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SOIL AND AIR TEMPERATURES AT OTTAWA

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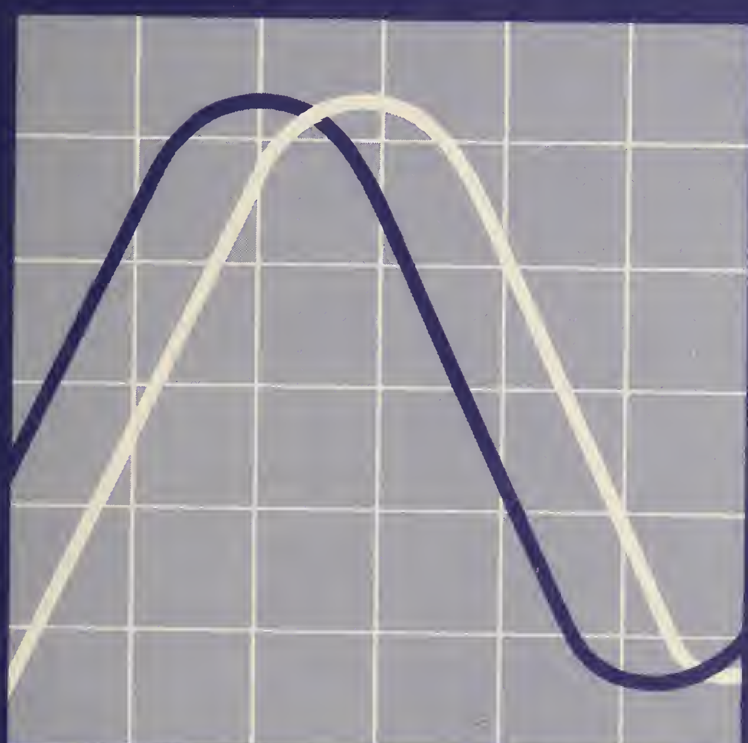

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CONTENTS

SOIL AND AIR TEMPERATURES AT OTTAWA

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INTRODUCTION

Temperature exerts a leading influence on all life processes by controlling the rate of chemical reactions. Diurnal and seasonal variations, relative soil and air temperatures, and particularly the extremes are vital to normal plant development, survival, and distribution (Threshow 1970). Although the influence of soil temperature (Ts) on plants is less obvious than that of air temperature (Ta), it is often more important (Chang 1968). Time of seeding, type and rate of fertilization, absorption of water and nutrients by growing plants, microbial activity, winter survival of plants, increase and winter survival of many insects, and occurrence of various plant diseases are influenced by Ts. The nutrition and resulting yields can probably be increased more by controlling Ts than by controlling any other single soil physical factor (Hillel 1972).

In this publication, soil and air temperatures at Ottawa for the 10 years 1961-1970 are compared and the main controlling factors as well as certain implications are discussed.

CONTROLLING FACTORS

Solar Radiation

Solar radiation is the main source of heat at the soil-air interface and 53% of it reaches the ground surface to constitute what is commonly called global solar radiation (Qt). One quarter of Qt is reflected, and the remainder is absorbed at the surface (Sellers 1969). In addition, heat is lost at the surface by long-wave radiation, but 80% of it is reradiated by the atmosphere to the ground. The overall effective radiant energy at the surface is termed net radiation (Qn) and is used chiefly to warm air and soil, to melt snow and ice, and to evaporate water.

At Ottawa, average daily Qt increases from 106 langley (ly) in December to 524 ly in June. The ratio of net to global radiation (Qn:Qt) ranges from −0.47 in December to 0.46 in June (Table 1). Plants benefit from such an annual cycle. Qt is greatest in spring and summer when it is needed to melt snow, to warm the soil and air, and to promote rapid growth and development of plants. Its gradual reduction in the fall is important for the hardening of plants. The lower level of Qt in winter ensures a continuous snow cover, which protects plant roots and low plants from the cold air above.

TABLE 1. TEN-YEAR AVERAGES (1961–70) OF RADIATION (QT AND QN, LY/DAY), WATER BALANCE (P-PE, IN.), AND GROUND SNOW COVER (MSD [IN.] and SCD [NO.])

