceedings National Institute of Science, India, Vol. 2, (No. 3) 1936, p. 131-43.

[14] R. K. DRAVID, Op. cit. 1940, p. 352-87.

ago to produce a warming. Wollny's[15] experiments showed beyond doubt this effect, and more recently Ramdas and Dravid[16] have verified this in the field. Everson and Weaver[17] also produced a warming, and Brooks[18] reports an advance in cotton ripening in Russia due to the application of coal dust. More recently still the International Ice Patrol have found carbon black more effective than explosives in destroying dangerous ice-bergs[19]. Many more practical applications await experiment, and herein lies a rewarding field of research.

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15 E. WOLLNY, Op. cit. 1878, p. 43-72.

16 L. A. RAMDAS and R. K. DRAVID, "Soil temperatures", Current Science (India), Vol. 3, No. 6, p. 266-7.

17 J. N. EVERSON and J. B. WEAVER, Op. cit. 1949, p. 1798-1801.

18 F. A. BROOKS, "Storage of solar energy in the ground", in Solar Energy Research by F. Daniels and J. A. Duffie, University of Wisconsin Press, 1955, p. 245-6.

19 W. H. Van ALLEN, "International Ice Patrol", Canadian Geographical Journal Vol. 62, No. 3, 1961, p. 87.

CHAPTER 7

SUMMARY OF CONCLUSIONS

Conclusions and the detailed data from which they were drawn are all included within the preceding body of the text. A brief summary of these conclusions is presented here, along with suggestions for further work along similar lines.

A. Results on the annual scale

All the familiar features of heat flow within the soil were observed, including the annual harmonic wave, the time lag for heat waves to penetrate to lower depths, diminution of wave amplitude with depth and the complex transition period between summer and winter conditions known as the "turnover".

1) Winter - conditions during the winter months showed a very marked stability associated with a snow cover and reduced isolation. The correlation, at this time of year, between soil temperatures and air temperatures was found to be low. The 32° F isotherm remained within the ground for nearly four months. This frost line reached a maximum depth of 50 cm and thawed from both above and below, finally disappearing at the 25 cm level. A plot of the 32° F isotherm and the air temperature deficiency below 32° F produced a mirror-image between the two. This relationship was better when the frost was penetrating than when the soil was thawing. It was calculated that a cover of

snow reduces the depth of frost penetration by an amount equal to its own depth. The annual minima at each depth were attained at the end of the winter period, and a graph of these values revealed an exponential relationship.

2) Spring - the spring overturn was found to occur in early April, with a "group-overturn" on April 6, the same date as that at the 75 cm level. The steadiness of the winter conditions was lost as soon as the snow left and soil temperatures ventured above the freezing point. The spring warming was hastened by rain during April.

3) Summer - immediately following the spring overturn there was a steep rise in soil temperatures, especially at depths within 100 cm of the surface. In contrast to the winter, extreme instability characterized the summer months, and a better correlation with macroclimatic air temperatures was noted.

4) Effect of snow cover - a cover of snow was observed to reduce temperature fluctuations within the soil and to reduce the depth of frost penetration.

5) Effect of rain - it was noticed that during the winter, rain contributed little to soil temperature changes, because it was unable to penetrate the frozen topsoil. However, during the spring rain did contribute considerably in helping to thaw the topmost soil layers once the surface had become unfrozen. During the summer period short intensive thunderstorm rains caused considerable cooling, and affected depths down to at least 100 cm.

In summary it is concluded that the soil under review is subject to large annual fluctuations in temperature (1 cm 28.75 - 99.0° F), and is readily responsive to macro-climatic changes. Dr. J. H. T. Wade[1] (Engineering Faculty, McMaster) has ascertained that the depth of zero annual range of soil temperature in this locality is 12 metres.* In this study the depth of zero diurnal range has been observed at approximately 75 cm which is in reasonable agreement with Sutton[2] who states that the depth of the annual wave is about 19 times greater than the diurnal wave.

