STUDIES ON SEASONAL CHANGES IN THE TEMPERATURE GRADIENT OF THE ACTIVE LAYER OF SOIL AT FORT CHURCHILL, MANITOBA*

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Soil temperature observations were made as early as 1837 (Forbes, 1837) near Edinburgh where readings were obtained at depths of 3, 6, 12 and 24 French feet (24 French feet = 25.6 English feet) using specially constructed mercury thermometers. Since then, numerous papers have been published on soil temperatures, with stress for the most part on soils of temperate climates and the economic aspects of the problem. As a result of the research, a number of factors, intrinsic and extrinsic, have been found to affect the change in soil temperature gradient throughout the year. Bouyoucos (1913, 1916) thoroughly and systematically reviewed the literature available at that time.

Since then, Crawford (1952) has published a comprehensive review of the wealth of pertinent soil temperature research. In this review, he discusses the roles played by the effect of rainfall and melting snow, snow cover, surface cover, soil-moisture content, moisture migration, thermal conductivity and diffusivity, freezing temperature of soils, daily temperature variation, temperature inversion with depth, and frost penetration and retreat. Generally, his review indicates that foremost among the extrinsic factors affecting soil temperature is the source and amount of heat given to the soil. The primary source of heat is the radiation of the sun; heat transferred to the soil by conduction is comparatively less. Latitude of the location has an important bearing on the amount of heat absorbed per unit area of surface.

Surface cover — its quantity and colour — is another important factor. It has been found that frost penetration is deeper and its disappearance slower under bare ground than under vegetal cover, since the vegetation acts as an insulatory layer to the soil. Black soil was found to thaw more rapidly and to freeze more slowly than did a light coloured soil.

The protective effect of snow cover has been known for many years. Atkinson and Bay (1940) found the depth of frost penetration changed in direct proportion to the depth of snow. They observed that in two out of

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three cases where there was 10 inches or more of snow, the frost depth decreased. Where there was 10 inches or less of snow, the frost depth increased correspondingly. The research of Diebold (1937) produced similar results.

The physical characteristics of the soil itself determine to a large extent its ability to conduct and absorb heat. In order of decreasing conductivity soils may be listed as sand, gravel, clay, humus and peat. Bouyoucos (1913) listed the specific heat properties of soils (Table I). Thus peat has the lowest

Table I
Specific heat properties of soils

Soil	Specific gravity	Specific Heat	
		Equal weight	Equal volume
Sand	2.664	.1929	.5093
Gravel	2.707	.2045	.5535
Clay	2.762	.2059	.5686
Peat	1.755	.2525	.4397

specific heat by volume yet the highest specific heat by weight. Moisture content alters these properties. Crawford (1952) showed that dry peat will heat or cool about twice as readily as sand or gravel, with equal application of heat. In the natural wet condition, it will heat or cool about one-third as readily, indicating the great importance of moisture content. Though sand and gravel have higher specific heats by volume than peat, and thus will heat or cool more slowly in the dry condition, Bouyoucos (1913) deduced that field moisture conditions altered the picture to the extent that the sand and gravel will cool or heat three times as rapidly as peat.

The experiments described in this paper on rates of freeze and thaw of the active layer have shown the complicated interaction of some of these factors as they occur in the Fort Churchill, Manitoba region. Since the fall of 1954 when the last of the data were collected, Cook (1955) has published his results on soil temperature measurements at Resolute Bay in the Northwest Territories. He describes and discusses the readings from two cables placed 225 feet apart in overburden of slightly different composition, but composed for the most part of frozen gravel and shattered rock overlying the limestone bedrock. This type of terrain unfortunately is not similar to any of those studied at Churchill, but the fluctuations in temperature through the year follow similar curves of change.

Description of the Churchill environment

Topographic and vegetation features

The Churchill area supplies many of the major terrain types of the North American tundra and the boreal forest (Beckel, Law and Irvine, 1954). From Cape Merry eastward to Half Way Point along the north shore for a distance of about 15 miles there occurs a series of rough quartzite ridges, which ridges range in height from 25 to 100 feet above sea level. To the south and east of these ridges, the country presents a picture of a relatively flat plateau dissected occasionally by small streams and old beaches of sand or gravel. A large proportion, perhaps 75 per cent of this plateau, is composed of sedge swamps and lakes of varying shapes and sizes. The remaining 25 per cent is made up of dry heath uplands and tussock or hummock muskeg.

The vegetation on the whole is that of the boreal forest with frequent representatives of the tundra population. Scattered clumps of spruce occur along the quartzite ridges and attain heights of up to 30 feet where they are relatively sheltered by the ridge from the prevailing northwesterly winds. On the open exposed portions of the ridge, the trees are stunted; their living branches are densest on their southeast side away from the wind, and very dense at their base where they are protected by snow from the drying effect of the winter winds. About 4 miles south of the Bay, the forest begins to thicken. The trees which are for the most part larch, and white and black spruce, are small and distorted here in the transition area. They are gradually replaced by taller members of the species as the distance between them and the Bay is increased. Occasional dense stands of tall spruce and larch are encountered along the margin of the forest zone, as, for example, along the small gravel ridges just east of the railway and west of the southern tip of the north-south runway (Fig. 1).

Table II

Climatic summaries for Churchill, Manitoba

(Canada, Department of Transport, 1947)

Month	Daily mean temp. °C	°F	Average snowfall (in.)	Average precipitation (in.)	Average monthly rainfall (in.)	Average no. of days with measurable ppn. of any sort
Jan.	—28	—19	4.8	0.48	0.00	5
Feb.	—27	—17	6.1	0.61	0.00	6
Mar.	—21	—6	8.5	0.87	0.02	6
Apr.	—10	14	7.7	0.89	0.12	6
May	—1	30	1.8	0.93	0.75	7
June	6	43	1.4	1.85	1.71	9
July	12	54	0.00	2.19	2.19	10
Aug.	11	52	Trace	2.69	2.69	12
Sept.	6	42	1.7	2.33	2.16	11
Oct.	—3	27	8.0	1.43	0.63	12
Nov.	—14	6	10.3	1.03	0.00	9
Dec.	—24	—11	6.6	0.66	0.00	8
Annual	—8	18	56.9	15.96	10.17	101
Years observed	30	30	30	30	30	10

Geology

Williams (1948, page 40) has described the rock outcrops characteristic of the Churchill area as quartzite "made up of fairly well rounded quartz grains, with a small amount of interstitial sericite . . . the quartz content of the rock is about 70%, half of coarse and half of fine grains. The sericite content is about 30% . . . . The white dolomites are extensively represented on both sides of the mouth of the Churchill river . . . . Out at Landing or Farnworth Lake, some seven miles to the south, piles of dolomite slabs are common." He suggests that the presence of particular fossils in some of the limestone formations indicates Silurian and Ordovician elements.

Soil

There is no "soil" in the Churchill area, according to the commonly accepted conception of a "developed soil". A layer ranging from 0 to 24 inches of peat is found above a subsoil of gravel, sand, or clay, or combination of these. The peat may vary from fine black and well-decomposed to coarse, fibrous material in which the plants from which it has been derived are clearly recognizable. The pH values of the peat, which range from 6.0 to 7.5, reflect the large proportion of limestone gravel and sand in the subsoil. The water content of the soil has not been ascertained, but generally speaking, may be said to be very dry on the crests of ridges and hummocks and saturated or near saturated elsewhere.

Climate

Table II summarizes the pertinent climatic data for the Churchill region as averaged over a ten- to thirty-year period. With a mean annual temperature of 18° F, perennially frozen ground would be expected, and is found, in the area. The depth of the active layer above it (that layer subject to seasonal freeze and thaw) varies from area to area depending upon soil type, soil moisture conditions, plant cover, and winter snow cover. The thickness of the perennially frozen ground has been found (Johnston, 1930) to be at least 115 feet. The high water table which results from the presence of the perennially frozen ground produces a marsh and lake-filled country not otherwise to be expected with the low annual precipitation of 16 inches.

Method

In the fall of 1950 a research program was initiated for the study of temperatures of the active layer of soil in the Fort Churchill, Manitoba region. The position (Fig. 1) of each of the stations selected was determined initially by the combination of needs of three projects under way at the time at the Defence Research Northern Laboratory. Some were placed in or near ponds which were being studied as habitats of particular colonies of mosquito larvae or other aquatic invertebrates; others were located on higher drier ground in an attempt to obtain representative samples of the drier terrain types, such as have already been described for the area. (Beckel, Law and Irvine, 1954). A total of thirty-one stations was established in the vicinity of Fort Churchill. Of these, twenty-two were located in or near pools or swamps; seven were located on dry terrain, and two (numbers 30 and 9) were accidentally destroyed by caribou during the first spring. In 1951, another twelve stations were added in order to more adequately represent the drier terrain of the region within the camp as well as outside it. Of these, numbers 34, 35 and 43 were the only ones located outside the camp, hence are the only ones discussed further in this paper.

During the first two years, and during the winter seasons in particular, it became obvious that the number of stations in the field was too many to service and to observe properly with the equipment and staff available. As

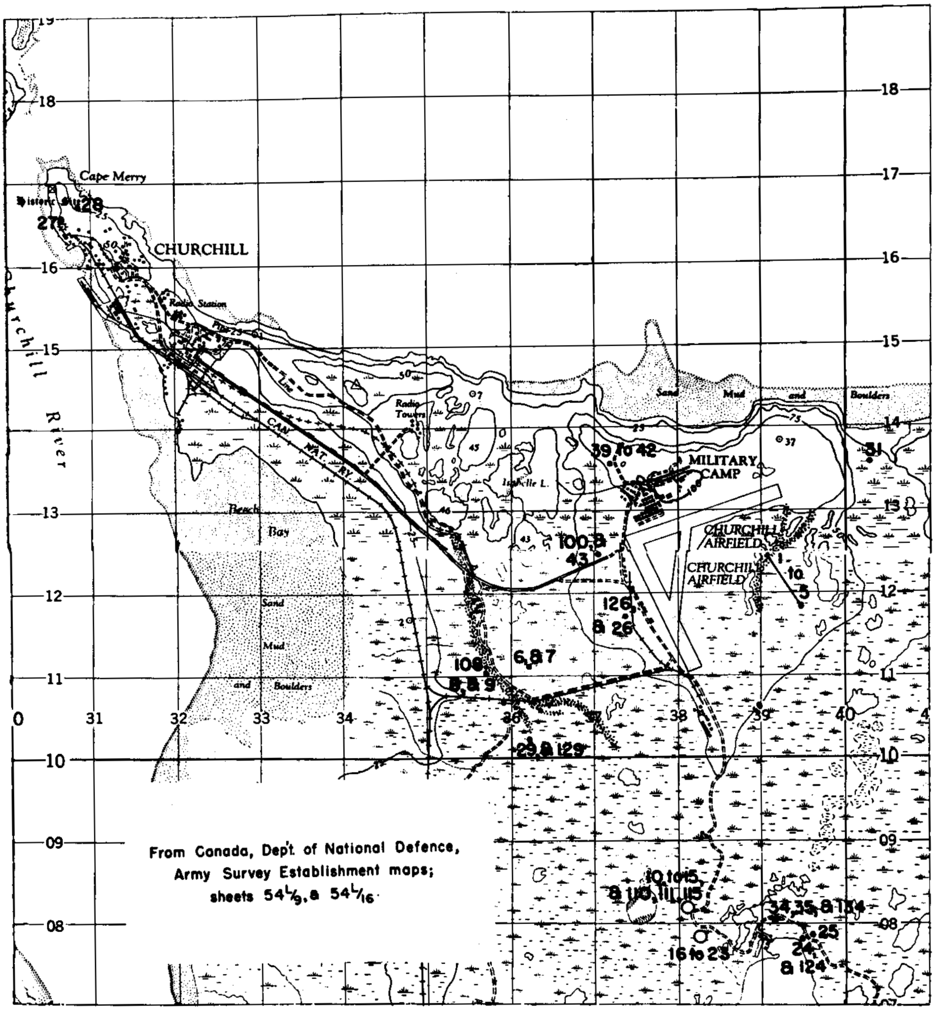

Fig. 1. Map of the Fort Churchill area, indicating the soil temperature stations.

a result, in the fall of 1952 seventeen stations (numbers 8, 10, 11, 12, 15, 16, 23, 24, 25, 26, 29, 34, 35, 36, 41, and 42) were selected as representative for continued observations and the remainder were discarded. In the fall of 1953, six further stations were established to measure snow depth and temperature as well as active layer temperatures. These new stations were located adjacent to stations 26, 34, and 43 (number 43 had been broken by an oversnow vehicle during the winter of 1951 and was not subsequently replaced), 11, 8 and 15; these new stations were designated 126, 134, 100, 111, 108, and 115 respectively. These six new stations, in addition to the following, were observed regularly during the next year; numbers 12, 15, 26, 8, 29, 24, 34, 35, 23, 10, and 11. The positions of the stations studied from 1950 until 1954 are indicated on the map (Fig. 1).