Variable	J	F	M	A	M	J	J	A	S	O	N	D
Qt	145	235	336	398	489	524	507	421	329	213	114	106
Qn	-49	-33	47	150	215	241	228	177	109	34	-16	-50
Qn:Qt	- 0.34	- 0.14	0.14	0.38	0.44	0.46	0.45	0.42	0.33	0.16	- 0.14	- 0.47
P				2.4	2.1	2.9	3.4	3.4	3.2	2.3		
PE				2.6	4.5	5.0	5.0	3.8	2.6	1.2		
P–PE				-0.2	-2.4	-2.1	-1.6	-0.4	0.6	1.1		
MSD	10.7	15.7	16.0	3.1						0.9	4.5	8.3
SCD	28.9	28.0	24.3	2.6	0.1					0.6	7.6	20.2

Qt: global solar radiation
MSD: maximum snow depth
P: precipitation
P-PE: water balance
Qn: net radiation
SCD: number of days with snow cover
PE: potential evapotranspiration

Advection

The horizontal motion of air masses (advection), which may be warmer or cooler than local air, influences the temperatures of both air and soil. This factor is important in the Ottawa area where weather usually changes every 3 or 4 days. However, its contribution to temperature is difficult to quantify.

Thermal Properties

Differences between soil and air temperatures may be largely explained by the following thermal properties: thermal molecular conductivity, volumetric thermal capacity, and thermal diffusivity.

The thermal molecular conductivity (λ) is the rate at which heat passes through a unit area of a given substance when a temperature gradient of 1.0° C/cm exists. It constitutes the main process of heat transfer through the soil. The λ is about 68 and 13 times greater in wet and dry soil respectively than in still air (Ouellet 1972). Heat is transferred through the air mainly by convection and turbulence, although λ is important close to the surface (Trewartha 1954).

The volumetric thermal capacity (c) is defined as the amount of heat needed to warm 1 cm^3 of a substance by 1°C. The c of water is 3,448 times greater than that of air and 2.9 and 4.0 times greater than the capacities of wet and dry clay respectively (Ouellet 1972). At Ottawa, as is general for Eastern Canada, the importance of c to agriculture is particularly significant in spring when the soil is saturated with water. The energy required is higher and, therefore, the period of time required to warm the soil is greater if the water content is high.

The thermal diffusivity (k) is the change in temperature (°C) that occurs in 1 sec when the temperature gradient changes 1°C/cm^3 (Chang 1968) and is expressed by the ratio λ:c. It indicates the facility with which the temperature of a substance is changing, and it controls temperature fluctuations in the soil. The k of still air and wet clay are respectively 143 and 8 times larger than that of water (0.0014 cm^2 sec^{-1}). When computed by comparing the temperature amplitude at two depths (Carson 1963), the k of soil at Ottawa has been found to be above the average for the country (Table 2). This is attributable to the relatively good moisture regime prevailing in this area.

TABLE 2. SOIL THERMAL DIFFUSIVITY (K,CM^2 SEC^{-1}) AT OTTAWA COMPARED WITH THE AVERAGE IN CANADA

Layer (in.)	Ottawa k	Canada k
1–4	0.00064	0.00060
4–8	0.00388	0.00134
8–20	0.00522	0.00304
20–39	0.00490	0.00384
39–59	0.00508	0.00372

Type of Soil

The type of soil influences soil temperature through its water holding capacity, which depends on its texture and structure. The color of the surface of the soil is also involved because pale-colored soils reflect more radiation than dark-colored soils and consequently absorb less heat of radiation.

Soil Water Content

The water content of the soil has the greatest influence on soil temperature by affecting all the radiative and thermal properties of soil. It is commonly determined by the difference between precipitation (P) and potential evapotranspiration (PE). At Ottawa, the soil loses more water than it gains from April to August (Table 1), whereas the reverse is true from September to March. There is generally no real deficit of water before the middle of June, because of the abundant reserves existing in spring. Here, PE was estimated by the model developed by Baier and Robertson (1965).

Ground Snow Cover

Because of its low thermal conductivity, ground snow cover reduces soil heat loss and temperature fluctuations. It prevents soil cooling by ground radiation and minimizes the depth of frost penetration. At Ottawa, the influence of snow cover on soil temperature is important from November to March. The snow cover season (difference between the first and last dates of snow cover) lasts 138 days (Potter 1965). However, the true number of days with snow cover averages 112 (Table 1).