B. Results on the diurnal scale

The general features of the diurnal wave were observed to be similar to those of the annual pattern but on much reduced scales of time and depth. The wave was of the sine form and the lag of maxima and minima at each depth down to 20 cm was found to follow a straight line relationship, indicating a constant rate of penetration. The lag of the maxima was noted to be greater than the lag of minima.

1) The form of the winter diurnal curve was largely governed by the presence or absence of a snow cover. If there was no snow cover the wave pattern was dominated by strong nocturnal cooling. If

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* Using similar thermocouple wire to that used in this investigation, and an automatic recorder, soil temperatures were taken down to a depth of 40 ft. on the campus, not far from this experimental site.

1 J. H. T. WADE, Personal Communication.

2 O. G. SUTTON, Op. cit. 1953, p. 194.

on the other hand, there was a snow cover the normal diurnal sine wave was partially or completely damped by the insulation provided. An investigation of the snow cover and its effects provided some interesting results: viz.

a) The snow surface absorbs little, but emits a considerable amount of long-wave radiation. The heat so lost is not easily replenished from below due to the poor conductivity of snow. The result is to produce an extremely cold snow surface, as much as 16.7° F below the macro-climatic air temperature.

b) The minima of both the snow surface and the air temperature are achieved at a similar time. The penetration lag of this minima was much reduced, again due to the very poor snow conductivity.

c) The insulation provided by a new cover of fresh snow was found to be much greater than that of an old layer of snow. The effect of a 4 ins. new cover was to provide complete insulation for the soil beneath.

2) The summer diurnal wave possessed a large amplitude and was divided into unequal heating and cooling periods. All the major features of such a pattern were well accentuated, including the lag of maxima and minima with depth.

C. Results of artificial modification experiments

1) Winter a) Straw mulch - this experiment proved in a quite outstanding manner the stability induced by the application of a poorly conducting layer of straw. Both over an extended period of 14 weeks, and on the diurnal scale, near perfect insulation was

provided equal to that of a fresh snow cover. The treatment was beneficial during the winter months for it maintained soil warmth, and reduced the depth of frost penetration by 41% of the depth in the untreated control plot. However, this stability delayed the time of spring turnover and kept the 32° F isotherm in the ground 21 days longer than in the control plot. The insulation proved so effective that most of the spring thawing was effected from below.

b) Snow cleared - due to mild conditions this treatment was not able to develop its expected effects fully. Being open to the atmosphere this plot warmed up and cooled down fastest, and during the night cooling was extreme. This cooling pushed the frost-line down 21% deeper than in the control and provided the best mirror-image of the temperature deficiency and frost-line.

2. Summer - it was noticed that treatment effects dependent upon albedo differences had their maximum influence at the time of maximum temperatures, and that at the minimum temperature epoch differences were very much reduced. This was because colour affects absorption but not radiation.

a) Crop of Oats - because the texture of the surface and not just the colour was changed in this plot, its climate was always different to other plots. When the grass sod was removed soil temperatures rose immediately, and demonstrated a large diurnal range. As the crop grew in height temperatures fell and ultimately became less than those in the control plot.

b) Carbon-Black - the effects of changing the surface colour to black took 9 days to become apparent. Gradually this plot became warmer than the control, due to increased absorption. After 5 weeks this plot was on average 6° F warmer at 1400 hours at the 1 cm level, representing an increase of 7% in soil warmth. The diurnal wave had an increased amplitude due to a higher maximum, but the turning points were not displaced in time. The increased warmth of this plot hastened the evaporation from its surface, and a corresponding reduction in soil moisture was observed.

c) Talc Powder - within a few hours of application this treatment became effective in reducing radiation absorption and so lowering soil temperatures in comparison to the control. Throughout the experimental period this plot remained on average 12° F cooler at 1400 hours at the 1 cm depth; a 14% reduction of soil warmth. Again the diurnal wave followed a similar course to the control with regard to phase, but the amplitude in this case was much reduced. The decreased absorption reduced evaporation losses and caused this plot to retain more soil moisture than the control.