Table III lists the thickness of the active layer at each station as determined in August of 1951 and three years later, in August of 1954. The type of terrain on which each station was located is also listed.

Table III

Thickness of active layer at soil temperature stations, August, 1951, and August, 1954

(Asterisk indicates depth measured by probing: lack of asterisk indicates depth determined by digging)

Description of terrain type	Site number	Frost depth (inches) Aug. 21 to 27 1951	Frost depth (inches) Aug. 23 to 25 1954	Water level (above or below surface)
A. HIGH DRY TERRAIN:				
low beach ridge (crest)	4	25	39*	—18″
low beach ridge (base)	54*	54*	35*	—36″
hummock	27	24	34*	not above frost level
mound	12	22	38*	not above frost level
mound	18	59*	78*	—34″
foot of gravel ridge	26	96*	96+*	—24″
foot of gravel ridge	126	—	96+*	—24″
sand beach	31	58	—	not above frost level
heath plateau scraped bare of vegetation	34	30*	80*	—
heath plateau	134	—	34*	—
heath plateau scraped bare of vegetation then planted to lawn grass	35	30*	95*	—
heath plateau	43	56*	—	—25″
heath plateau	100	52*	54*	—25″
B. WET TERRAIN:				
edge of pool	1	52*	—	0 to 6″
edge of pool	2	52	51*	0 to 6″
middle of pool	10	84+*	92+*	0 to 6″
edge of pool	11	60*	86+*	—1 to —7″
edge of pool	111	—	86+*	—1 to —7″
middle of pool	16	84+*	90+*	6 to 12″
small hummock	21	84+*	—	—
middle of small lake	3	43*	—	0 to 6″
middle of sedge-lined pool	6	39*	43*	—30″
sedge swamp	8	64*	64*	4 to 10″
sedge swamp	108	—	64*	4 to 10″
sedge-lined pool	9	56*	—	4 to 8″
sedge swamp	13	65*	—	4 to 10″
edge of pool	14	44*	83+*	0 to 6″
sedge swamp	15	58+*	87+*	0 to 12″
sedge swamp	115	—	87+*	0 to 12″
edge small pool	17	51*	—	—0 to —6″
edge small pool	20	62*	—	—3 to —7″
small dried pool	22	60*	—	—3 to —7″
small pool	23	67*	82*	0 to 6″
edge quaking sedge swamp	24	78*	90+*	0 to 8″
small pool	25	84*	—	4 to 15″
pool on quartzite outcrop	27	solid rock bottom		0 to 24″
edge sedge swamp	28	48*	—	—
margin sedge swamp in woods	29	132*	132*	0 to 8″

The thickness of the active layer at each station was determined by probing with an iron rod, or, where possible, by digging; these measurements were obtained during the latter part of August when the active layer had reached its maximum depth of thaw. On the basis of these measurements, the depth to which soil measurements would be made was determined. At no station were temperatures of 0° C encountered throughout the summer; it was thus obvious that the thermocouple placed at the greatest depth in the active layer was still above the upper limit of the perennially frozen ground despite our preliminary examination of the stations.

Limitations of space have made it necessary to select only four representative sites for illustration of the information collected during the four-year study period. These four stations are described in detail in Table IV; the soil temperature observations over the four-year period for each of the four stations are recorded graphically in Figures 5 to 8. Snow depth and its effect on snow and soil temperatures at all stations is discussed later in the paper.

Equipment

At each site, dowel stakes with regularly spaced copper-constantan thermocouples on them were installed in the ground (Fig. 2). Leads from each couple were connected to a plug. This installation was permanent and e.m.f.'s could be read at regular time intervals by means of a field potentiometer similar to that described by Lytle (1954). That used for our research differed from that described by Lytle in our use of a Rubicon pointerlite galvanometer with a range of $-50°$ C to $+50°$, and our use of a copper rather than a copper-constantan plug. The e.m.f.'s were then converted to °C by means of conversion tables (Am. I. of Physics, 1941). Most previous soil temperature research has utilized solid thermometers and thermographs, but they are less convenient to use under winter conditions and require greater disturbance of the natural soil conditions. Copper-constantan thermocouples have been found by us and by Weaver and Clements (1929), Bouyoucos (1913) and Diebold (1937) to be thoroughly reliable; the combined possible error due to differences between thermocouples and to variation in potentiometer readings is negligible (Lytle, 1954).

At each station a "dummy" dowling stake was first hammered into the ground to clear the way for the stake with the thermocouples on it; the thermocouple bearing stake was then hammered into place and marked by a post bearing its station number and a flag to make it easier to locate during the winter months. Field installations for reading snow temperatures (Fig. 2) were installed in the fall of 1953. Preliminary field trials indicated that considerably less disturbance of the soil occurred when a stake with copper-constantan couples attached (Fig. 2) was hammered into the ground than when the method of previous workers (Diebold, 1937) of excavating soil, installing of couples at set levels, and re-filling of excavation, was used.

Procedure

During the first year soil temperature readings were made on the average of once every five weeks. During the second season, as quirks in field and recording equipment were ironed out, it was possible to increase the frequency of readings until, during the final season, they were made once every two weeks at the minimum. Concurrently with the soil temperatures, snow and water depth measurements were made at each site from November, 1951 until 1954. Before 1953, snow temperatures were recorded

Table IV

Description of stations for soil temperature readings

(Asterisk indicates frost depth measurements made by probing: depths indicated without an asterisk represent measurements ascertained by digging)

Site no.	Frost depth (inches)		Soil profile	Position of site and vegetal cover	Water level (above or below the surface)
	Aug. 21-27 1951	Aug. 23-25 1954			
12	22	38*	0—2″ dry lichen moss mat 2—8″ black fibrous peat 8—22″ gravel-clay, with occasional limestone plates 22″ frost level	on high dry mound in thinly forested area; 5′ above swamp level Primary species: *Cladonia rangiferina* Secondary species: *Ledum groenlandicum* *Picea mariana* *Empetrum nigrum* *Vaccinium vitis-idaea var. minus* *Rubus chamaemorus*	not above frost level
35	30	95*	0—10″ black fibrous peat with occasional limestone plates 10—30″ gravel clay mix 30″ frost level	High dry heath plateau just north of Farnworth Lake scraped bare of vegetation, then planted to lawn grass mix	not noted above frost level
8	64*	64*	0—8″ unconsolidated brown peat 8—?″ black muck, well decomposed 64″ apparent frost level	In small patch (6′ x 10′) of open water in sedge swamp Primary species: *Carex aquatilis* Secondary species: *Triglochin maritima* *Ranunoulus gmelinii* *Eriophorum angustifolium* *Arctagrostis latifolia*	4—10″
29	132*	132+*	0—8″ medium coarse black peat 8—132″ sandy with occasional gravel and boulders	Margin of heavily wooded spruce forest and sheltered sedge swamp region; deep soft snow in winter Primary species: *Carex limosa* *Scirpus hudsonianus* Secondary species: *Salix arctica* *Picea mariana* *Larix laricina* *Betula glandulosa* *Vaccinium uliginosum*	0—8″

at only such stations as had spare thermocouples above the surface of the ground or water; during the winter of 1953-4 snow temperature measurements were made each time the soil temperature readings were made for each station. In all cases, the temperatures were taken during the daytime.

Ambient air temperature records were obtained from the local Department of Transport Meteorological office and averaged over ten-day periods (Fig. 3). Solar radiation data (Fig. 4) collected at this laboratory (Blakely, 1954) have been graphed similarly. The changes in temperature gradient of the active layer at four typical sites are illustrated in Figures 5 to 8. The temperatures at all depths for which data were collected are not indicated in the figures; rather enough to give a picture of temperature gradient have been selected and graphed. In all cases, temperatures for the upper and

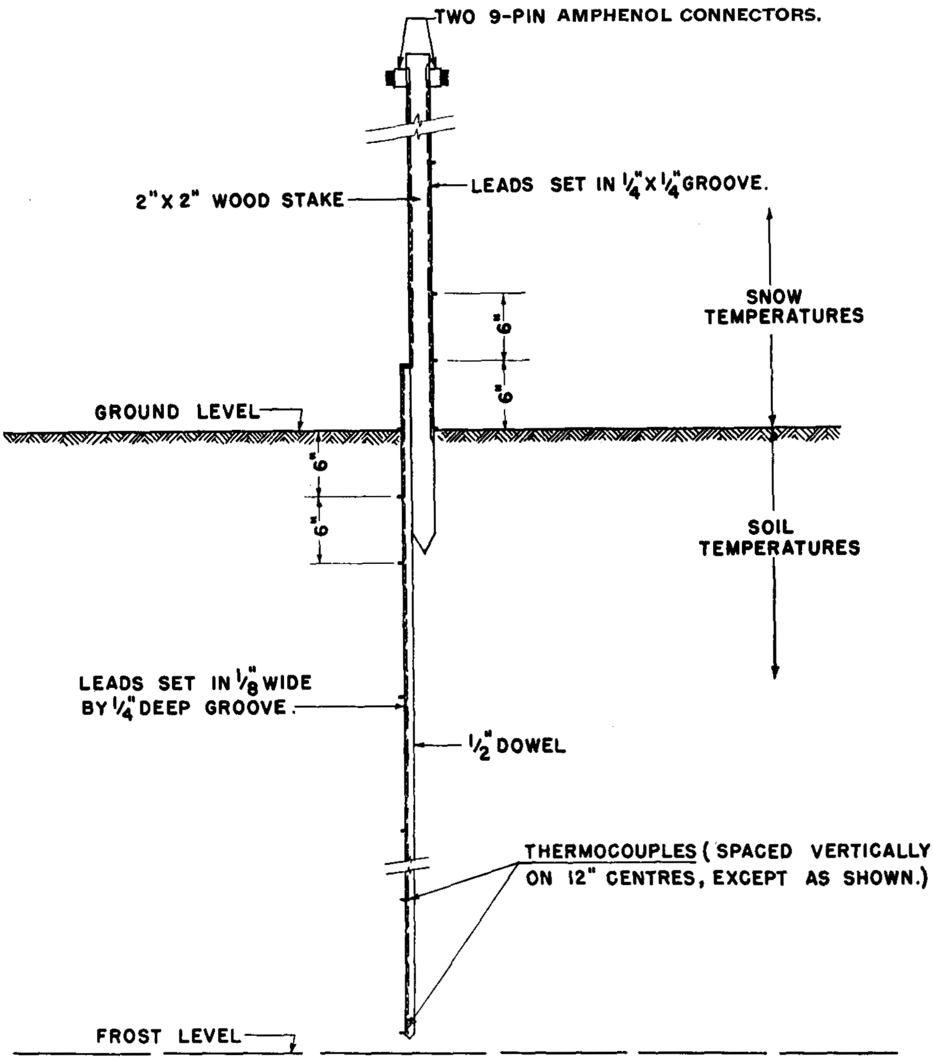

Fig. 2. Field thermocouple installations. Typical test site.

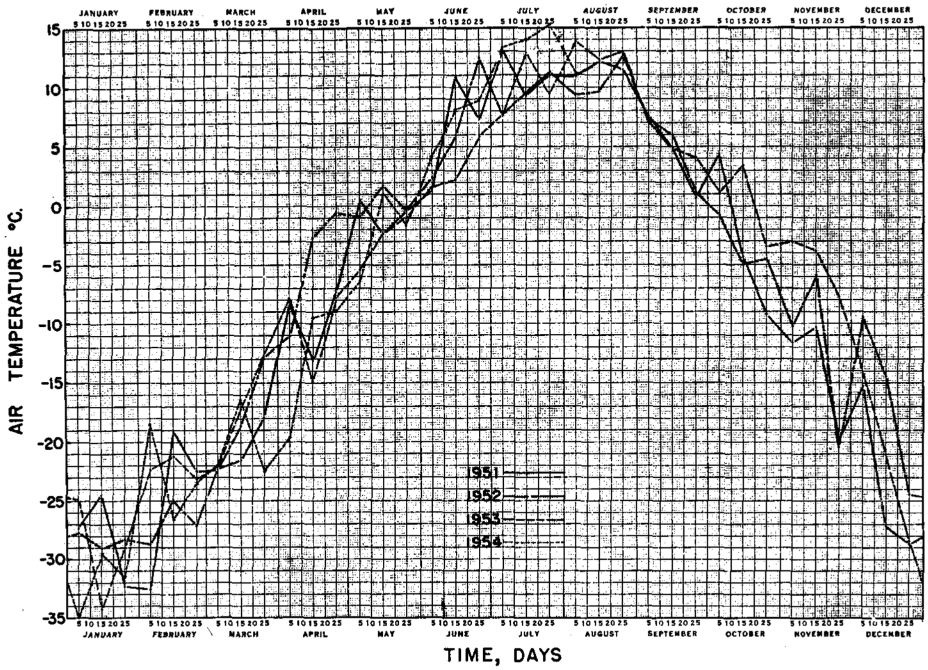

Fig. 3. Ambient air temperatures with time. Ten-day averages compiled from data collected by Meteorological Division, Department of Transport, Churchill, Manitoba.

