Snow Cover and Winter Soil Temperatures at St. Paul, Minnesota

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FOREWORD

This Bulletin is published in furtherance of the purpose of the Water Resources Research Act of 1964. The purpose of the Act is to stimulate, sponsor, provide for, and supplement present programs for the conduct of research, investigations, experiments, and the training of scientists in the field of water and resources which affect water. The Act is promoting a more adequate national program of water resources research by furnishing financial assistance to non-federal research.

The Act provides for establishment of Water Resources Research Institutes or Centers at Universities throughout the Nation. On September 1, 1964, a Water Resources Research Center was established in the Graduate School as an interdisciplinary component of the University of Minnesota. The Center has the responsibility for unifying and stimulating University water resources research through the administration of funds covered in the Act and made available by other sources; coordinating University research with water resources programs of local, State and Federal agencies and private organizations throughout the State; and assisting in training additional scientists for work in the field of water resources through research.

This Bulletin is number 37 in a series of publications designed to present information bearing on water resources research in Minnesota and the results of some of the research sponsored by the Center. The study described was concerned with winter soil temperatures under a sod cover at St. Paul. The configuration of the soil isotherm patterns, in particular that of OC, and which soil thermal characteristics can be estimated by snow cover were determined.

This Bulletin serves as the Research Project Technical Completion Report for the following Center project:

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Project Title: Vertical Migration of Moisture in the Soil Induced by Winter Thermal Gradients and Its Influence Upon Spring Water Resources

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Publication Abstract:

The objectives of this study of winter soil temperatures under a sod cover were to show the configuration of the soil isotherm patterns, in particular that of OC, and to determine which soil thermal characteristics can be estimated by the snow cover. The temperature data were obtained at the University of Minnesota Agricultural Experiment Station plots on the St. Paul Campus with copper-constantan thermocouples during the winters of 1961-62 through 1968-69. Based upon the depth and persistence of

the snow cover there were in effect 3 kinds of winters: one with deep and persistent snow cover, one with very little snow cover and all other winters. There was a close relationship between the kinds of winters and the maximum depth to which the OC isotherm penetrated, and a fair relationship to the rate of movement of the OC isotherm into the soil. The combination of type of winter (snow depth and duration) with cumulative heating degree days proved to be a simple and effective means of predicting the maximum freezing depth.

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Publication Descriptors: / *soil temperature/ *snow cover/ *isotherms/ Minnesota/ soil moisture/ soil/ vegetation/ thermocouples/ frost/ winter

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INTRODUCTION

If the cover and physical state of the soil remain constant, soil temperature and soil freezing rate and depth are functions of 3 factors: The soil water content, the radiation regime to which the soils are exposed, and, more particularly, the snow cover. The variability of these 3 factors is such that an equation for the accurate prediction of winter soil temperatures has been a most difficult task. Anderson (1) developed a formula for determining the frost (OC isotherm) depth which does take into account the presence of a snow cover. Unfortunately the application and success of this formula remains questionable due to the 7 variables required for the solution. The numerical values of these variables are either not readily available or are unknown quantities until the site has been fully instrumented. For that reason it has been necessary to depend upon a knowledge of the average and the range of winter conditions that may be expected if a reasonable estimate of the winter soil thermal conditions is to be made.

The objectives of this study were twofold. The first objective was to show the patterns that may be expected within the soil of the isotherms and especially that of the OC isotherm. The second was to determine which winter soil thermal characteristics can be estimated on the basis of the snow cover.

METHODS AND MATERIALS

The temperature data were obtained at the University of Minnesota Agricultural Experiment Station plots on the St. Paul Campus with copper-constantan thermocouples. The output of the thermocouples was automatically recorded on a Brown Instrument 32 point strip-chart recorder. Thermocouples at depths of 1, 5, 10, 20, 40 and 80 cm were placed in soil covered

with bluegrass sod in September 1960 using a technique (4) which causes a minimum disturbance of the soil. In May, 1961, additional thermocouples were installed under the sod at 120, 160 and 320 cm. Even deeper thermocouples were added in July, 1962, and in July, 1967, thermocouples at 50, 60 and 100 cm were placed under the plot. Data used in this study are from the 1700 hour CST observation.

Soil water measurements were not taken until the winter of 1965-66. Snow depth measurements were taken daily, but snow density was not determined. Additional meteorlogical measurements were taken at the weather station adjacent to the plot.

The bluegrass on the sod plot, which slopes less than 1% to the south, was mowed whenever it reached 10-15 cm height, and this was, therefore, the maximum over-winter height of the grass.

The soil was Waukegan silt loam which is a loessial soil developed under prairie vegetation. The loess extends to a depth of only 70-80 cm with underlying sand and gravel outwash extending to depths greater than 30 m. The water table is greater than 15 m deep.

Soil does not necessarily freeze at OC and may freeze at appreciably lower temperatures if salt concentration is high or water content very low. However, it was our experience that Waukegan silt loam soil froze so close to OC that any variation from it was not detected. Evidence for this was the behavior of the OC isotherm as it progressed through the soil with a phase change induced lag in the temperature when either freezing or thawing occurred. The freezing isotherm and OC isotherm were therefore considered identical in this study.