D. Methods of Presentation

An evaluation of the methods used to present soil temperature was made, and represents an original contribution to the subject. A new method of representing the total energy budget of the soil was used utilizing the readings from all depths within the profile, and called the "Total Profile Average". The Time/Temperature method was deemed best to portray these averages, and proved very simple and illustrative. For presentation of monthly averages at each depth the Time/Temperature method again proved best but Tautochrones, and Isopleths could also be used to good effect. For the annual curve using daily readings both Time/Temperature and Isopleths appeared equally good, and complimentary. The diurnal wave was shown to best effect by the Time/Temperature graph. For showing the depth of the frost-line Isopleths were undoubtedly superior. Polar Co-ordinates proved poor, mainly due to the distortion provided by the radial time segments.

E. Method of Correction

Similarly a new method was designed to apply corrections to readings to make them comparable to the control plot. The method was based on temperature gradients, and used a correction for depth rather than plain temperature. Extremely satisfactory results were obtained.

F. Further Work

The most promising field for further work lies in the artificial modification of sub-surface temperature conditions. The winter straw mulch proved to be beneficial in maintaining soil warmth. However, it would be of considerable value to find out by experiment the exact times in the autumn and spring when the treatment should be applied to achieve maximum benefit. Similarly snow cover has been shown to reduce frost penetration and this would be of value to engineers and farmers alike. Further work is needed to ascertain the true freezing point of soils in the field, and a more exact prediction of frost depth under various snow covers. Permafrost studies are being hindered by an incomplete knowledge of the two above factors. Of considerable interest to micro-climatologists, and micro-meterologists would be more detailed studies of the conditions within, and immediately above a layer of snow. A correlation of snow density, thermal conductivity, and albedo with snow temperatures and powers of radiation would constitute a complex but most rewarding subject for research.

A treatment which colours the surface of the ground white or black has been shown to affect the temperature regime radically. If the black treatment was used during the spring, when soil warmth is critical for germination, it may well prove to be of value, rather than in the summer when conditions are already too hot. Probably the most important agricultural result of the white talc treatment was the definite conservation of soil moisture. This could prove to be a vital factor in areas where unpredictable droughts may hazard farming. A treatment which was not used in this study may also provide interesting practical results. The wetting of the ground by irrigation will have distinct influences on ground temperatures. In an area such as this, where irrigation is practised, experiments concerning its exact effects should prove valuable.

APPENDIX I

Calibrated Temperature/E.M.F. Values for 24 Gauge

B and S Copper: Constantan Thermo-couple

(a) Preliminary Calibration (September 29, 1963)

E.M.F. (millivolts)	Temperature ($^{\circ}$ F)
1.171	85.3
1.129	83.5
1.038	79.6
1.012	78.4
0.868	72.3
0.707	65.0

(b) Full Calibration (November 19, 1963)

E.M.F. (m/v)	Temp. ($^{\circ}$ F)	E.M.F. (m/v)	Temp. ($^{\circ}$ F)
1.493	99.4	0.456	53.8
1.450	97.7	0.401	51.0
1.380	94.6	0.291	46.0
1.323	92.1	0.230	43.0
1.270	89.9	0.176	40.6
1.222	87.7	0.139	38.7
1.209	87.2	0.054	34.2
1.173	85.6	0.000	32.0
1.000	77.8	-0.020	31.0
0.948	75.5	-0.046	29.5
0.903	73.9	-0.078	28.4
0.781	68.4	-0.211	21.9
0.599	60.1		

Appendix I cont'd

(c) Recalibration (September 2, 1964)

E.M.F. (millivolts)	Temperature (° F)
1.165	85.2
0.802	69.9
0.501	56.0
0.136	38.5

APPENDIX IIa

Site Characteristics

Position - 43° 16' N., 79° 55' W., McMaster University Campus, Hamilton, Ontario.