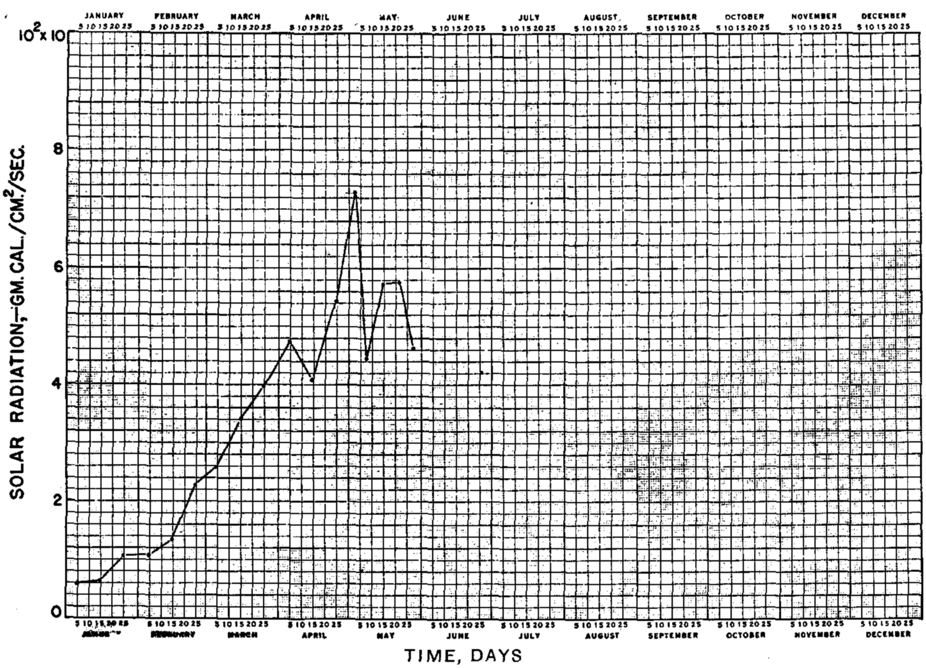

Fig. 4. Solar radiation with time, for January to May, 1954.

lower depths and for one or more intermediate depths are indicated. It was not possible to thrust the stakes into the ground to the full depth of the active layer, but the depth of the lowest recording couple is indicated for each site in the figures. Pertinent data for the remaining sites are included where applicable in other sections of this paper.

Results and discussion

Factors affecting soil temperature

Climatic factors. Ambient air temperature (Fig. 3) and solar radiation (Fig. 4) follow, generally speaking, the same curve of rise and fall over the period during which data are available for the latter. Over this period the soil temperature curves follow more closely in form that of the ambient air temperature than that of solar radiation. Comparison of the soil temperature curves (Figs. 5-8) with ambient air temperature (Fig. 3) indicates that during the winter the majority of stations lag behind ambient air temperatures in reaching extremes (see also Table V). Those stations which reach their coldest extreme at the surface before the ambient air temperature reaches its lowest extreme, are located in sedge swamps and early in the winter are covered by a thick insulating layer of snow. For the remainder of the stations the surface soil reaches its lowest extreme from 3 to 50 days after the ambient air reaches its lowest extreme. No significant difference is noted between dry and wet stations or hard and soft snow. With medium and lowest soil depths, however, the extreme lows in temperature are reached from 12 to 83 days after that of the ambient air temperature. Generally, the earliest lows are reached in the dry stations and the latest lows in the soil of the wet stations.

In the daytime, during the summer, the upper few inches of soil reach their maximum temperature in wet and dry areas 13 to 67 days before the ambient air temperature does. The fact that this soil temperature is recorded during the daylight hours and that the record does not represent an average through the day, accounts for this seeming anomaly. The expected lag, as noted by Cook (1955), was recorded for depths below the level affected by diurnal variation in the temperature of the ambient air. The lower soil of the active layer was noted to reach its maximum temperature 20 to 50 days after the maximum ambient air temperature was reached. Two exceptions to this occurred, one at a dry site (35) and one at a wet site (15); an explanation for these exceptions has not as yet been found. Of the rest which reached their extremes after that of the ambient air temperature, wet and dry stations were among the early and middle extremes; the two very late extremes were reached at the lowest depths of wet stations (sites 8 and 29). The overall picture seems to be that the dry peat overlying the mineral soil of the dry stations provides insulation against the continued change in temperature which takes place in the saturated peat and mineral soil of the wet stations. The maximum depth of thaw in terms of dates

Table V

Comparison of extreme temperatures recorded for upper and lower depths of the active layer for selected stations, and of extremes for ambient air temperatures averaged over ten-day periods

Station no.	Depth in. of soil	1951				1952				1953				1954			
		Temp. °C	Date	Temp. °C	Date	Temp. °C	Date	Temp. °C	Date	Temp. °C	Date	Temp. °C	Date	Temp. °C	Date	Temp. °C	Date
8	2	— 9.5	Mar. 2	+11.0	Aug. 17	—15.0	Feb. 21	+ 8.5	Aug. 12	—8.5	Mar. 4						
	55	— 6.5	Apr. 25	0.0	July 24	— 9.0	Mar. 19	+10.0	Oct. 16	—4.0	Mar. 17						
108	0													—13.0	Jan. 28	+13.0	July 19
	54													— 6.5	Mar. 31		
10	8					— 1.0	Mar. 8	+ 6.5	Aug. 12	—1.0	Jan. 4	8.0	Aug. 18	— 3.5	Jan. 29		
	30					0.0	Nov. 1	+ 4.0	Sept. 13	—1.0	Jan. 4	5.0	Sept. 8	— 1.0	Apr. 1		
110	0													—11.0	Jan. 29	+19.0	July 27
	60													— 0.5	Apr. 1		
11a	0					— 2.5	Jan. 21	+17.0	July 16			21.0	Aug. 18	— 4.5	Jan. 29	+23.0	July 19
	66					— 1.0	Apr. 8	+ 1.5	Sept. 13	— 1.0	Jan. 4	3.5	July 21	0.0	Nov. 3		
111	0													to —1.0 — 7.0	Jan. 29	+22.0	July 19
	60													0.0	Dec. 17		
12	1	— 7.0	Jan. 9	+16.5	Aug. 15	— 8.0	Feb. 5	+15.0	July 16	—8.0	Feb. 10	23.0	July 21	— 9.0	Jan. 29	+22.5	July 6
	21	— 4.0	Feb. 26	+ 0.5	June 12	— 4.0	Mar. 7	+ 1.0	Sept. 13	—4.0	Feb. 10	2.5	Aug. 3	— 4.5	Apr. 1		
112	0													—21.0	Jan. 29	+24.5	July 5
	22													— 5.5	Apr. 1		
15	9	—15.	Jan. 5	+11.5	Aug. 24	— 1.5	Dec. 18	+12.0	July 16								
	45	— 0.5	Jan. 5	+ 5.0	Aug. 28	— 0.5	Dec. 18	+ 5.5	Aug. 12	—1.0	Jan. 4						
115	1													— 1.5	Jan. 17	+10.5	July 26
	53													0.0	Feb. 13		

Table V (cont'd)

Station no.	Depth in. of soil	1951 Temp. °C	Date	Temp. °C	Date	1952 Temp. °C	Date	Temp. °C	Date	1953 Temp. °C	Date	Temp. °C	Date	1954 Temp. °C	Date	Temp. °C	Date
23	6					— 1.0	Feb. 21	7.0	Aug. 12	0.0	Dec. 5	9.5	July 15	— 7.5	Jan. 15	9.5	July 27
	60					0.0	Feb. 5	4.5	Sept. 13	0.0	Mar. 16	6.5	Sept. 23	— 4.0	Feb. 12		
123	0.5															19.0	July 19
24	0					— 3.0	Feb. 5	15.0	June 19	— 0.5	Jan. 4	17.0	Aug. 21	— 1.0	Dec. 29	14.0	July 27
	72					— 1.0	Mar. 21	12.5	Sept. 12	+ 0.5	Jan. 4	8.5	Aug. 21	— 1.0	Mar. 16		
124	1													— 1.5	Mar. 31	12.5	July 27
	73													+ 0.5	Mar. 31		
26	0							25.0	July 21	— 1.0	Mar. 3	25.0	Aug. 21			26.5	July 7
	84					— 1.0	Jan. 26	3.5	Sept. 13	0.0	Mar. 3	5.5	Sept. 11				
126	0													—15.0	Dec. 30	26.5	July 20
	96													0.0	Mar. 18		
29	0					— 4.0	Mar. 7	18.5	July 21	— 0.5	Feb. 4	20.5	July 8	— 4.0	Jan. 28	19.0	June 29
	112					0.0	May 27	6.0	Oct. 16	+ 0.5	Apr. 26	5.5	Sept. 10	+ 1.0	Feb. 27		
129	0													— 3.0	Jan. 28	19.5	July 19
	120													+ 1.0	Feb. 27		
34	0					—17.0	Jan. 17	16.0	July 21	— 9.5	Mar. 2	24.5	Aug. 4	—29.0	Jan. 15	24.5	July 19
	24					—16.5	Mar. 6	6.0	Sept. 13	— 6.3	Feb. 10	7.0	Sept. 10	—13.5	Jan. 29		
134	0													—26.0	Jan. 29	27.0	July 19
	30													—14.0	Jan. 29		
35	0					—23.0	Jan. 17	14.0	July 21	—11.0	Jan. 4	25.0	Aug. 4	—34.0	Jan. 15	21.5	July 19
	24					—18.5	Mar. 7	7.0	Aug. 11	— 6.5	Mar. 16	7.5	Aug. 4	—13.5	Mar. 31		
100	0													—27.5	Jan. 29	21.0	July 6
	42													—13.5	Feb. 26		
Ambient air		**—32.5**	**Feb. 5**	**12.2**	**Aug. 15**	**—29.0**	**Jan. 15**	**12.8**	**Aug. 25**	**—34.2**	**Jan. 15**	**13.8**	**Aug. 5**	**—35.0**	**Jan. 5**	**15.2**	**July 25**

generally takes place between the middle of August and the middle of October; the average date is September 15.

The effect of change in ambient air temperature on the soil was well illustrated in March of 1954 when a sharp drop of 6° C in air temperature (Fig. 3) around March 20 was followed by a drop in soil temperatures in the March 31 readings (Figs. 5-8). The snow was wetter at this time than is the case for the winter months, hence was a better conductor, and the drop in temperature was reflected at greater depths in the soil than could otherwise be expected.

Discrepancies in the 1951 and 1954 frost-level measurements (Tables III and IV) in cases other than sites 34 and 35 may be attributable to the extraordinarily warm and dry summer of 1954. As the water level in the ponds decreased, the temperature of the water increased rapidly during the day, and with it, that of the saturated soil below. Ultimately, all but the deeper pools (stations 8, 108, and 24 and 124) were devoid of standing water. The surface soil here, however, as in the case of the "high dry" stations, remained damp despite the comparatively dry summer. In spite of the apparently higher insulating capacity of the peat that is merely damp as compared with peat that is saturated (such a difference in insulating capacity is indicated by the fact that the frost level is higher under damp peat than under saturated peat), the frost level still receded with the added number of hot days. Frost level data collected during August of 1952 and 1953 could have helped substantiate this.

Temperature Inversion with Depth (Figs. 5-8; Tables V-VI). The temperature inversion due to a temperature lag as recorded in temperate climates is observable here with the temperature curves systematically lagging as the depth increases. In the fall, for example, the soil reaches 0° C at successively later dates at successively lower depths. But in that region of the active layer immediately above the frozen ground the temperature reaches 0° C before the middle of the active layer does, though later than the upper few inches.