With respect to the 3 factors influential in winter soil temperatures only secondary consideration need be given to soil moisture and the external environment if a snow cover is present. Figure 1 (A-H) shows that the

external environment based upon cumulative heating degree days is an inadequate basis for prediction of the freezing rate and depth in the soil. Only in the winter of 1964-65, and perhaps in 1963-64, did the cumulative heating degree days prove to be a reasonable prediction of the maximum penetration of the OC isotherm. The over-whelming influence of snow reduced the effect of the external environment. The insulating value of snow may be judged from some measurements obtained during each of the 8 winters, Table 1.

According to the precipitation records, which have to be depended upon for the first 4 years, and the soil water measurements taken the last 4 years, there were only 3 winters in which the influence of the soil moisture content needs to be considered. They were 1963-64 and 1967-68 when only an estimated 20-25 cm of water and a measured 24 cm, respectively, were in the first 152 cm of soil, and the winter of 1968-69 when a high of 46 cm of water was measured. The variation in water content in the other winters was either estimated or measured to be within these limits. The influence of soil moisture on the soil temperature regime was negligible compared to that of snow cover. It is interesting in this regard that Krumbach (2) found that the water content of soil could not be statistically correlated with frost depth.

Because snow cover remained as the probable major factor determining the winter thermal regime of soils, the 8 winters (1961-62 through 1968-69) considered in this study were categorized into 4 kinds based upon snow cover characteristics. They were (I) deep and persistent snow cover, (II) deep but non-persistent snow cover with an ice layer, (III) an "Average" snow cover and (IV) a light and non-persistent snow cover. In local terminology category IV is an "open" winter.

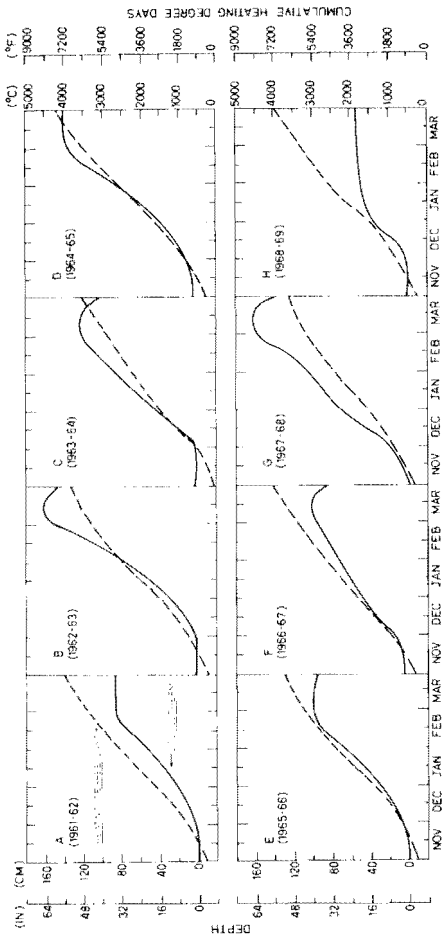

Figure 1 (A-H). Comparison between the depth of the OC isotherm (solid line) and cumulative heating degree days (dashed line; base temperature is 18.3 C or 65 F) for the 8 winters of 1961-62 through 1968-69.

Table 1. Selected examples of temperature differentials found between the snow surface and at 1 cm depth in the soil under sod cover.

Date	Soil Temperature at 1 cm under sod cover	Air Temperature immediately above snow surface	Depth of Snow	Temperature gradient*
Feb. 17, 1962	-3.0°C	-31.7°C	10.2 cm	2.56° C/cm
Jan. 23, 1963	-7.9	-31.2	3.8	4.85
Jan. 13, 1964	-11.7	-25.0	5.1	2.18
Jan. 14, 1965	-5.3	-31.9	14.0	1.77
Jan. 29, 1966	-7.3	-34.5	15.2	1.68
Dec. 11, 1966	-2.1	-26.1	7.6	2.79
Dec. 31, 1967	-11.1	-31.8	2.5	5.91
Jan. 1, 1969	-1.2	-29.3	25.4	1.71

* The temperature gradient was calculated for the indicated snow depth plus the 1 cm depth under the sod covered soil.

The depth portion of these categories is based upon an arbitrarily established departure of the mean daily snow depth for December-March from a long-term mean. A departure that exceeded the long-term mean daily snow depth by 50% defined a deep snow cover winter (Category I), and a departure that was more than 50% lower than the long-term mean resulted in an "open" winter (IV). An "average" winter (III) was one in which the mean daily snow depth departed no more than $\pm$ 50% from the long-term mean. Category II is the same as I except for a brief period of melting or of rain sufficient to produce an ice layer on the soil surface.

At Minneapolis - St. Paul the long-term mean daily snow depth for December-March is 10.9 cm, Table 2. Therefore, a Category I winter according to our definition is one in which the mean daily snow depth exceeds 16.4 cm. An "open" winter (IV) in the mean has less than 5.5 cm of snow on the ground, and an "average" winter (III) ranges between 5.5 - 16.4. The 2 "average" winters at our station, Table 2, barely fell within this category with a mean daily snow depth of only 5.6 cm.