CLIMATE

Based on the location of the meteorological station operated by the Canada Department of Agriculture, Ottawa stands at the latitude 45° 23′N, the longitude 75° 43′W, and the altitude of 260 ft above sea level. Located in southeastern Ontario, Ottawa is about 250 miles east of the Great Lakes, 550 miles west of the Gulf of St. Lawrence, and 700 miles south of Hudson Bay. The effect of the Great Lakes is scarcely noticeable in southeastern Ontario (Canada Department of Transport 1962).

The Ottawa area lies on one of the main storm tracks of North America. Alternate high and low pressure systems moving from west to east (Chapman 1966) are the causes of frequent weather changes, particularly in winter. The climate is characterized by a cool to warm summer, frontal summer rainfall, westerly winds, a cold winter, and a long snow cover season. This type of climate is termed "humid continental" by Trewartha (1954).

Degree-days above 42°F numbered 3,400 for the April—October period. The frost-free period averages 137 days extending from May 13 to September 28. The moisture regime is one of the most favorable to agriculture in Canada, even if some irrigation may be necessary in midsummer (Chapman 1966). Precipitation, which is well distributed throughout the year, amounts to 33 in. The season with snow cover extends from November 19 to April 6 (Potter 1965).

DATA

Observations

Soil and air temperatures data were obtained within the climatological network administered by the Atmospheric Environment Service. Daily maximum and minimum air temperatures were recorded at a height of about 4.6 ft in a standard meteorological shelter. Soil temperatures were measured under short grass by thermistors twice a day (8:00 a.m. and 3:00 p.m.) at the depths of 0.4 (1961–65), 2.0 (1966–70), 4.0, 8.0, 20.0, 39.0, and 59.0 in. The observations taken at 0.4 and 2.0 in. were averaged and are reported as the mean temperature at the 1-in. depth. The soil observed was an imperfectly drained loam, originating from glacial till deposition and belonging to the soil series Mathilda.

Units

Data are reported in English units, so that the comparison with other stations may be facilitated. The Fahrenheit (F) scale is still used by the Canadian national weather service for climatological observations and publications.

Definitions

The types of temperature referred to in this publication are defined as follows.

Daily maximum, minimum, and mean temperatures are the highest, lowest, and mean temperatures during a continuous period of 24 hr.

Monthly and annual maximum, minimum, and mean temperatures are the monthly and annual averages of daily maximum, minimum, and mean temperatures for the period concerned.

Highest and lowest temperatures are the highest and lowest daily temperatures recorded during the periods concerned.

Symbols

The following symbols are used throughout the text. Qt and Qn are global and net solar radiations. TS and Ta are soil and air temperatures referred to in general. Tmax and Tmin are maximum and minimum temperatures. T1, T4, T8, T20, T39, and T59 are soil temperatures at the depths of 1, 4, 8, 20, 39, and 59 in. $\overline{\text{T}}$a and $\overline{\text{T}}$s are mean air temperature, and mean soil temperature for the top 39-in. layer.

Tables

Unless stated otherwise, data included in the tables represent 10-year averages (1961–70).

ANNUAL TEMPERATURES

Annual Cycles of Temperatures

Annual cycles of Ts and Ta at Ottawa exhibit a colder period from November to April and a warmer one from May to October. Ts and Ta show the same type of sigmoid curve as Qn (Figure 1). However, extreme values of Qn, $\overline{T}a$, and $\overline{T}s$ lag