Table VI lists the dates at which the surface of the soil, the soil at a 12-inch depth, and the lower stratum of the active layer reach 0° C in the spring and in the fall. Generally the lower layer freezes or thaws later than the upper by as much as a week or a hundred days. At a constant depth of 12 inches the lag varies from station to station and, even at a particular station, from year to year. Occasionally in the spring the soil at this depth or even lower may reach 0° C before the surface does. This is probably a function of "warming" from below. None of the stations reached the level of the perennially frozen ground, and therefore, no measurements were made of its temperature. But the data collected at the various stations, including those used for purposes of illustration in this paper (numbers 8, 12, 35, and 29), indicate that the soil at the surface of the perennially frozen ground or just above it does not necessarily freeze during the winter, and therefore could exert a warming effect on the layers above it. A longer lag of 10 to 40 days is found both spring and fall in areas where the soil is relatively dry (sites 34, 35, 134, 100) and thus, a better insulator. This holds

Table VI

Comparison of dates at which ambient air, surface, 12-inch depth, and lower portion of active layer reach 0°C

Station no.	Depth in.	1951		1952		1953		1954
		Spring	Fall	Spring	Fall	Spring	Fall	Spring
8	2	June 8	Nov. 19	May 8	Nov. 4			
	15	June 20	Nov. 24	June 5	Nov. 4			
	55	July 24	Nov. 19	Oct. 16	Oct. 16			
108	0						Nov. 4	May 29
	12						Dec. 2	June 11
	54						Dec. 18	July 28
10	8	April 26	Oct. 31	Apr. 23	Dec. 5	Mar. 16	Dec. 1	May 13
	30	all winter	Oct. 31	all winter	Nov. 18	Mar. 16	Dec. 17	May 10
110	0						Nov. 1	May 10
	12						Dec. 17	May 17
	60						Jan. 29	Apr. 26
11a	0			Apr. 23	Oct. 15		Nov. 1	May 10
	12			Apr. 23	Jan. 4	May 23	Nov. 3	May 10
	66			Apr. 23	Oct. 15	all winter	Nov. 3	all winter
111	0						Nov. 3	May 13
	12						Dec. 17	May 13
	60						Dec. 17	all winter
12	1	May 15	Oct. 2	Apr. 22	Oct. 15	May 20	Nov. 1	May 8
	11	May 15	Nov. 15	Apr. 23	Oct. 15	June 20	Nov. 17	May 15
	21	May 15	all summer	Apr. 23	Oct. 15	July 8	Nov. 17	May 17
112	0						Oct. 26	May 13
	12						Nov. 17	May 18
	22						Dec. 17	May 20
15	9	May 15	Nov. 16	Apr. 23	Nov. 4	May 20		
	45	Feb. 26	Dec. 12	Feb. 5	Dec. 13	May 20		
115	1						Nov. 3	Apr. 28
	13						Feb. 13	Apr. 1
	53						Feb. 13	all winter
23	6			Apr. 23	Dec. 5	Apr. 15	Dec. 1	Apr. 26
	60			all winter	Mar. 15	all winter	Dec. 28	Feb. 25
123	0.5						Dec. 1	May 10
	12.5							May 10
	61.5							May 13
24	0			Apr. 23	Dec. 26	Mar. 10	Dec. 21	Apr. 26
	12			Apr. 23	Jan. 4	Jan. 4	Dec. 21	Apr. 26
	72			Apr. 23	above freezing all winter		Dec. 24	Apr. 13
124	1						Dec. 1	May 13
	13						Feb. 26	June 15
	73						above freezing all winter	

Table VI (cont'd)

Station no.	Depth in.	1951 Spring	1951 Fall	1952 Spring	1952 Fall	1953 Spring	1953 Fall	1954 Spring
26	0			May 27	Nov. 4	June 1	Nov. 17	
	12			May 8	Dec. 6	June 1	Dec. 8	May 18
	84			Feb. 21	above freezing all winter		Mar. 18	Mar. 18
126	0						Nov. 9	June 15
	12						Dec. 4	May 28
	96						Mar. 18	all summer
29	0			Apr. 24	Dec. 6	Mar. 31	Nov. 4	
	8			Apr. 24	Dec. 6	all winter	Dec. 18	May 12
	112			all winter	above 0° all winter	all winter	above 0° all winter	
129	0						Dec. 1	May 4
	12						Dec. 20	May 11
	120						above 0° all winter	
34	0			Apr. 27	Oct. 13	May 20	Oct. 24	May 12
	12			May 27	Nov. 25	May 20	Nov. 24	May 20
	24			May 27	Dec. 5	June 1	Dec. 1	May 24
134	0						Oct. 22	May 10
	12						Dec. 3	June 4
	30						Dec. 17	June 21
35	0			Apr. 27	Oct. 8	May 24	Oct. 22	May 12
	12			May 7	Nov. 4	May 28	Nov. 24	May 26
	24			May 26	Dec. 17	May 31	Nov. 2	June 1
100	0						Nov. 7	May 9
	12						Nov. 17	June 9
	42						Nov. 17	Aug. 2
Ambient Air		**May 27**	**Oct. 10**	**May 8**	**Sept. 30**	**May 29**	**Oct. 20**	**May 12**

true not only for a temperature of 0° C, but for the low and high extremes of temperature occurring in the winter and the summer (Table V). Stations where standing water occurs, or where the soil is saturated, usually reach 0° C in the spring at all depths at about the same time, and often before the ambient air temperature reaches this average. The higher conductivity of water over that of damp, but not saturated, peat, offers an explanation for this. The better conductivity of sand as compared with that of peat also can help to explain the rapid warming of stations 26 and 126, where the water table is well below the surface of the ground. Stations 8 and 108 are in an open exposed swamp where a relatively thin mantle of hard snow collects. As a result the soil generally becomes much colder throughout, and freezes and thaws with the lower strata lagging behind the upper, much as in the higher, drier areas. In the fall on the other hand, the lag of the lower strata behind the upper in wet areas may vary within a range of from zero to over a hundred days, the amount depending upon the depth to which the active layer extends, and upon the amount of snow cover to provide insulation. The effect of snow cover will be discussed in a later section.

Soil at or near the surface of the ground reaches 0° C in the spring sometimes as early as 80 days before, or as late as 19 days after the ambient air temperature reaches 0°C. These readings were taken during the daytime in all cases. The early extremes occur in areas where the soil is saturated or water covered (and often frozen at this time of year), and topped by a layer of soft snow of at least 12-inch depth. The snow is wet at this time of year, and this, combined with the frozen saturated soil, provides an excellent conductor for heat. The late extremes occur where the soil, whether dry or wet, is topped by a thick or thin layer of hard-packed snow. Under this snow the soil temperatures were lower during the winter months than was the case for the soil under soft snow. Hence, it appears that greater extremes of cold in this soil simply cause it to take longer to warm up in the spring. In the fall the soil reaches 0° C from 2 to 70 days after the ambient air does. The late extremes are found where the soil is under water and covered by a 10-or-more-inch thick insulating layer of snow. The early extremes occur in the open areas where little or no snow accumulates until late winter, and thus provides little insulation for the soil.

Extreme Temperatures of the Soil (Table V). The surface of the soil in the ponds and at the edges of ponds in the wooded areas where an ample layer of snow (over 15 inches) collects, reached temperatures through the winters of 1950-52 of +0.5° to —4.0° C. Little snow accumulated during the winter of 1953-4 until five or six weeks later than had normally been the case. As a result, the ground was more poorly insulated and the pond surfaces reached temperatures of —1.0° to —11.0° C. Stations 8 and 108, which normally have little snow cover, regularly reach temperatures of —8.0° to —15.0° C at their soil surfaces.

At the lowest soil levels at which temperatures were recorded, many stations in the swamp and pond areas in the forested zones rarely go below +0.5° to —1.0° C.

At the higher drier stations, much greater extremes in temperature at or near the surface are reached both winter and summer (Table V). In the non-forested region, temperatures at certain stations may reach —25° C. Where insulated by thick soft snow in the forest, the extremes are —7° to —9° C. The gradient quickly falls in areas such as 12 and 112 where a thick dry peat layer insulates the soil below, and where snow adds insulation during the winter months. At stations in the open with little snow for insulation, as for example, 34, 35, 134, and 100, the soil may reach temperatures of —14° C at the lowest depths (24 to 40 inches). The soil is damp enough that, when frozen, it offers little insulation without the assistance of snow.

In the summer, the heat penetration varies considerably, depending not only upon soil type and moisture content, but upon density of plant cover. In most cases the upper layers of soil reached their highest temperatures a

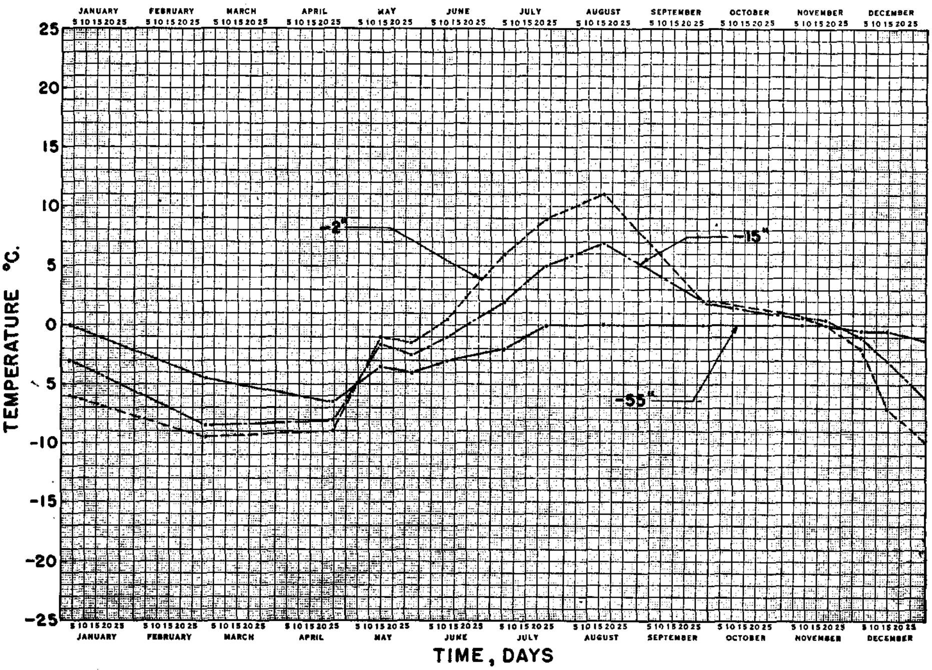

Fig. 5a. Soil temperature with time, for soil temperature station no. 8 for 1951.

month or two before the lower layers did. At station 8 in the summer of 1951 and station 11a in the summer of 1953, however, the lower layers were recorded to have reached their highest temperatures before the upper layers did. It is difficult to account for this except by assuming that plug connections were poor when the readings were made. The upper layer readings in most cases, except where they were 6 or more inches below the soil surface, reflect the temperature of the air during the morning or afternoon when they were recorded; thus a close correlation between them and air or lower soil temperatures cannot be expected. The soil at lower depths, however, is not as subject to change, according to hourly air temperature changes; the records of the temperature at this level then should be suitable for study. At two of the high dry stations, numbers 12 and 35, the temperature of soil at the lowest depths recorded reached its highest extreme earlier than was the case for the other dry stations or for the wet stations. The time of year for these two stations corresponded approximately with the time of year when the air reached its highest average temperature, while the remainder of the stations usually reached their highest temperatures at this depth a month or two later.

Density of plant cover. Plant cover can be divided roughly into two categories, forested and non-forested. The type of cover when considered alone appears to have little effect on the depth of the active layer. Where differences in type of cover affect the accumulation and retention of snow, marked differences in frost penetration occur. This will be discussed later. In the case of sites 34 and 35, the natural vegetal cover was bulldozed off.