Table 2. Mean daily snow depths in cm for the 4 winter categories and the long-term mean.[1]

Months	Type of Winter I 1961-62 and 1968-69	II 1964-65 and 1966-67	III 1963-64 and 1965-66	IV 1962-63 and 1967-68	Long-term Mean[2] 1947-48 through 1968-69
November	0.0	2.1	0.6	0.6	1.7
December	16.7	10.7	9.9	1.8	7.5
January	29.3	20.9	7.4	5.6	12.5
February	34.5	25.6	2.7	3.0	14.5
March	17.6	18.7	2.3	4.2	9.3
April	0.0	0.0	0.0	0.0	T[3]
Total (Dec-Mar)	98.1	75.9	22.3	14.6	43.8
Mean (Dec-Mar)	24.5	19.0	5.6	3.7	10.9

[1]Based upon snow depth values on the 10th, 20th and 30th (or last in case of February) day of each month.

[2]Data from the Minneapolis-St. Paul Weather Bureau airport station (5).

[3]T signifies trace.

Persistence of the snow cover is of obvious importance. In Table 3 are shown the mean number of days with a snow cover for the 4 categories and the long-term period. For December-March more than 90% of the days had snow cover in the type I and II winters. The "average" winters (III) had snow cover on 60.7% of the days compared to the long-term mean of 67.6%. The "open" winters of 1962-63 and 1967-68 with 59.9% had nearly as many days as the so called "average" winters.

The criterion for a persistent snow cover winter (I) was arbitrarily set for the December-March period at a duration greater than the long-term plus 20%, "open" winter (IV) was set at a duration less than the long-term mean minus 10% and the snow cover which falls between these values defined an "average" winter (III). It is to be noted that the

Table 3. Mean duration of snow cover in percent of possible days for the 4 winter categories and the long-term mean.

Month	Type of Winter I 1961-62 and 1968-69	II 1964-65 and 1966-67	III 1963-64 and 1965-66	IV 1962-63 and 1967-68	Long-term Mean[1] 1947-48 through 1968-69
November	0.0	50.0	13.3	11.7	25.7
December	83.3	83.3	60.0	53.3	65.1
January	100.0	100.0	96.7	96.7	78.8
February	100.0	100.0	50.0	80.0	75.7
March	100.0	83.3	35.0	11.7	51.5
April	0.0	0.0	6.7	3.3	1.5
Mean (Dec-Mar)	95.7	91.4	60.7	59.9	67.6

[1]Data from the Minneapolis - St. Paul Weather Bureau airport station (5).

"average" winters of 1963-64 and 1965-66 were marginal with respect to this empirical criterion.

It is believed that the 8 winters experienced, particularly the extremes I (1961-62 and 1968-69) and IV (1962-63 and 1967-68), represent a range of conditions that ordinarily would be expected only in about 5 years out of a 100 year period (3). It was our good fortune to have been able to measure such a broad range of conditions in such a brief period.

RESULTS AND DISCUSSION

The soil isotherm pattern under the sod covered plot and the associated snow cover for the winters of 1961-62 through 1968-69 are shown in Figure 2 (A-H). The mean long-term (1947-48 through 1968-69) snow depth at the Minneapolis - St. Paul Weather Bureau airport station is also shown in Figure 2 (A-H) for comparison with each of the 8 years considered. The reader should be aware of the deceiving picture presented. The long-term