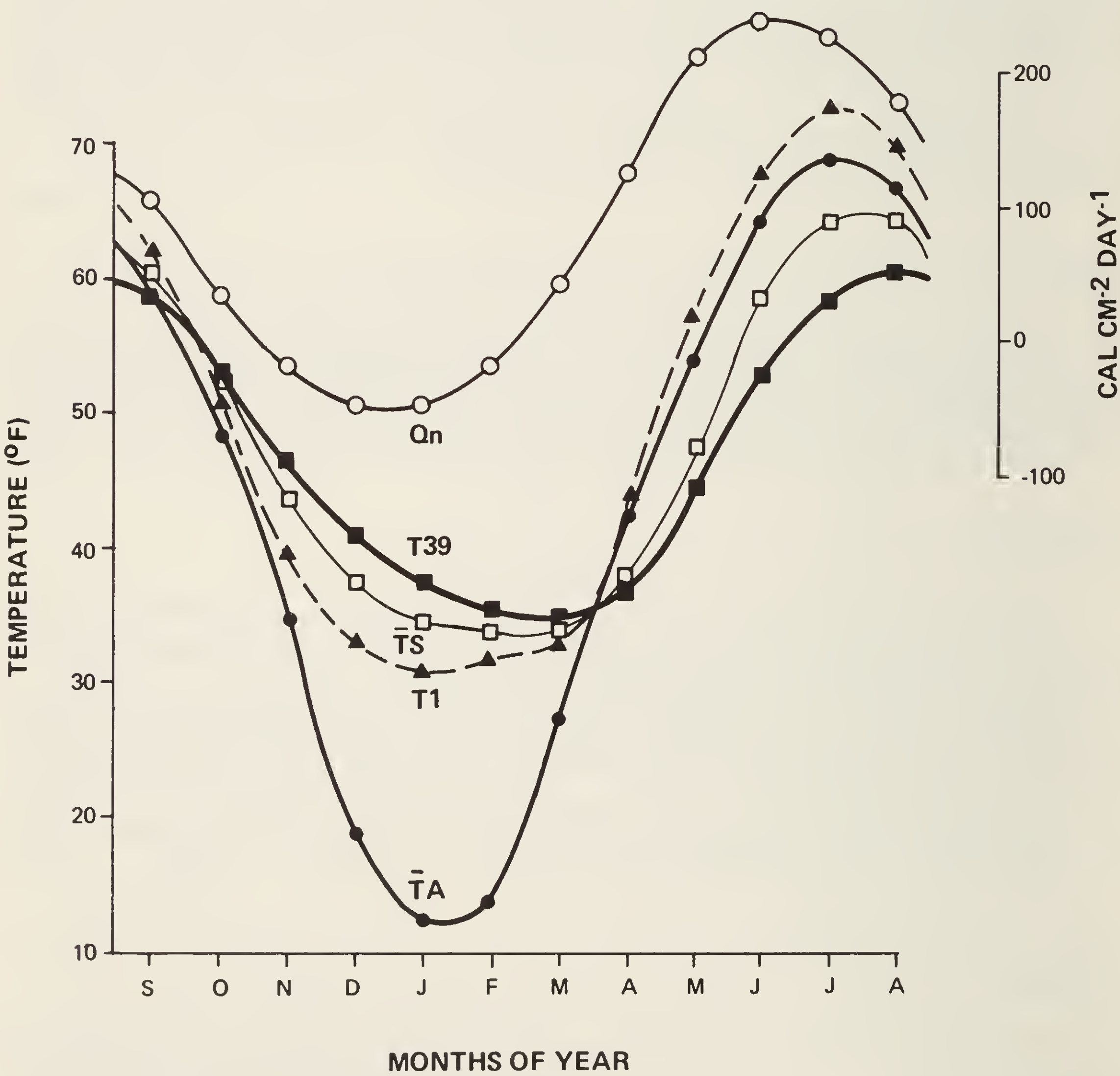

Fig. 1 Mean annual cycles of soil and air temperatures (T1, T39, $\overline{T}s$, $\overline{T}a$) and net radiation (Qn).

behind each other by 3 to 6 weeks. Their maximums occur on about June 21, July 15, and August 1 respectively, and their minimums on December 21, January 21, and March 6.

During the colder period $\overline{Ts}$ greatly exceeds $\overline{Ta}$ and its amplitude is much smaller. During the warmer period $\overline{Ta}$ is higher than $\overline{Ts}$. So their curves cross on about April 1 and September 3 and $\overline{Ts}$ becomes respectively lower and higher than $\overline{Ta}$.

Based on Figure 1 the periods above 42°F (the basic temperature assumed for growth) are 199 days for $\overline{Ta}$ and 205 for $\overline{Ts}$. In the air this period is 62 days longer than the frost-free period, that is, about 1 month both in spring and in fall. In spring, this interval of 1 month is hazardous to trees because the buds may open before the risk of frosts is over and they may be injured. In fall, $\overline{Ts}$ remains above 42°F about 2 months longer than the end of the frost-free period. This is beneficial to the root development of grass and trees planted early in the fall.

Mean Annual Temperatures

Annual $\overline{Ts}$ (47.4°F) is 5°F higher than annual $\overline{Ta}$ (Table 3). The difference is explained by the mean annual minimum being about 13°F higher for Ts than for Ta, whereas the mean maximum is only a few degrees lower. This is attributed to the considerable ground snow cover of winter and the abundant radiation of summer (Carson 1961). Annual Ts varies little with depth, being 47.7°F at 4 in. and 47.2°F at 59 in.