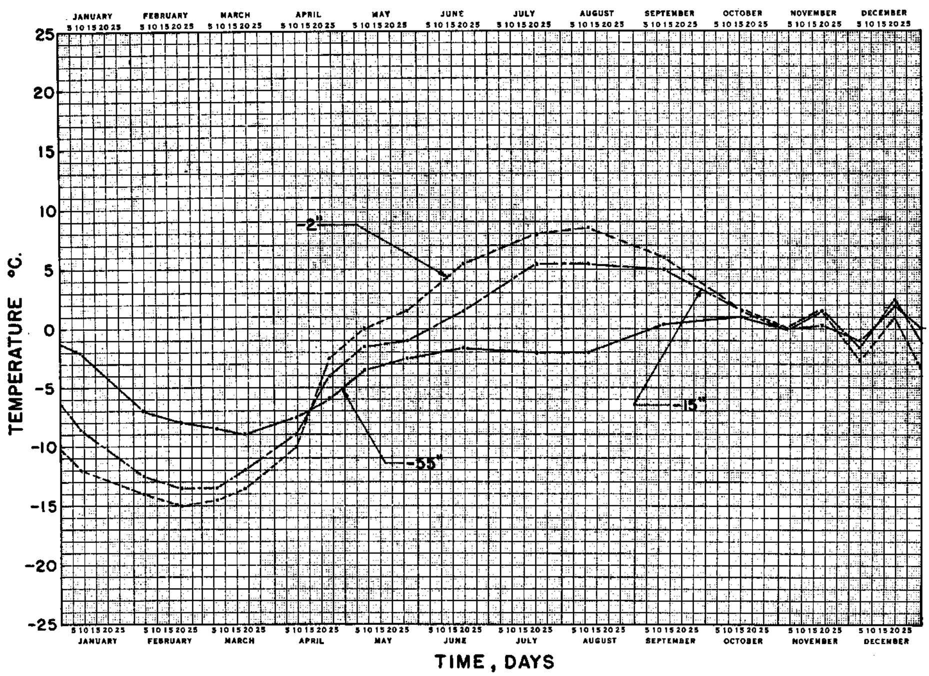

Fig. 5b. Soil temperature with time, for soil temperature station no. 8 for 1952.

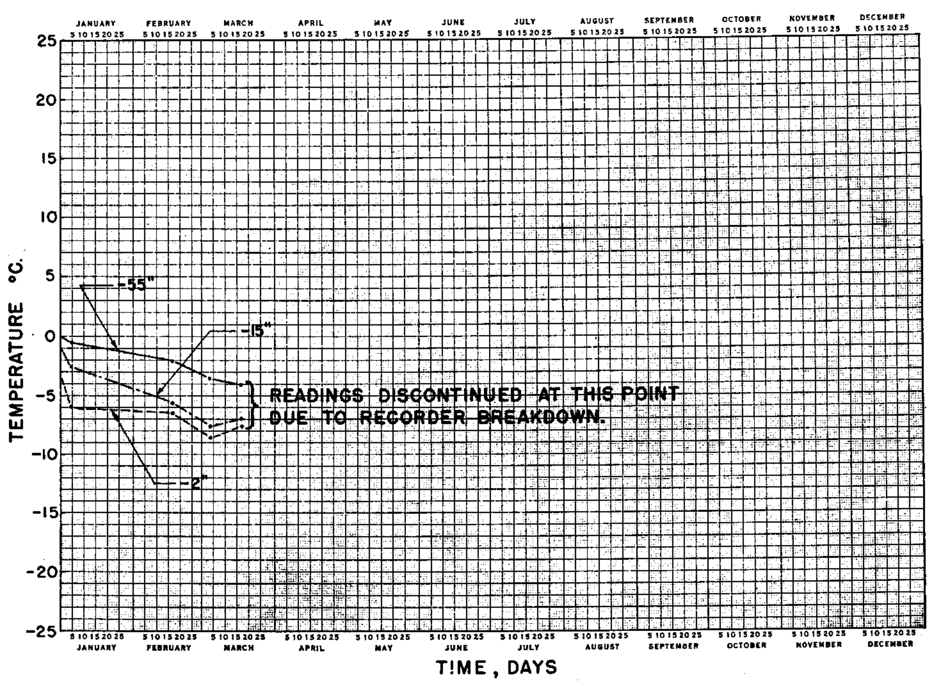

Fig. 5c. Soil temperature with time, for soil temperature station no. 8 for 1953.

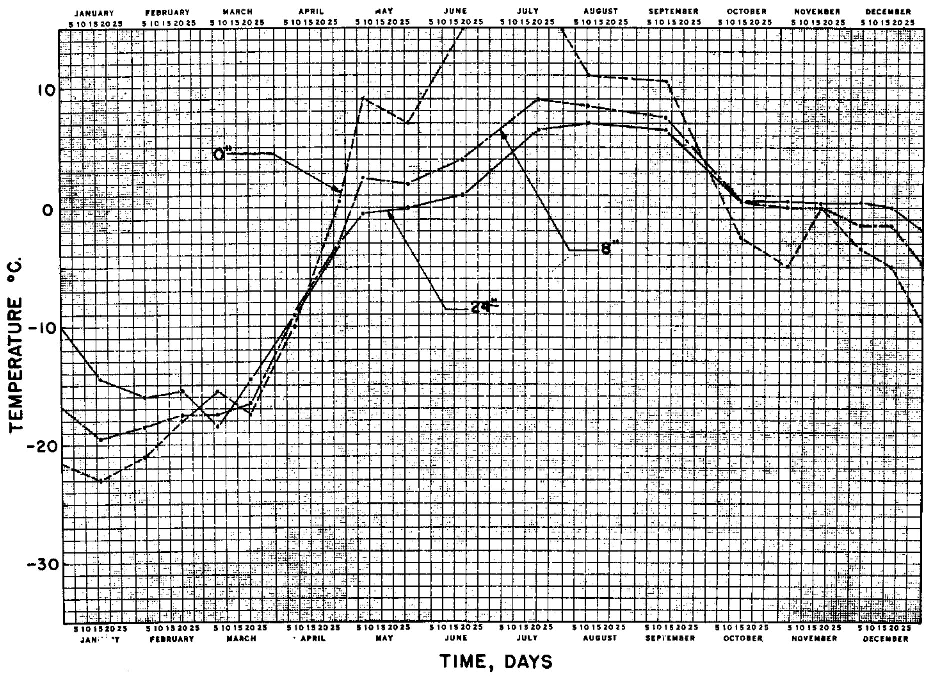

Fig. 6a. Soil temperature with time, for soil temperature station no. 35, for 1952.

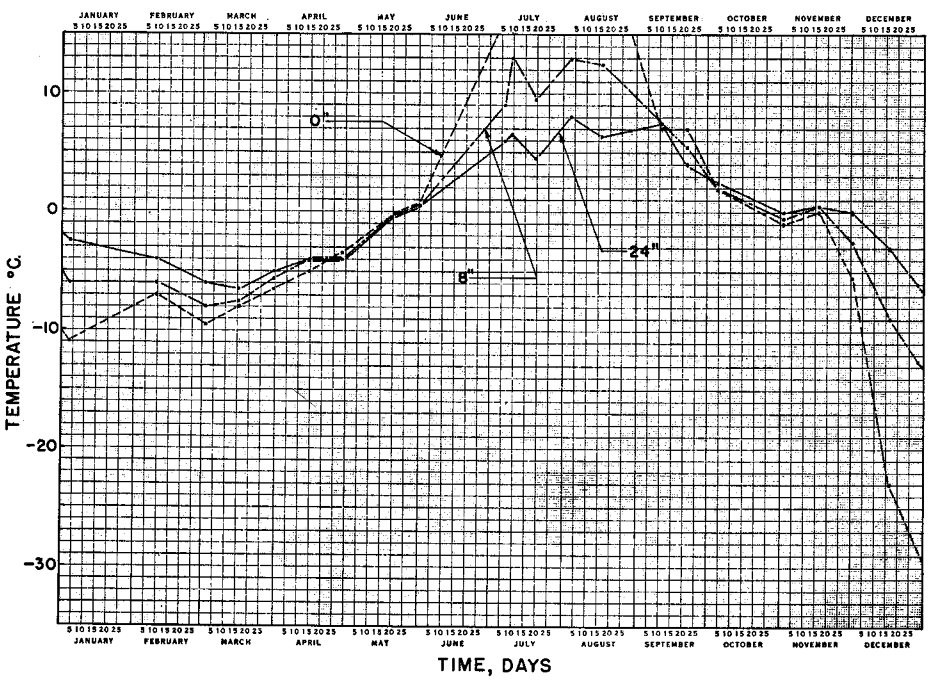

Fig. 6b. Soil temperature with time, for soil temperature station no. 35, for 1953.

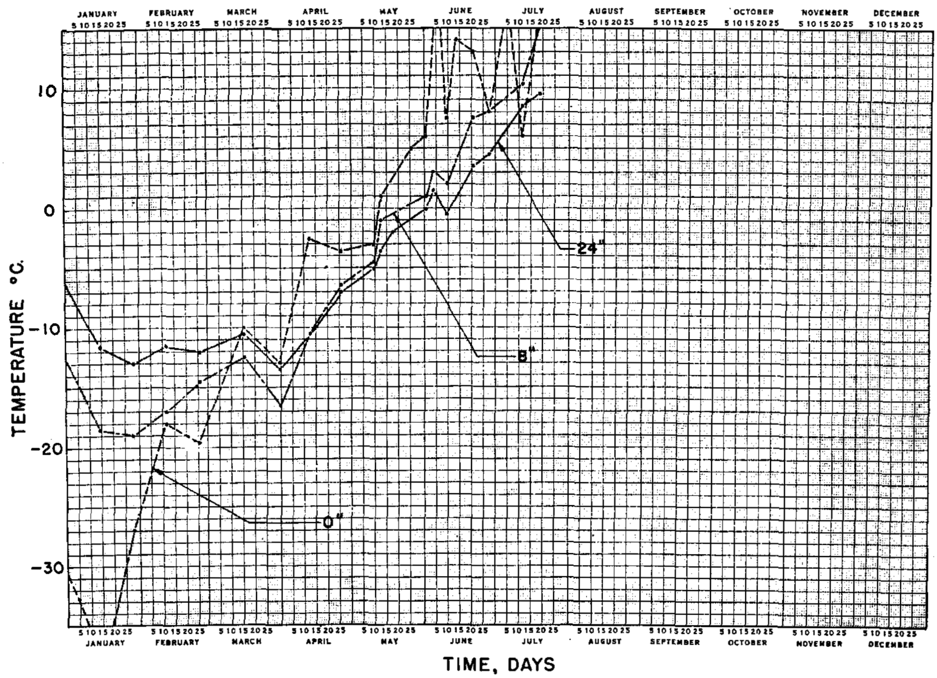

Fig. 6c. Soil temperature with time, for soil temperature station no. 35, for 1954.

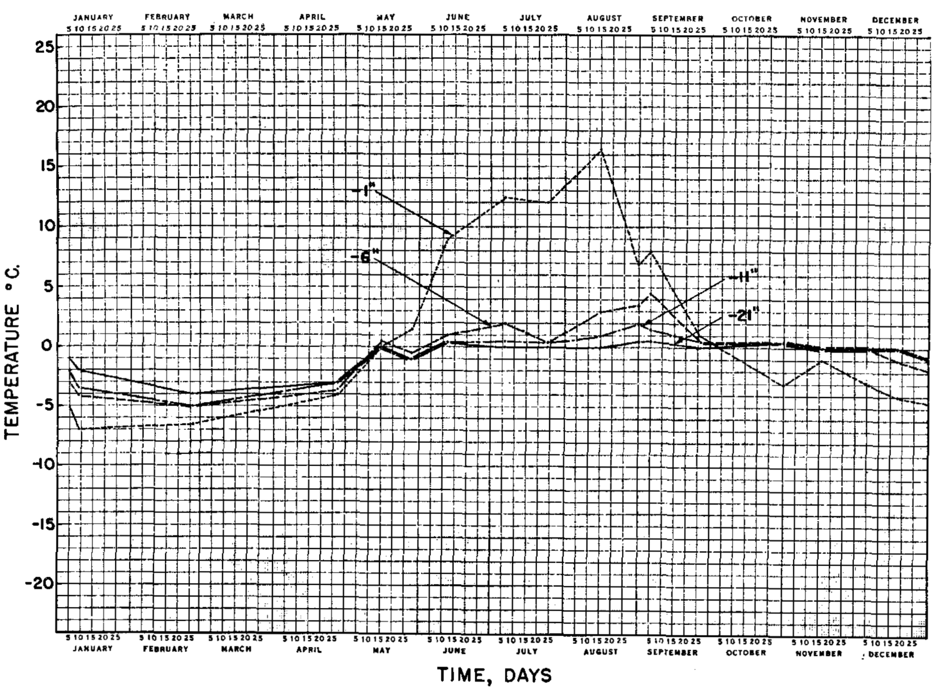

Fig. 7a. Soil temperature with time, for soil temperature station no. 12, for 1951.