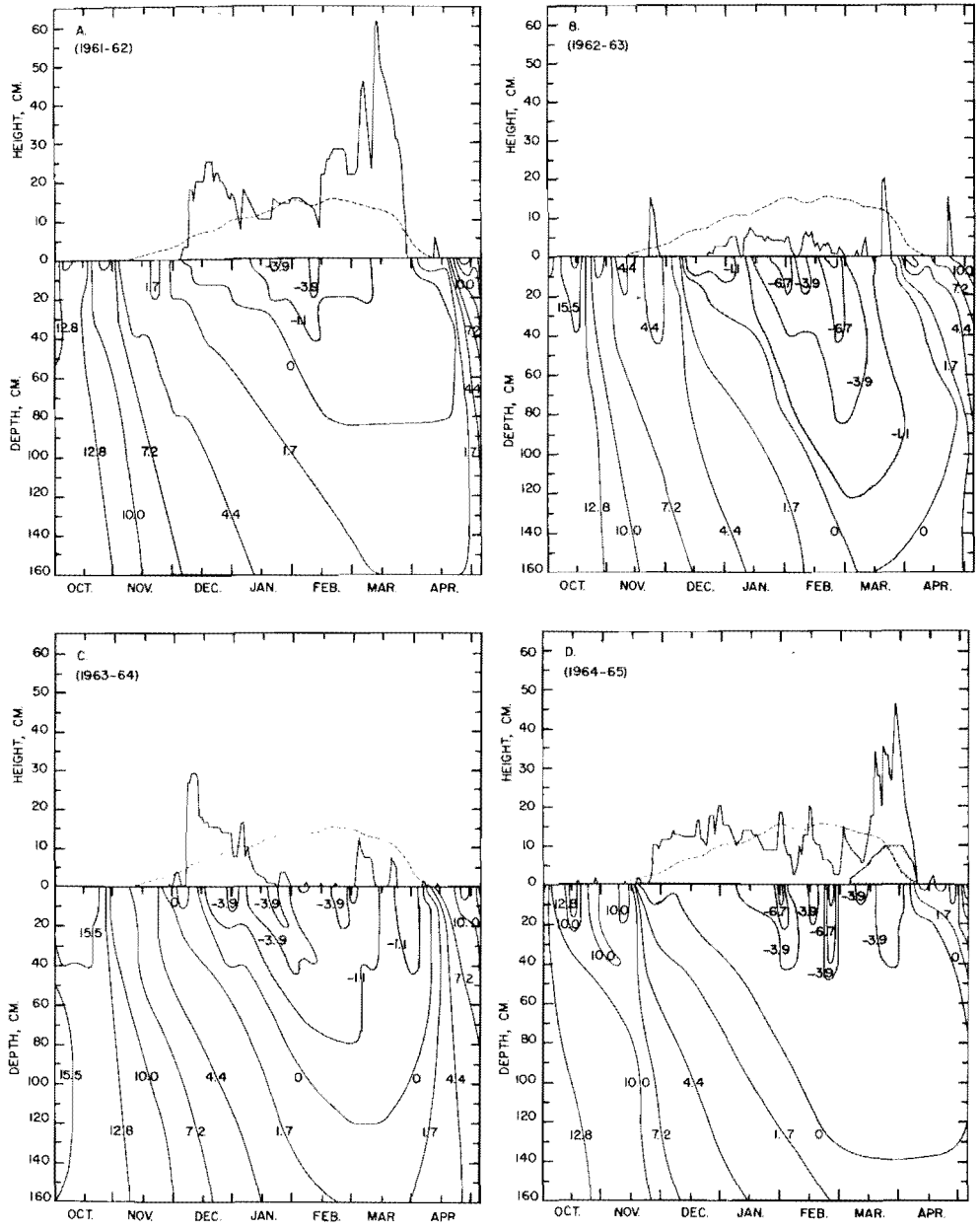

Figure 2. (A-H) Snow depth and soil isotherms (in degrees C) from October 1 - May 5 for the winters of 1961-62 through 1968-69. The long-term mean snow depth is shown by a dashed line, and the soil which is at or below 0C is within the shaded area. The diagonal lines above the surface indicate ice. Note difference in scale between the height above ground and the soil depth.