TABLE 3. ANNUAL TEMPERATURES (F): 10-YEAR AVERAGES (AV) AND STANDARD DEVIATIONS (SD), 1961–70

		Ta	T1	T4	T8	T20	T39	T59	$\overline{Ts}$
Maximum	AV	51.1	51.3	48.9	48.1				
	SD	0.6	0.6	1.0	1.2				
Minimum	AV	33.6	46.2	46.5	47.2				
	SD	0.9	1.1	0.9	1.2				
Mean	AV	42.4	48.8	47.7	47.6	47.6	46.4	47.2	47.4
	SD	0.7	0.6	0.9	1.2	1.0	1.3	1.8	

The values of the standard deviation (SD) indicate that Ts varies more than Ta from year to year, except at the 1-in. depth (Table 3). Based on a normal distribution it may be assumed that the annual variation above or below the long-term average will not exceed 1, 2, or 3 SD in 68.0, 95.0, and 97.7% of the years respectively. Through the soil profile, the variability of Ts increases with depth. SD ranges from 0.6°F at 1 in. to 1.8°F at 59 in.

Annual Range of Temperature

Mean annual range of temperature (difference between the warmest and coldest months) is much greater in air (59.1°F) than in soil where it is decreasing from 42.7°F at the 1-in. depth to 20.6°F at 59 in. (Table 4). The annual variability of the range is larger in air (SD = 4.1°F) than in soil (SD = 1.5°F at the 8-in. depth). The largest and smallest ranges observed during the 10 years are also indicated in Table 4.

TABLE 4. ANNUAL RANGES OF TEMPERATURE (F): LARGEST, SMALLEST, 10-YEAR AVERAGE, AND STANDARD DEVIATION (SD), 1961–70

Range	Ta	T1	T4	T8	T20	T39	T59
			Based on monthly mean temperatures				
Largest	64.1	47.6	42.4	39.4	34.8	28.2	22.3
Smallest	53.6	37.1	35.7	34.5	29.8	23.0	19.4
Average	59.1	42.7	38.6	36.7	32.2	25.7	20.6
SD	4.1	3.6	2.0	1.5	1.5	1.4	0.8
			Based on annual extreme temperatures				
Largest	122.0	73.0	56.0	50.0	37.0	31.0	25.0
Smallest	103.0	49.0	44.0	38.0	33.0	26.0	21.0
Average	114.7	60.4	49.2	43.8	35.5	27.5	22.2
SD	5.6	8.0	4.0	4.2	1.5	1.4	1.3

The 10-year average of the absolute annual range (difference between the highest and lowest daily temperatures) is 114.7°F in the air, and it varies through the soil from 60.4°F at the 1-in. depth to 22.2°F at 59 in. Here again, the variability (SD) is larger in air than in soil, except at the 1-in. depth.

These considerable annual ranges reflect the continentality of the climate at Ottawa. The biological cycle of plants grown there are adapted to these marked ranges of temperature. The growth period of the plants is normally short enough to allow them to mature before the first killing frost in the fall and to harden before the severe cold of winter. Their rest period is long enough to preserve them against the last killing frosts in spring.

Annual Maximum Depth of Frost in Soil

Depths of frost in soil (32°F) reported in Table 5 are of two types. One type is based on monthly mean soil temperature and reflects a state of relatively long duration. The other type is based on the lowest daily temperature during the cold period; this type may be of short duration. When derived from monthly Ts, frost is

TABLE 5. ANNUAL DEPTH (IN.) OF FROST ($\leqslant 32^\circ$F) BASED ON MONTHLY MEAN SOIL TEMPERATURE (MEAN), AND LOWEST MINIMUM TEMPERATURE (AMIN)

	Annual frost depth based on				
YEAR	MEAN	AMIN	YEAR	MEAN	AMIN
1960–61	17	20	1965–66	9	14
1961–62	10	14	1966–67	0	4
1962–63	12	14	1967–68	5	8
1963–64	8	8	1968–69	0	2
1964–65	39	39	1969–70	12	18

indicated for 8 years out of 10 at a depth varying from 5 to 39 in. Based on the lowest daily Ts, frost was recorded each year at a depth varying from 2 to 39 in.