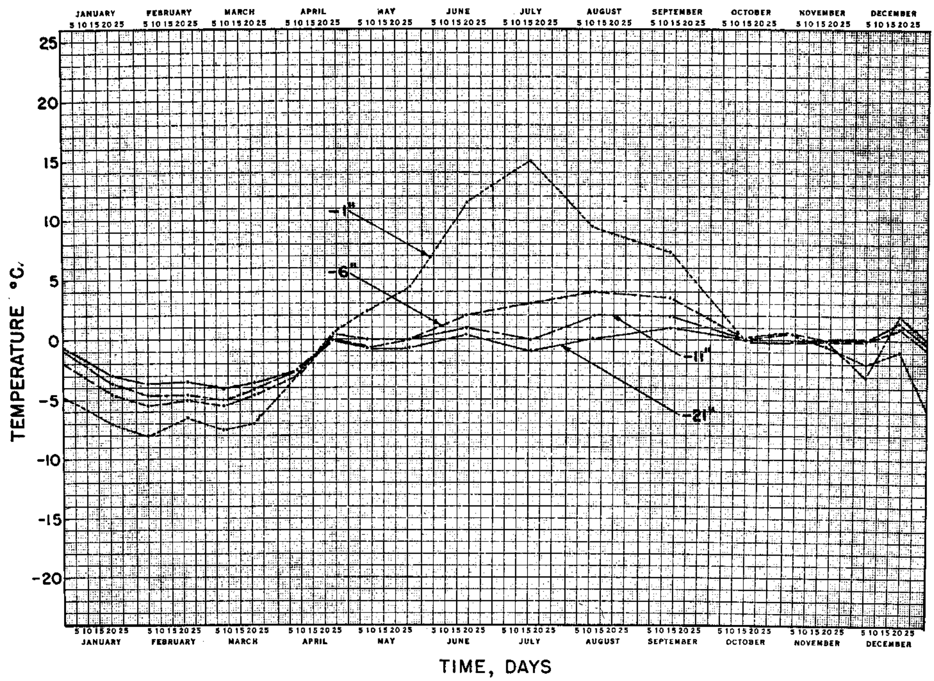

Fig. 7b. Soil temperature with time, for soil temperature station no. 12, for 1952.

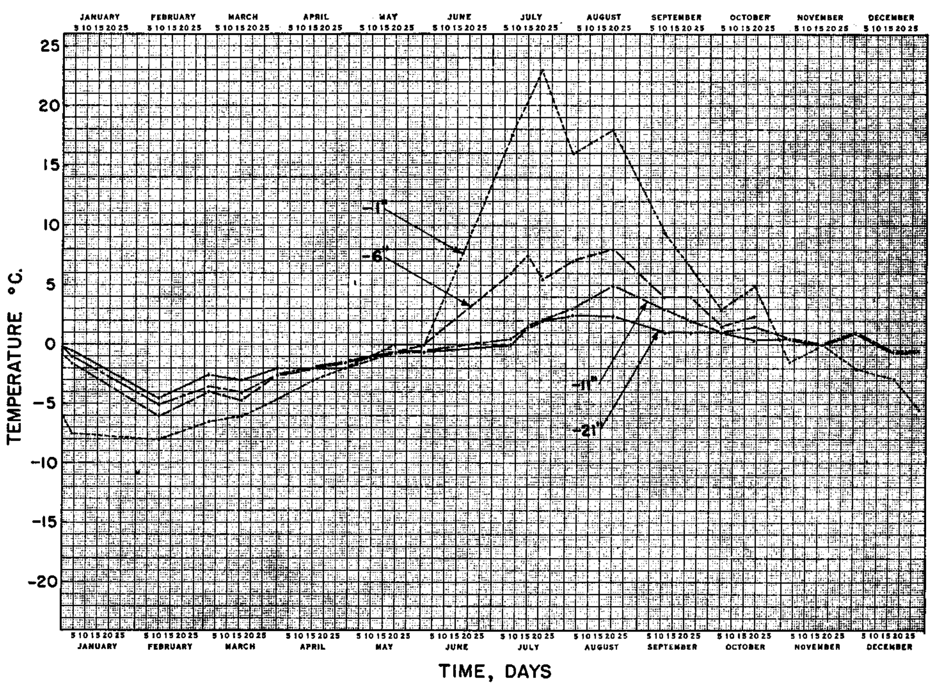

Fig. 7c. Soil temperature with time, for soil temperature station no. 12, for 1953.

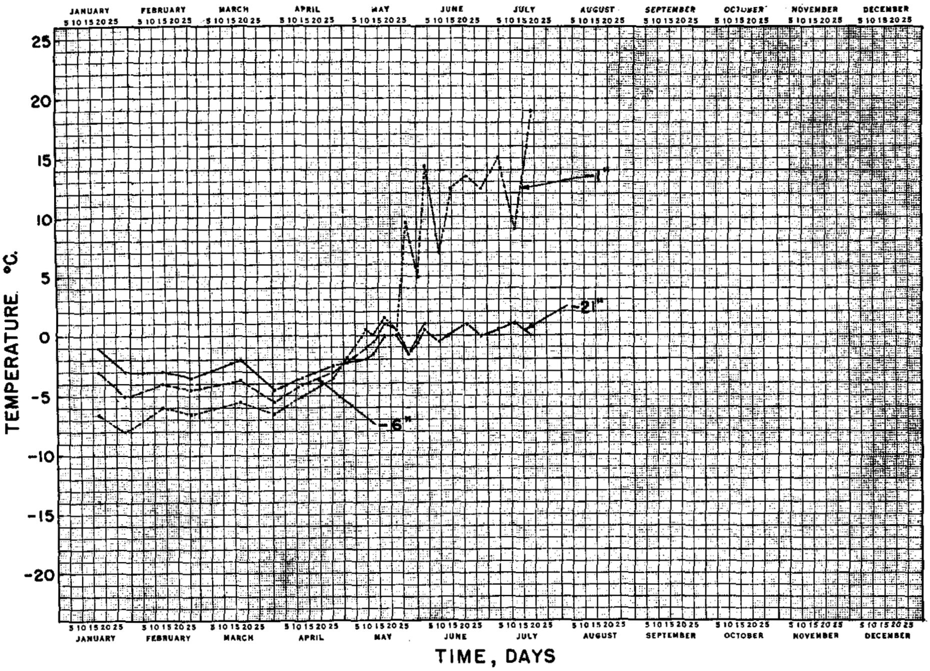

Fig. 7d. Soil temperature with time, for soil temperature station no. 12, for 1954.

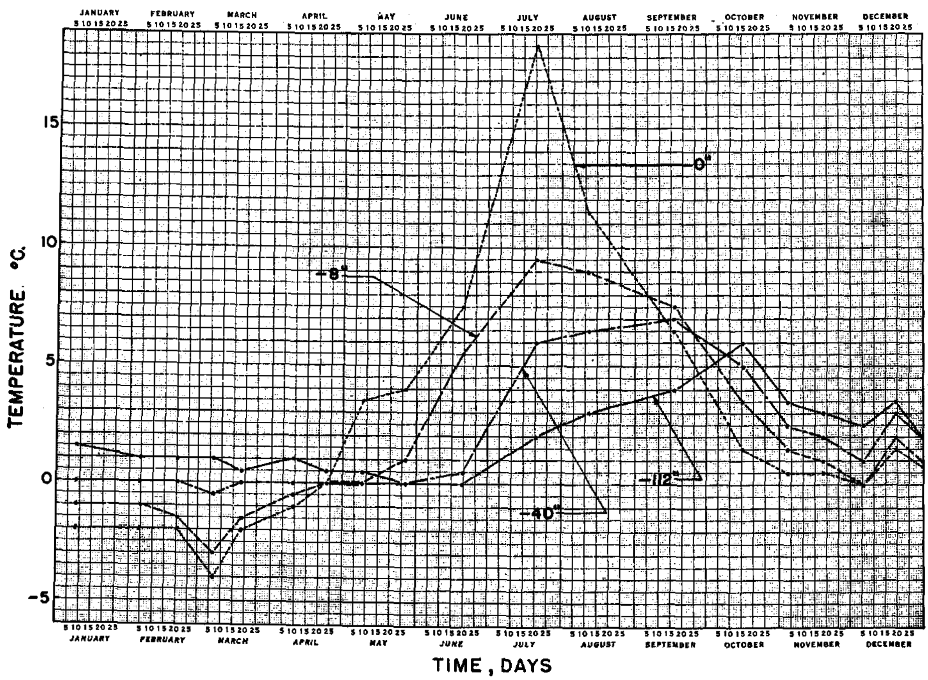

Fig. 8a. Soil temperature with time, for soil temperature station no. 29, for 1952.

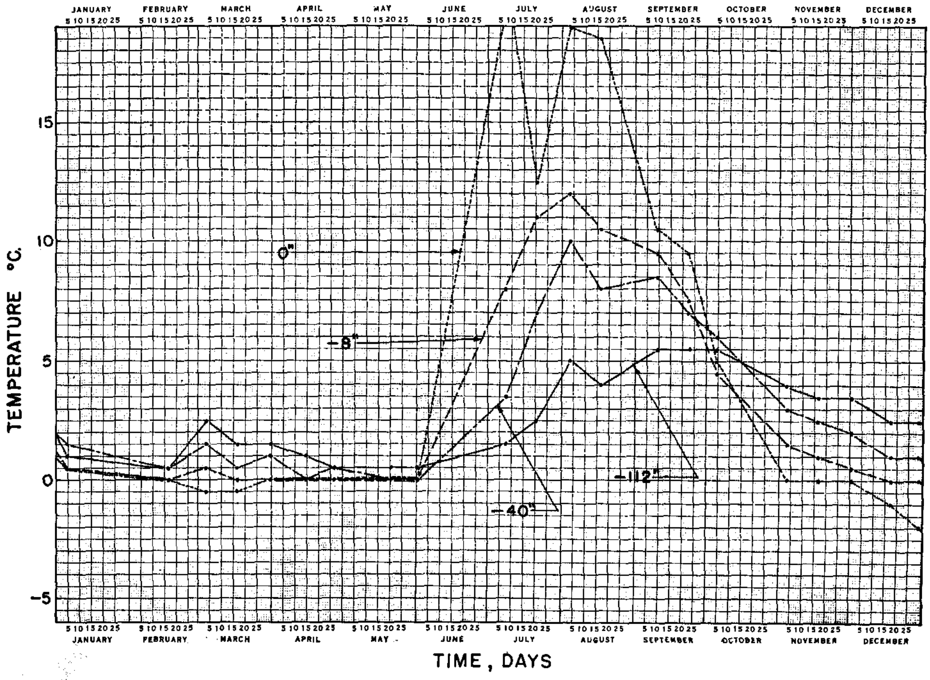

Fig. 8b. Soil temperature with time, for soil temperature station no. 29, for 1953.

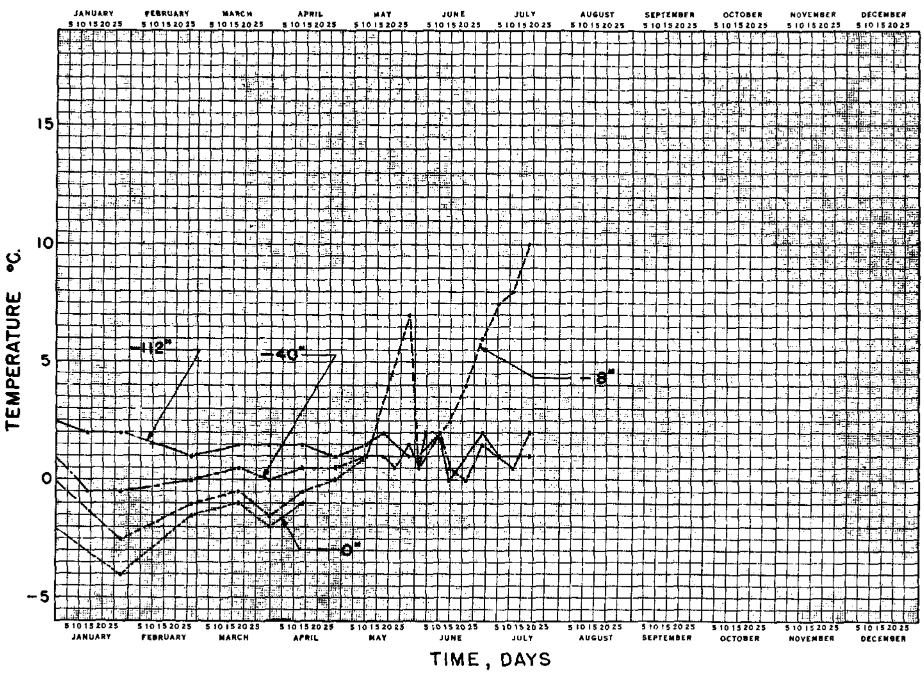

Fig. 8c. Soil temperature with time, for soil temperature station no. 29, for 1954.