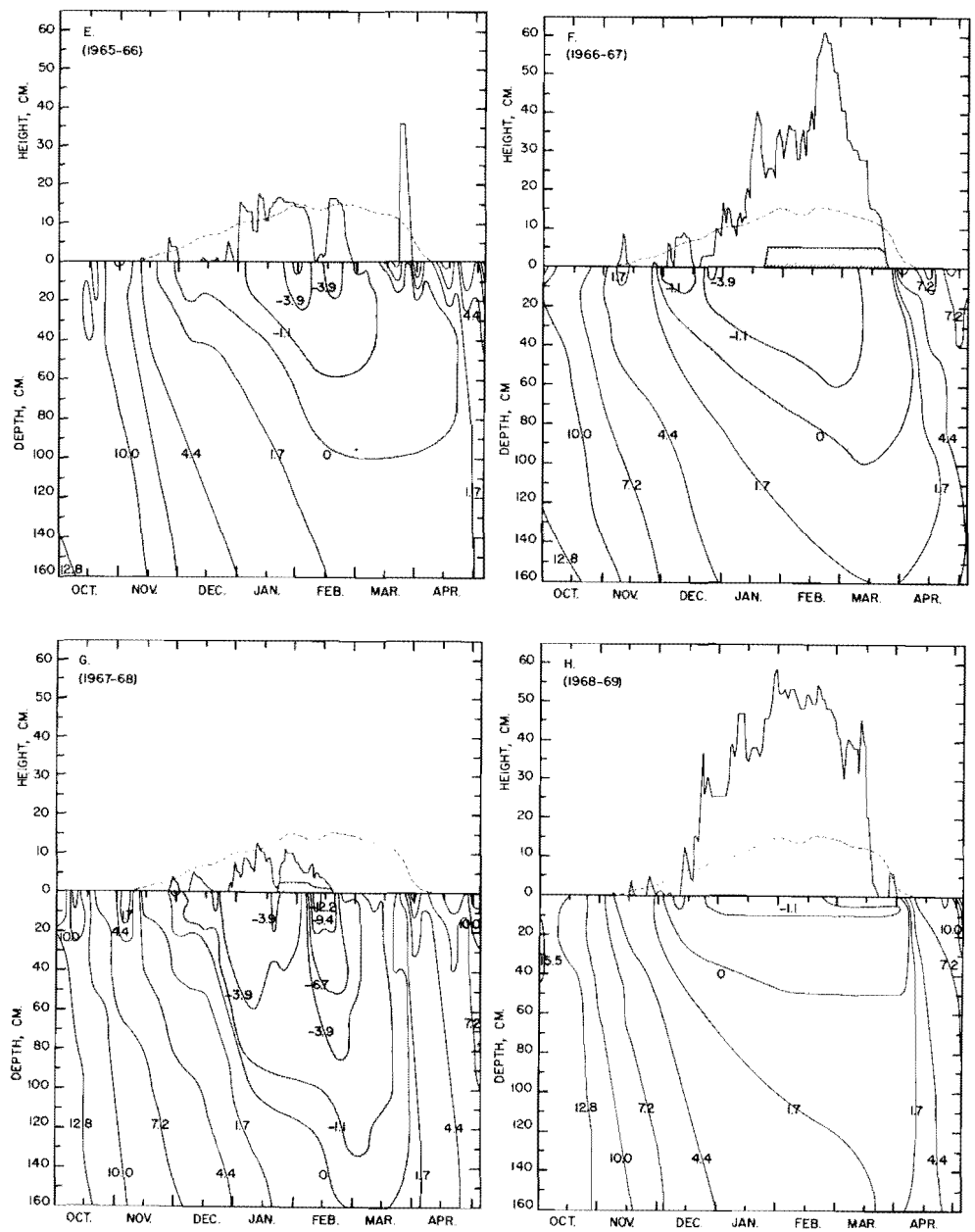

Figure 2. (A-H) Snow depth and soil isotherms (in degrees C) from October 1 - May 5 for the winters of 1961-62 through 1968-69. The long-term mean snow depth is shown by a dashed line, and the soil which is at or below 0C is within the shaded area. The diagonal lines above the surface indicate ice. Note difference in scale between the height above ground and the soil depth.

mean snow cover appears to last from November 5 - April 10. In reality, however, Table 3 shows that the long-term mean snow cover was present on only 67.6% of the days from December - March.

The winters of deep and persistent snow cover were 1961-62 and 1968-69, Figure 2 (A and H). The OC isotherm reached a depth of only 84 and 50 cm, respectively. The deep snow cover was an excellent insulator and not only resulted in a relatively shallow frozen soil but a distinctive flat shape of the OC isotherm from early February to the spring thaw. That is, the freezing isotherm progressed slowly into the soil and relatively early in the winter reached a depth where it remained constant until the spring thaw. This is particularly evident in the 1968-69 winter.

Deep but non-persistent snow cover occurred in 1964-65 and again in 1966-67, Figure 2 (D and F). In both winters a brief period of thawing or rain resulted in an ice sheet several cm thick and a greatly increased density of any remaining snow. This permitted greater loss of heat which resulted in lower soil temperatures and deeper freezing than would be expected when viewing the succeeding snow cover.

The OC isotherm reached a maximum depth of 139 and 100 cm in March 1965 and 1967, respectively. By late March 1965 there was more than 13 cm of water stored on the soil surface in frozen form, and in early April serious flooding occurred locally and in much of the state.

In contrast to the two pervious kinds of winters were those of 1962-63 and 1967-68, Figure 2 (B and G) when the snow cover was very light. With little snow cover there was a rapid loss of soil heat which resulted in steeply sloping isotherms. The combination of the greater depth and V-shape of the OC isotherm, which is due to rapid freezing with depth until early March followed almost immediately by rapid thawing, is typical of "open" winters. The greatest depth to which the soil froze in the 8 year period, 160 cm, occurred in both of these winters.

The winter of 1967-68 was one of 2 winters in which the soil was quite dry. Under otherwise equal conditions in an "open" winter the drier soil would be expected to freeze deeper than the wetter soil. However, conditions were not equal. Based upon cumulative degree days as a measure of the external environment, the winter of 1967-68 was milder than that of 1962-63, Figure 1 (B and G).

Finally, there are the winters of 1963-64 and 1965-66, Figure 2 (C and E), which have been placed in an "average" year category with respect to snow cover. These 2 winters differed in that the former had an early winter snow cover and the latter a mid-winter snow cover.

The OC isotherm reached maximum depths of 120 and 99 cm by mid-March of 1964 and 1966, respectively. The configuration of the freezing isotherm was approximately midway between the extremes of the "open" winters and the winter of deep and persistent snow cover.

The deeper and more rapid penetration of the OC isotherm in the 1963-64 winter may have been due to either of two things or a combination of both. First, this was one of the 2 dry years, and it is very probable that the soil was dry enough to greatly reduce its heat capacity but not so dry as to appreciably reduce its thermal conductivity. Secondly, this winter had less mid-winter snow cover than that of 1965-66, which permitted greater heat loss in the heart of winter.