Elevation - 326 ft. above sea level.

Slope - horizontal, the gradient never being greater than 1 in 120.

Micro-relief - flat ground with short grass.

Drainage - good.

Parent material - glacio-fluvio-lacustrine stratified sediments of Lake Iroquois age.

Climate - temperature modified Continental.

Vegetation - short grass.

Land use - sports field.

Great Soil Group - grey-brown forest soils.

Summary

The site area is a flat grass covered field (Plate 2). The location ensures that there are no extraneous influences due to topographic position, or exposure to rain, wind or snow, or any other 'unnatural' features.

APPENDIX IIb

Depth (cm)	Clarity	Regularity	Moisture	Colour	Texture	Org. mat.	Stones	Structure	Consistency	Porosity	Roots	pH
0-2.5	Grass		Dry	Dark Brown	v. fine Sa. L	Discrete humus	None	None	Loose	fissured	Many, fine	
2.5-27.5	Clear	Irregular	"	Grey-brown	Fine Sa. L	Intimate humus	Slight	Sub-angular Blocky	Hard	fissured	Many	
27.5-40	Sharp	"	"	Light tan	Loam	Little	None	Weak	Compact	"	Fine	
40-75	Faint	"	Sl. moist	Reddish tan	Clay Loam	"	"	"	"	"	V. fine	
75-88.5	Clear	"	"	Reddish brown	Clay	None	"	Structureless	Hard	Nil	"	
88.5-100	"	v. irregular	v. sl. moist	Light tan Reddish brown	Variable sand clay	"	"	Variable granular colloidal	Compact	Slight	"	
100-c.104.5	Indefinite		"	Greyish	Coarse sand	"	"	Granular	Loose	Porous	"	
104.5-125	"		"	Red-brown Brown	Sand Clay	"	"	Variable	Compact	"	"	
125-130		Merging	"	Red Grey	Variable	"	"	"	"	V. Sl. Porous	v.v. fine	
130-142.5	Distinct	Wavy	"	Grey-brown	Coarse sand	"	"	Granular	Loose	Porous	"	
142.5-146.5				Red sand / Clay								
146.5-150				Clay/sand mixture								
150-156				V. coarse, loose sand								
156-161				Red sand over v. sticky, wet clay								
161-185				Coarse, loose sand. Clay band at 66½"								
185-193.5				Red clay/sand mixture over wet clay at base								
193.5-203.5				Dryer sandy clay over clay/sand mixture								
203.5- 240				Coarse, grey, loose, sand								

APPENDIX III

Monthly averages of daily maxima (1400 hours), and

Total Profile Averages, of depths in control Plot A.

Monthly depth averages

Depth	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.
1	31.85	31.60	30.35	37.95	54.95	76.15	84.70	89.80	77.40
2.5	32.00	31.65	30.30	36.80	54.05	74.90	83.00	88.55	76.65
5	32.15	31.65	29.20	35.85	52.15	71.65	79.65	86.45	75.55
10	33.70	32.15	30.65	32.60	44.70	61.50	69.25	76.30	69.15
15	34.25	32.40	31.00	32.35	43.25	59.50	67.30	74.65	83.35
20	35.20	32.80	31.55	32.15	41.90	58.05	65.60	72.95	67.90
25	35.50	32.95	31.75	32.15	41.65	57.65	65.30	72.55	67.85
30	36.25	33.35	32.15	32.45	41.25	57.00	64.70	72.20	68.10
40	37.45	33.95	32.65	32.65	40.80	56.15	64.10	71.45	68.20
50	38.25	34.50	33.15	32.95	40.55	55.60	63.30	70.65	68.10
75	40.50	35.75	34.00	33.65	39.55	53.50	61.55	68.95	67.85
100	42.90	37.35	35.25	34.45	38.85	51.35	59.50	66.65	66.95
150	48.00	41.40	38.40	36.80	38.35	47.20	55.05	61.40	64.45
225	51.30	45.30	41.75	39.80	39.70	44.85	51.55	56.95	60.95

Total Profile Averages

37.90	34.75	33.00	34.45	43.70	58.95	66.75	75.55	69.10

Graphs of these results are shown in Figs. 8, 9, 10, 11, 12 and 13.