Site 35 was sown to lawn grass and site 34 left bare; site 134 represents the same type of area but is undisturbed. Sites 34 and 35 had active layer depths of approximately 30 inches when first disturbed; by August of 1954, the frost level had receded to a depth of over 80 inches in these two, while that of site 134 measured 34 inches. The value of an undisturbed vegetal cover in preserving a relatively constant depth of active layer appears to be great.

Soil Type. Of the areas studied, those stations with a sandy soil (numbers 26, 126 at the sandy base of a clayey-gravel ridge; numbers 29 and 129 on the top of an old sandy beach) have an active layer noticeably deeper than those of other stations (Table III). Stations 26 and 126 are located on high ground, but have soil saturated from a depth of 24 inches below the surface down to the frost level, thereby increasing the conductivity of the sand. The drier area above apparently insulates the layers below sufficiently to produce the difference in frost depth between this site at +96 inches from that of sites 29 and 129 at +132 inches where 2-6 inches of standing water usually is present.

The remainder of the stations where the substratum consists of gravel-clay, sand-clay or other mixtures have frost levels which range from 34 to 90 inches below the soil surface. Within this group those stations in the higher drier undisturbed areas have frost levels ranging from 34 to 78 inches, while those in saturated soil or soil with standing water range from 43 to 92 inches. A broad overlap between these groups exists, probably due to the fact that the water table, even at the high dry stations, is at such a level usually that a relatively shallow layer of moist or dry, but not saturated, peat is present to act as insulation. In areas such as 134, 12 and 7 where the frost level occurs above the water table, the level of its occurrence is higher generally than where the water table occurs a few to several inches above it (Table III). With no precise data on the soil moisture content and exact frost level for the different soil types at varying depths through the season, even generalizations of this broad order are subject to error, and serve to point out the need for further study on this aspect of the problem.

Snow Cover. Normally the first snowfall comes during the last 10 days of September. Scattered snow flurries occur after this time, but not until the middle of October or the first week in November (Table VII), some 10 to 28 days after the average ambient air temperature reaches 0° C, is a measurable depth of snow to be found on the ground. In the flat, open tundra, hard snow may collect to a depth of 12 to 14 inches during the winter. In the forested areas, softer snow collects to depths sometimes reaching 50 or 60 inches.

In the lee of ridges or of trees lining a forest opening, soft or hard drifts of snow occur which may reach a depth of 60 to 130 inches, the hardness of the snow depending upon the degree and duration of exposure to wind. The snow gradually increases in depth through the winter until the end of March or mid-April when it reaches its maximum depth. After this, it melts rapidly and disappears from most areas by the end of May. This melt may take place as early as the middle of April, depending upon the average ambient air temperature and whether or not an April blizzard takes place. In years such as 1952, the daytime temperature may be very high, thus

Table VII

Dates of first and last measurable snow for the spring of 1951, spring and fall of 1952 and 1953, and fall of 1954 at soil temperature stations with dates when average (over 10-day periods) ambient air temperature reached 0° C.

Station no.	1951	1952		1953		1954
8	Oct. 20	Apr. 15	Oct. 15	May 31		
108					Nov. 5	May 12
10	Nov. 1	May 10	Oct. 15	June 15	Nov. 3	May 15
110					Nov. 3	May 20
11	Nov. 1	Apr. 30	Oct. 21	June 10	Nov. 3	May 27
111					Nov. 3	June 5
12	Nov. 5	Apr. 30	Oct. 15	June 10	Nov. 22	May 25
112					Nov. 4	May 22
15	Oct. 31	May 5	Oct. 20			
115					Nov. 4	May 25
23		May 1	Oct. 15	June 10	Nov. 4	May 20
123					Nov. 4	May 27
24		May 1	Oct. 15	June 15	Nov. 1	May 15
124					Nov. 1	May 20
26		June 10	Oct. 15	June 15	Nov. 5	June 15
126					Dec. 2	June 15
29		Apr. 30	Oct. 15	June 2	Nov. 4	May 20
129					Nov. 4	May 22
34		Apr. 20	Oct. 15	June 5	Nov. 20	May 15
134					Nov. 4	May 4
35		Apr. 20	Oct. 15	May 25	Nov. 4	May 13
100					Feb. 20	May 22
Ambient Air	**Oct. 10**	**May 8**	**Sept.30**	**May 29**	**Oct. 20**	**May 12**

producing a rapid melt and an average ambient air temperature of not more than a few degrees below zero. The average weekly ambient air temperature did not reach 0° C until May 8, but the snow had disappeared from all but heavily drifted areas during the period April 15-May 5. During the following springs, the snow had not melted until much later in the year — May 25 to June 15 in 1953, and May 4 to June 5 in 1954. In 1953, the weekly-averaged, ambient air temperature reached 0° C on May 29; the snow had disappeared in a period ranging from 23 days before this date in some areas to as late as 24 days after this date. Those areas where early melt occurred in these years were in open exposed high areas where less snow collected during the winter.

The temperature of the soil at a particular depth may vary considerably from station to station at a particular time. An example of such a variance is shown in Figure 9 where the relation between depth of snow and temperature of soil at a 12-inch depth is shown for February of 1952, 1953 and 1954. By February, the majority of stations have reached their maximum coldness at a 12-inch depth. Some have begun to warm up again, but, on the average, it is the most stable month for this comparison. With increasing depth of snow, the insulation it affords (as indicated by the thermal gradient) also apparently increases; however, after 20 to 25 inches of snow, little change in insulating effect appears to take place. Other variables, however, may enter into the problem. Some of the stations have

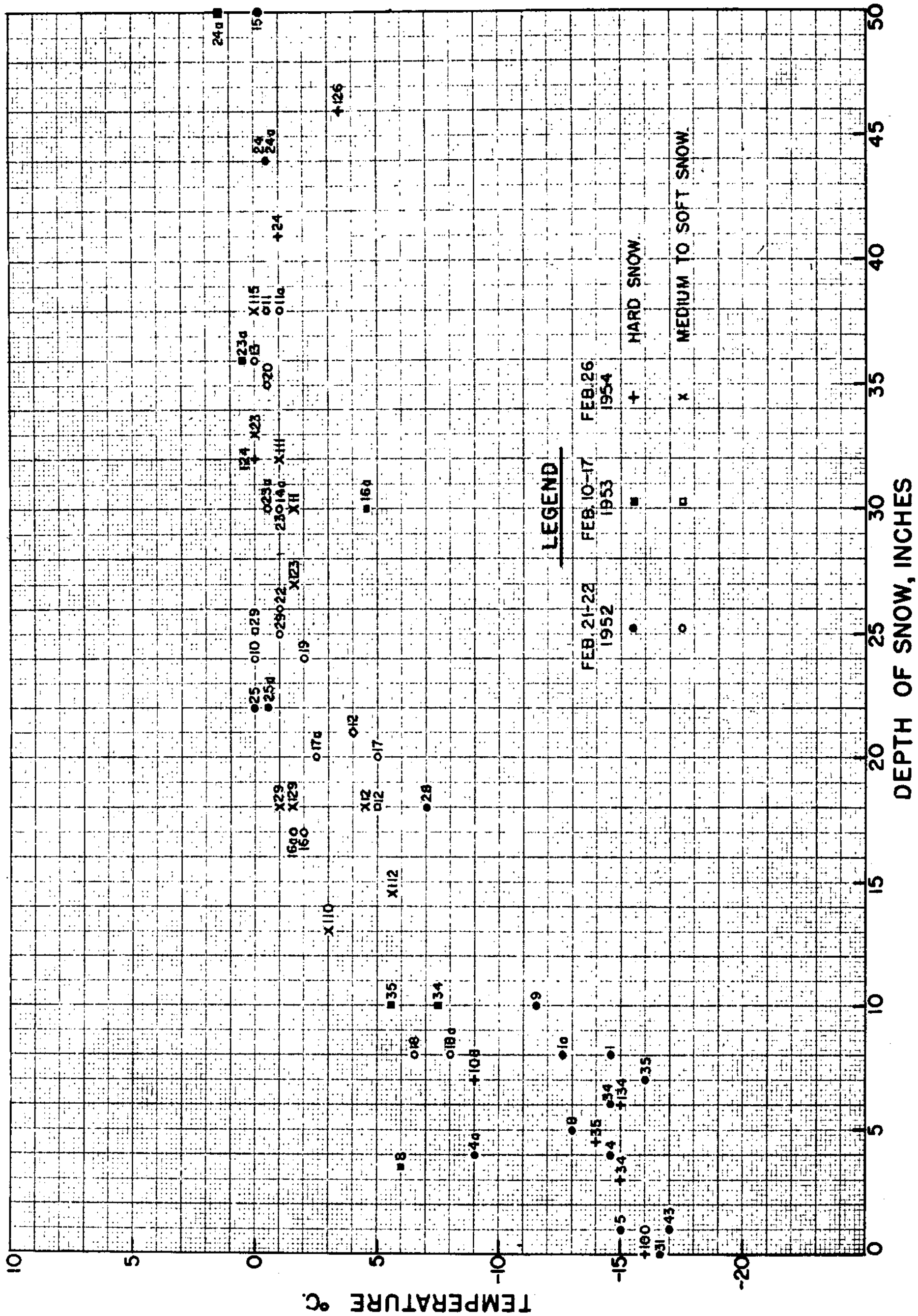

Fig. 9. Relation between snow depth, and soil temperature at 12-inch depth, at different stations.

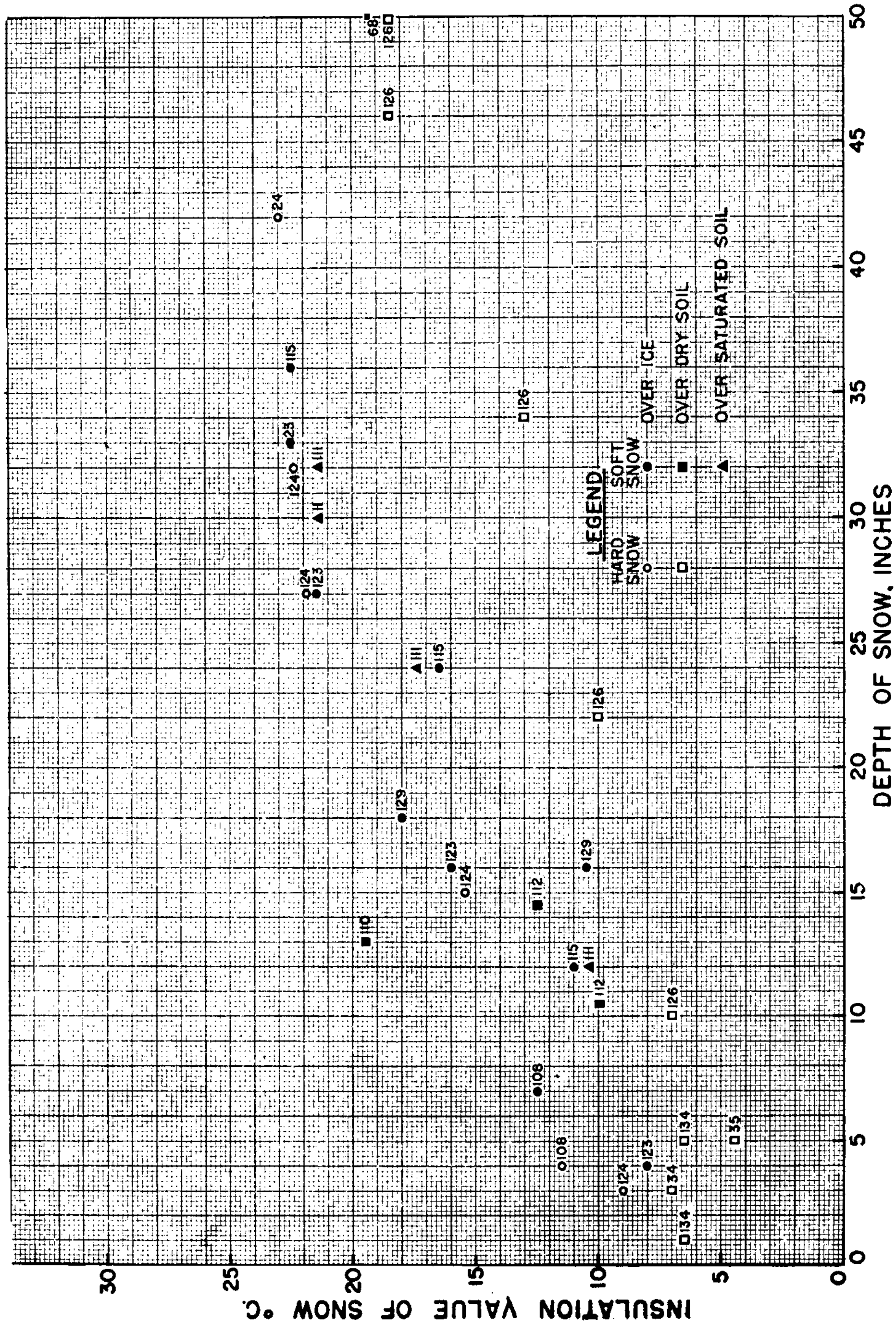

Fig. 10. Relation between depth, and insulation value (difference between snow temperature and ambient air temperature average for previous week) of hard and soft snow, for Feb. 26–27, 1954.

hard-packed snow, others, soft. Some stations have ice between the snow and the soil.