The average OC configuration for each of the 4 kinds of winters is shown in Figure 3. Plotted in this manner it is apparent that the shape of the OC isotherm for the "average" winters of 1963-64 and 1965-66 were not greatly different from the deep but non-persistent snow cover years of 1964-65 and 1966-67. A major conclusion therefore seems to be that there were in reality only 3 kinds of winters with respect to the OC isotherm depth and configuration: those with deep and persistent snow cover at one

extreme, "open" winters at the other extreme, and "intermediate" winters which encompass all others that ordinarily fall well within the limits of the 2 extremes. The mean configuration of the 0C isotherm for the 8 winters is shown in Figure 4. The mean maximum depth of the 0C isotherm was 114 cm.

Table 4 has been arranged so that the "intermediate" winters, which are composed of the deep, non-persistent snow cover years (1964-65) and (1966-67) and the "average" years (1963-64 and 1965-66), are shown. It is apparent that this "intermediate" winter fits within the 2 extreme winters.

Figure 5 is presented to show three things. First, that the categorization of the winters into types based upon snow depth and duration does serve as a means of estimating the freezing depth of the soil. For example, the type I winter may be expected to result in a maximum freezing depth of 90 cm or less, and in a type IV winter to 150 cm or more.

The second thing apparent in Figure 5 is that the type II and III winters are not different in so far as depth of freezing is concerned, and they can be grouped into an "average" type of winter. A similar conclusion was reached when considering the configuration of the isotherms, Figure 3. The maximum freezing depth of the "average" winter may be expected to range between 90-150 cm deep.

The third item of interest shown in Figure 5 is that there seemingly is no relationship between cumulative heating degree days and freezing depth in soils. This point was also illustrated in Figure 1.

It has just been shown that there is a fairly close relationship between snow depth and duration (that is, type I, type II-III, and type IV winters as shown in Figure 5) and the maximum freezing depth. We have also seen that apparently cumulative heating degree days have little bearing upon the freezing depth under a snow covered surface, Figures 1 and 5.

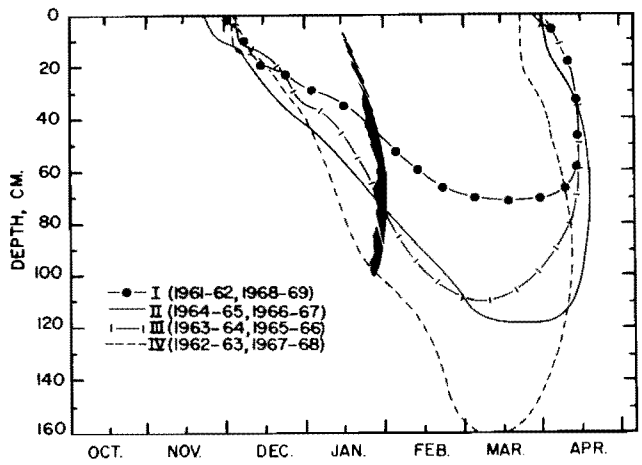

Figure 3. The mean position of the 0C isotherm for the 4 kinds of winters.

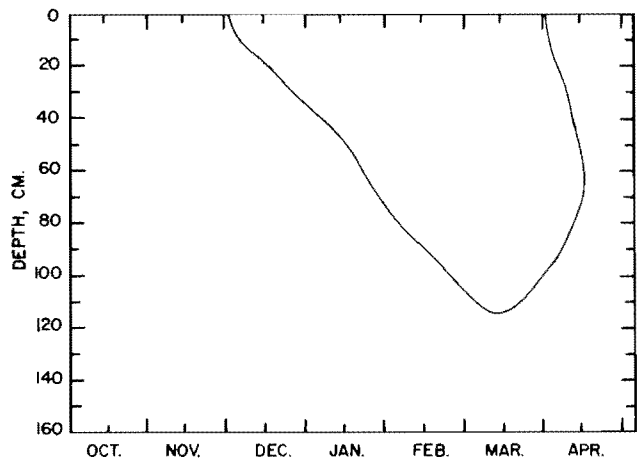

Figure 4. The mean position of the 0C isotherm for the 8 winters of 1961-62 through 1968-69.

Table 4. Summary of the winter soil temperature regime at St. Paul, 1961-62 through 1968-69.

Kind of Season	Years	Soil Moisture (cm H_2O/152 cm soil)	Last Date When 1 cm Soil Temperature Remains ≤ 0C	Last Date When 5 cm Soil Temperature Remains ≤ 0C	Maximum Depth of OC and First Date of Occurrence
I. Deep, persistent snow cover	1961-62	E[1]30-36	12/5	12/7	84 cm 3/11
	1968-69	46	12/5	12/5	50 3/15
	Mean		12/5	12/6	67 3/13
II. Deep, non-persistent snow cover with ice layer	1964-65	E[1]30-36	11/20	11/21	139 4/1
	1966-67	34	11/28	11/29	100 3/13
	Mean		11/24	11/25	119 3/23
III. "Average"	1963-64	E[1]20-25	12/13	12/13	120 3/7
	1965-66	37	11/27	11/27	99 3/5
	Mean		12/5	12/5	110 3/6
IIIa. "Intermediate" (Mean of II and III)	Mean		11/29	11/30	115 3/15
IV. "Open"	1962-63	E[1]38-40	12/7	12/7	160 3/7
	1967-68	24	11/26	11/26	160 3/2
	Mean		12/1	12/1	160 3/4
Overall Mean			12/1	12/1	114 3/11

1. E. means the value is estimated.
2. As defined in the text.

Table 4. Continued.