APPENDIX IV

Corrected values and preferred depths in B, D and E.

Depth (cm)	May 8	10	12	18	19	29	30	June 1	2	3	4	5	8	11	12	13	14	16	"Real" Depth
PLOT B																			
1	2.5	3	4	4.5	4	3	4.5	4.5	3	3	4.5	3.5	3.5	3.5	3.5	5	5	3	3.5
2.5	5	4.5	5.5	5.5	7	5.5	6	7	6	5.5	6	5.5	5.5	5	7	5.5	6	5.5	5.5
5	6	6	6.5	6.5	7.5	6.5	7	7.5	7	6	6.5	6	6	5.5	6.5	6	6	6	6.5
10	7	7	7.5	7.5	9	8	8	9	8	7.5	7	6.5	8	6.5	7.5	6.5	7	6.5	7.5
20	12.5	11.5	11	13.5	11.5		11	12.5	12		13	12.5	11	12	11	13	12.5	10	12
50	44.5	34	49.5	56	50	60		66	49	52	60	62	61	55	48	48	46.5	48.5	52
100	100	100	100	96	103	102	102	106		106	108	106	112	107	104	107	103	102	104
150	133	141		142	148	139	139	143	140	140	148	140	138	143	140	140	140	139	141
225			246	246	243	243	239	236	235	244	244	246	246	244	244	245	243	245	243
PLOT D																			
1	3.5	3.5	3	3.5	3		4.5	3	3	2.5	4.5	2	2	3	2.5	3.5	4	2.5	3
2.5	4	4	4	4.5	4.5		5	4.5	4.5	4.5	5.5	4.5	4	3.5	3	4.5	5	3.5	4
5	6	6	7	7.5	8		7.5	8	7.5	5.5	7	6	7	6	7.5	6	7	6.5	7
10	8	8	7.5	8.5	9.5		9	9.5	8.5	9	8.5	7.5	8	7.5	9	7.5	8.5	7	8
20	16.5	13	18	17	18		14	19	16.5		19	19	19	17	14	17	17	14	17
50	43	34.5	42.5	44.5	40		38	45		52	42	56	47	42.5	48	47	44	45.5	45
100	100	95.5	100	95	103		103	101	106	102	101	101	101	101	102	103	101	102	101
150	138	147	131	144	144		146	143	145	146	147	142	142	145	142.5	146	140	143	143
225			226	225	230		233	226	224	228	227	233	227	226	231	320	229	232	228

APPENDIX IV Continued

Depth (cm)	May 8	10	12	18	19	29	30	June 1	2	3	4	5	8	11	12	13	14	16	"Real" Depth
PLOT E																			
1		2	0.5		0.5		2	1		1.5	2.5		0.5	0.5	0.5				0.5
2.5	3	3	4.5	2	3		3	3	3	3.5	4	4	3.5	3	1.5	2.5	3		3
5	4.5	5.5	6	5	6		5.5	6.5	6	5.5	6	5.5	5.5	4.5	5	5	5.5	5.5	5.5
10	8.5	7.5	8.5	9	9		9	9.5	8.5	8.5	7.5	7.5	8	7	8.5	7	7.5	7.5	8
20	11.5	18	16	17	16		13	15	15		16.5	15.5	13	14	11	14.5	14	14	14.5
50	27.5	42.5	46.5	44	49		36	45		39	42	46	40	34	36	34	34	32	39
100	96	100	98.5	102	102		102	97	105	98	103	102	103	103	102	102	99	103	101
150	136	142	144	139	140		140	140	141	140	142	139	138	140	140	140	135	138	140
225	226	225	232	232	232		230	228	225	231	231	238	234	236	231	232	228	233	231

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