During the winter of 1953-4, temperatures of snow at different depths were taken. Where the thermal gradient of the snow, i.e. the difference in °C between the temperature of the snow at a given depth and that of the ambient air averaged over the previous week, is plotted against snow depth (Fig. 10), a relationship similar to that noted for snow depth and temperature of the soil at a 12-inch depth is found. In both cases, beyond approximately a 20- to 25-inch depth of snow, the insulating effect of the snow alters little. In the case of packed snow over dry ground, such as is found at station 126, the insulation afforded at greater depths is less than for other pack snow stations which are over ice (124, 24). At snow depths of 6 inches or less, the thermal gradient is shallower for the ambient air temperatures of the afternoon when the readings made are reflected more nearly by the snow temperature.

Hard snow, as is expected, is a better conductor of heat than is soft snow (Figs. 9 and 10). While this may be in part a result of the shallower snow cover, the flatter thermal gradient at stations 26 and 126 provides further evidence that hardness of snow is another important factor.

The thermal gradient of snow fluctuates through the winter such that it increases until December then gradually falls to almost zero by late April or May. An example of this is shown in Figure 11. This change in gradient would normally be expected to follow the change in ambient air temperature through the winter: with lowering of ambient air temperature the gradient would increase, with raising of ambient air temperature the gradient would decrease. However, the steepest gradient occurs in mid-December, while the ambient air reaches its lowest temperature early in January. This suggests that a factor other than the insulating value of snow is operative. This factor is probably the "warming" effect of the soil below.

Figure 13 illustrates the change in thermal gradient of 20 to 25 inches of snow at station 111 during the winter of 1953-4. This depth was selected because with this thickness and more of snow, less change appears to take place in the thermal gradient at a given time; i.e. the snow has reached its maximum insulating effect (Fig. 10). However, the gradient increased until a sudden rise in the ambient air temperature (rain was recorded for February 7) caused a drop in its slope. With the end of February, the gradient rose again with the concurrent decrease in air temperature, then fell off until, by May, it was almost flat. The drop in February and through April reflects the diminishing difference between snow and ambient air temperatures, as well as the increasing wetness and consequent increased conductivity of the snow.

The temperature of the snow at the surface fluctuates comparatively little throughout the winter (Fig. 12). Eight inches above the soil surface, however, the temperature fluctuates more erratically, indicating the decrease in the effect of the temperature of the soil below, and an increase in the effect of the temperature of the air above.

Summary

Soil temperatures were obtained at varying depths through the active layer at regular intervals at forty stations in swamp and high dry areas of forested and non-forested localities of the Churchill, Manitoba region, by means of copper-constantan thermocouples and a portable potentiometer. Some have been recorded since November, 1950, some since November, 1951, and the remainder since September, 1953; snow depth and water level measurements have been recorded since November, 1951; snow temperatures have been recorded since November, 1953.

The results of the studies may be summarized as follows:

1. At Churchill, the average thickness of the active layer ranges from 8 to 12 feet for sandy soil; from 3 to 8 feet for clay, clay-sand, or clay-gravel soils topped by a 6- to 12-inch layer of peat. In swamp areas the depth of the upper limit of perennially frozen ground varies depending upon the amount and depth of water. Under water, or in areas of saturated soil, the perennially frozen ground may be 43 to 92 inches below the surface; where tussocks, hummocks, mounds and hillocks occur, the level of the frost rises to within 34 to 73 inches of the surface of the ground.
2. Deeper levels of perennially frozen ground are found in areas with a thin peat overburden than in those areas with a thicker overlying layer of peat.
3. Where plant cover has been removed, the frost level may recede as much as 50 inches during a period of 3 years.
4. Soil temperatures over a period of a year follow a curve of increase and decrease which, on the average, lags behind that of ambient air temperature.
5. During the summer the maximum depth of thaw of the active layer is reached between August 15 and October 15; the average date is September 15.
6. During the winter months the lower limits of the active layer reach their lowest temperature between December 15 and May 15; the average date is approximately March 1.
7. The temperature inversion due to a temperature lag is observable with temperatures systematically lagging as the depth increases.
8. The first measurable snow appears in the fall about 10 to 28 days after the average ambient air temperature reaches 0° C, and disappears in the spring as early as 23 days before and as late as 24 days after the date at which the average ambient air temperature reaches 0° C. The snow disappears earliest where its accumulation has been slightest during the winter months.
9. Generally the lower soil depths freeze or thaw later than the upper by as much as a week to a hundred or more days.
10. In winter, the surface temperatures of soil in ponds in wooded areas with normal snow cover of over 15 inches vary from +0.5° to —4.0° C; in the non-wooded areas where hard snow prevails to depths rarely exceeding 10 inches, the temperature may reach —15° C. Where insulated by

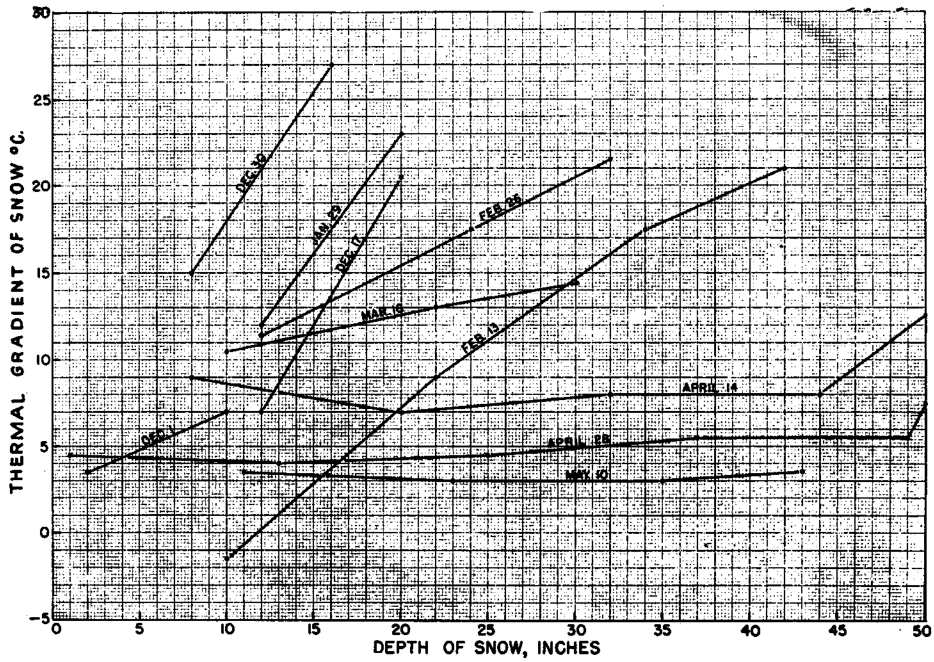

Fig. 11. Relation between insulation value of snow, and snow depth, station no. 111, winter of 1953-4.

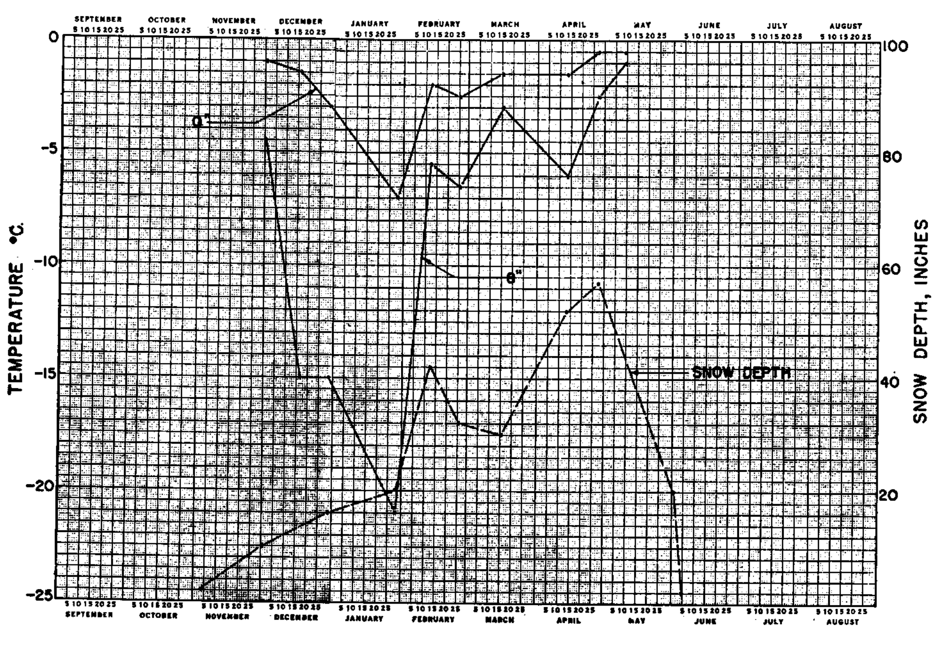

Fig. 12. Change in temperature of snow at 0 inches, and 8 inches above soil surface, with change in snow depth, at station no. 111, winter of 1953-4.

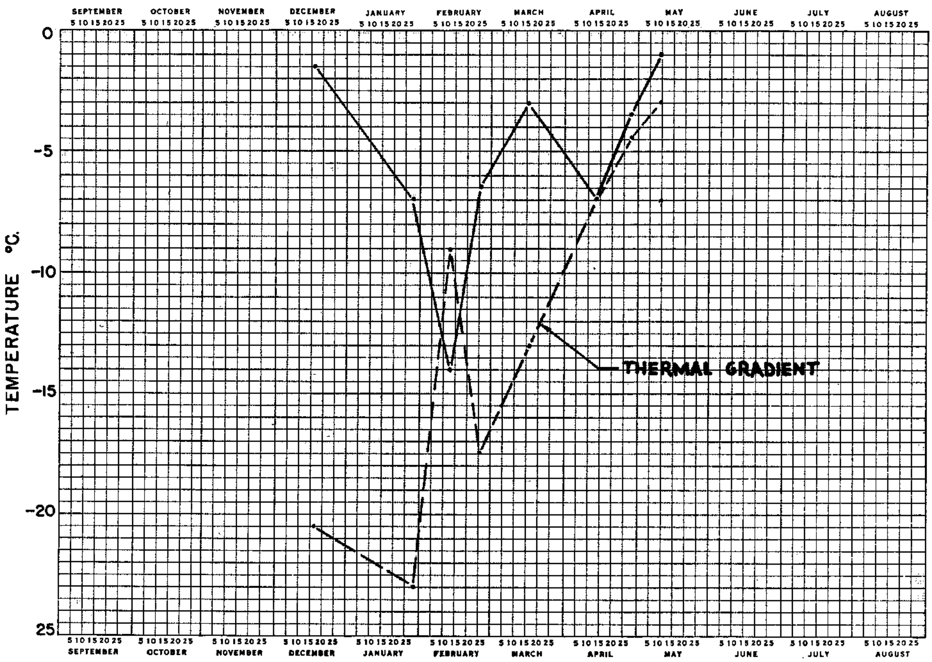

Fig. 13. Change in temperature, and thermal gradient of snow 20 inches below surface of snow, at station no. 111, through winter of 1953-4.

a thick, soft mantle of snow in the forest, the extremes of the drier soils are —7° to —9° C.

11. Where snow accumulation is great during the early part of the winter the lower levels of the active layer may never go as low as 0° C; rather, they may remain at temperatures just above this value. The same situation is found where the upper limit of perennially frozen ground occurs at great depths, as in wet sandy soils or where there is deep standing water.

12. The role of snow as it affects the rate of freeze and thaw of the active layer varies according to its hardness, moisture content and depth. During the winter months, the snow which collects in the densely wooded areas is soft and, as a rule, deep. In the thinly wooded areas and in the open it is hard packed. Hard and/or wet snow was found, as expected, to be a better conductor of heat than snow which was soft and/or dry. The thermal gradient of the snow, i.e. the difference in temperature of the snow with depth, is affected by changes in ambient air temperature and by the temperature of the soil, ice or water below. The thermal gradient was taken to indicate the insulating effect of the snow at the particular time involved.

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