Average Rate of Movement of OC with Depth 12/1-3/15	Minimum Temperature at 1 cm Depth and Date of Occurrence		First Date When 1 cm Soil Temperature Remains > 0C	First Date When 5 cm Soil Temperature Remains > 0C	Depth and Date of Last Occurrence of OC		Duration of Restricted water Movement Period[2]
0.97 cm day^{-1}	-6.1C	2/8	4/15	4/15	40 cm	4/22	136 days
0.55	-2.2	1/4	4/5	4/7	50	4/8	124
0.76	-4.2	1/22	4/10	4/11	45	4/15	130
1.42	-10.0	1/30	4/5	4/5	80	5/6	166
0.94	-4.4	2/12	3/28	3/29	50	4/7	129
1.18	-7.2	2/5	4/1	4/1	65	4/21	147
1.33	-11.7	1/13	4/9	4/10	40	4/10	118
0.98	-7.2	1/29	4/7	4/7	40	4/21	145
1.15	-9.5	1/21	4/8	4/9	40	4/15	131
1.16	-8.3	1/28	4/5	4/5	53	4/18	139
1.78	-11.1	2/21	3/24	3/26	80	4/26	140
1.53	-13.3	2/11	3/25	3/25	120	3/30	124
1.65	-12.2	2/16	3/25	3/25	100	4/13	132
1.18	-8.3	1/31	4/3	4/4	63	4/16	136

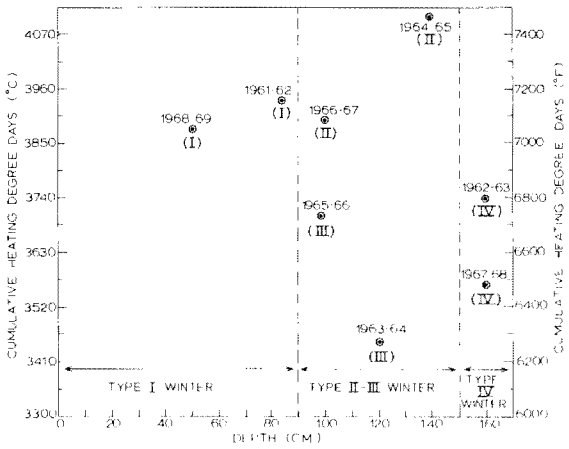

Figure 5. Graph showing lack of correspondence between maximum depth of freezing and cumulative heating degree days and the superior relationship between freezing depth and types of winters.

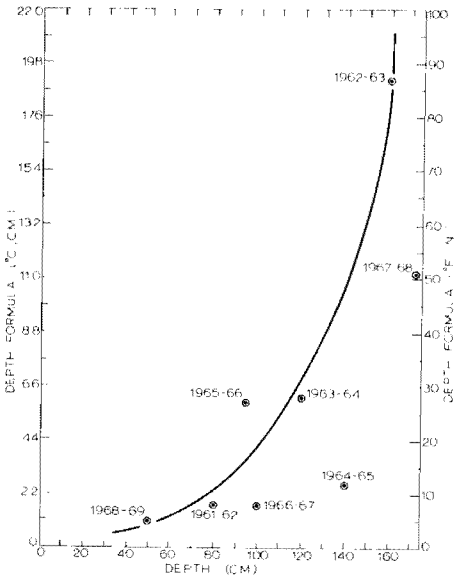

Figure 6. Maximum freezing depth plotted against the freezing depth formula. The curved line (hand drawn) is the prediction line for determining maximum freezing depth from the depth formula.

Nevertheless, the cumulative heating degree day method remains as perhaps the only readily available and quantitative means of indicating winter thermal conditions. It remains also as a factor in soil freezing depth if the insulating effect of snow can be accounted for. Further, due to the ease of calculating cumulative heating degree days it remains as a tempting quantity to use in an equation to predict soil freezing depth.

Now, since cumulative heating degree days is directly related and snow cover is indirectly related to the freezing depth, a prediction equation taking these direct and indirect relationships into account might improve the use of either one of these factors separately. Although we have only 8 years' data the results in Figure 6 show that the equation developed is superior to the use of either one of the factors singly. The formula developed for the maximum freezing depth (D) in the soil is

$$D = \frac{\Sigma \ (HDD)}{\Sigma \ (d1 \times d2)}$$

where: HDD is the heating degree days summed from October through March, d1 is the average monthly depth of snow cover, and d2 is the number of days per month with a measureable snow cover (0.5 inch or more). The product of d1 and d2 is summed for each month from November through March.

The heating degree days are accumulated beginning in October so that some measure of the heat escaping from the soil is obtained before snow falls. It is believed that this gives a more realistic measure of the soil temperature condition than waiting until snow falls or calculating freezing degree days. The snow depth and duration, d1 and d2, are not considered until November, since a snowfall in October is quite rare. No snowfall occurred in October during any of the 8 years in this study.

The curved line in Figure 6 is an eye-ball line of best fit. It is noted that all except the winters of 1964-65 and 1967-68 fall along the

prediction line. These two are the winters with ice cover and naturally are difficult periods to predict. The formula cannot take this into account and the freezing depth in both years was under-estimated. This consistency in the under-estimation, however, shows at least that the depth formula provides a minimum depth value for the freezing isotherm under ice-cover conditions.

The duration of the frozen soil at 1, 5, 10, 20, 40, 80 and 100 cm averaged 123, 123, 122, 117, 98, 65 and 34 days, respectively.

The mean freezing rate of the soil was calculated for the period December 1 to March 15, Table 4. The reasons for the selection of these two dates were because the OC isotherm persisted in the soil from about December 1 onward, Table 4, and because the deepest penetration of the freezing isotherm occurred on the average in mid-March, Table 4 and Figure 4. The mean freezing rate of the soil ranged from 0.76 cm per day in type I winters to 1.65 cm per day in type IV winters. Table 4 shows, however, that the type of winter based on snow cover failed to clearly distinguish the type I, II, and III winters.

It is perhaps not too surprising that upon plotting the freezing rates versus the freezing depth formula that a curvilinear prediction line is obtained, Figure 7, similar to that in Figure 6.

It is apparent in Figure 2 (A-H) and Figure 3 that thawing occurred from both the top and bottom of the frozen part of the soil. The major thawing, of course, progressed from the surface downward. As a result of thawing from 2 directions there often remained within the soil for some time a frozen layer at intermediate depths. The presence of this layer hampered internal drainage and presented a very deceiving picture of the internal soil conditions when viewed from the surface. For example, on the average at 1 cm depth the soil temperature remained above OC

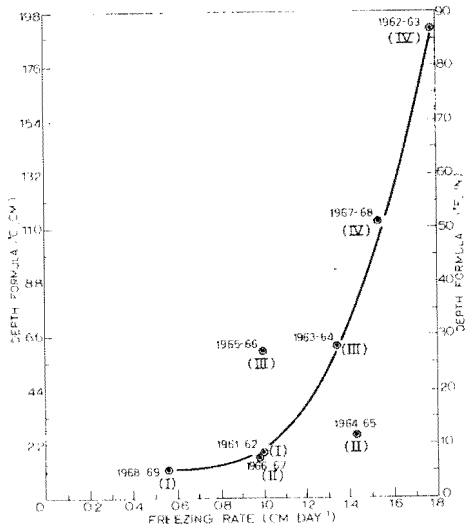

Figure 7. Freezing rate (averaged over period December 1 - March 15) plotted against the freezing depth formula. The curved line (hand drawn) is the prediction line for determining the freezing rate from the depth formula.

after April 3, but the OC isotherm last disappeared from the soil only on April 16 at a mean depth of 63 cm, Table 4.

In the "open" winters thawing of the surface soil (1 cm depth) averaged about 19 days before the OC isotherm had completely disappeared from the soil. And, in the mean, the 1 cm depth thawed about 12 days earlier in the "open" winters than at the same depth in the other 6 winters, Table 4. The mean thaw date of the soil at 1 and 5 cm was related to the kind of winter: at 1 cm the date was March 25 in the "open" winters, April 5 in the "intermediate" winters and April 10 in the winters of deep and persistent snow. At the 5 cm depth the dates were the same or only 1 day later.

The dates and depths at which the OC isotherm last occurred in the soil varied from March 30 - May 6 and from 40-120 cm, respectively. With the winters of deep and persistent snow cover as well as the "open" winters the isotherm depth showed strong dependence upon the snow cover, but only moderate dependence occurred during the other two kinds of winters. The dates at which the OC isotherm disappeared entirely from the soil had no apparent relationship to the kind of snow cover.

The period when liquid water is restricted in movement through the soil is of obvious importance. This is defined as the period extending from the time when the temperature at the 5 cm depth remained less than OC until the OC isotherm completely disappeared from the soil. The commencement date of this period was selected to ensure that the water was in solid form and that a reasonable depth of soil was frozen to serve as an effective barrier to surface water.

The mean commencement date of this period was December 1 and the mean termination date was April 16. Thus the mean duration was 136 days and over the 8 years ranged from 118 to 166 days, Table 4. There did not seem to be any relationship between the duration of the period and the kind of winter.

CONCLUSIONS

Based upon the depth and persistence of the snow cover there were in effect 3 kinds of winters: one with deep and persistent snow cover, one with very little snow cover (an "open" winter) and all other winters, which ordinarily fall well within the 2 extremes.

There was a close relationship between the kinds of winters (based upon depth and duration of snow cover) and the maximum depth to which the OC isotherm penetrated, and a fair relationship to the rate of movement of the OC isotherm into the soil.

In general the time of occurrence of any phenomena discussed could not be estimated by knowing the kind of winter.

The combination of type of winter (snow depth and duration) with cumulative growing degree days proved to be a simple and effective means of predicting the maximum freezing depth.

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