The depth of frost depends mainly on the ground snow cover and the air temperature. The effectiveness of the snow cover in reducing the depth of frost increases with its earliness, persistency, and depth, and it decreases with its density and moisture content. For identical snow cover, the depth of frost is a function of the difference between soil and air temperatures. Increase in the water content of the soil may also reduce the penetration of frost.

Because the earliness, depth, and intensity of frost in soil vary from year to year, fall plantings are more risky at Ottawa than those in spring. If the seeding of a lawn is done in the fall, it should be early enough so that a satisfactory root system develops before the soil freezes. One of the most important effects of frost is heaving of the soil. Heaving is particularly serious when the water content of soil is high and alternate freezing and thawing occur in the absence of snow cover. Plant roots may break, dry out, and die.

MONTHLY TEMPERATURES

Monthly Mean Temperatures

$\overline{T}$s exceeds $\overline{T}$a from September to March, whereas $\overline{T}$s is lower than $\overline{T}$a from April to August (Table 6). Due to the abundant solar radiation in summer and the protective snow cover in winter, T1 exceeds $\overline{T}$a every month except in April. T20 is representative of $\overline{T}$s, which is the mean temperature of the top 39-in. layer, the most important in agriculture.

In fall, temperature drops rapidly because of the strong reduction of Qn, which becomes negative in November. The decreasing rate is larger in the air than in the soil. Averaged for the season, $\overline{T}$s is 4.6°F higher than $\overline{T}$a. The difference between $\overline{T}$s and $\overline{T}$a is particularly large in November (8.4°F), which may be attributed to the 7.6 days with snow cover and the relatively low soil thermal diffusivity during this month. The hardening of plants is one of the biological processes most affected by fall temperature.

TABLE 6. MEAN MONTHLY AND SEASONAL TEMPERATURES (F), 1961–70

	$\overline{T}a$	T1	T4	T8	T20	T39	T59	$\overline{T}s$
September	58.6	61.7	60.6	60.6	60.5	58.4	57.6	60.1
October	48.2	50.4	50.5	50.9	52.4	53.1	54.4	52.0
November	34.9	39.2	40.1	41.3	43.6	46.3	49.6	43.3
Mean	47.2	50.4	50.4	50.9	52.2	52.6	53.9	51.8
December	18.4	33.0	34.0	35.1	37.6	40.4	44.2	37.2
January	12.1	30.6	31.4	32.2	34.6	37.1	40.6	34.2
February	13.7	31.2	31.4	32.2	33.6	35.4	38.8	33.4
Mean	14.7	31.6	32.0	33.1	35.3	37.6	41.2	34.9
March	27.1	32.2	32.0	32.4	33.5	34.6	37.7	33.3
April	42.2	41.3	38.8	37.8	37.4	36.2	37.6	37.5
May	53.9	56.1	53.5	52.5	49.8	44.8	43.4	49.8
Mean	41.1	43.2	41.4	40.9	40.2	38.5	39.6	40.2
June	64.5	67.4	64.0	62.7	59.2	52.6	49.6	59.2
July	68.8	72.6	69.1	67.8	64.5	58.2	55.0	64.5
August	66.2	69.3	67.0	66.3	64.5	60.1	57.9	64.3
Mean	66.5	69.9	66.7	65.6	62.7	57.0	54.2	62.7

In winter $\overline{T}s$ (34.9°F) is higher than $\overline{T}a$ by 20.2°F. The difference is explained by the horizontal movement of cold air masses and the negative Qn resulting in a sharp drop of Ta, whereas the decrease of $\overline{T}s$ is minimized by the protective snow cover and the soil water releasing heat in freezing. December is the most risky winter month for plants. There is an average of 11 days without snow cover, so that roots are exposed to freezing temperatures and to physical damage by soil heaving.

In spring the difference between $\overline{T}s$ and $\overline{T}a$ varies from 6.2°F in March to −4.1°F in May. Averaged for the season, $\overline{T}s$ (40.2°F) is 0.9°F lower than $\overline{T}a$. From the agricultural point of view, March is more like a winter month than a spring month; the days with snow cover average 24.3 and the maximum snow depth is 16.0 in. Early melting of snow (the average last date of snow cover is April 6) may lead to alternate freezing and thawing, which may result in plant damage by freezing and soil heaving.

In summer $\overline{T}s$ (62.7°F) is 3.8°F lower than $\overline{T}a$. However, T1 is 3.4°F higher than $\overline{T}a$. July is the warmest month both in air (68.8°F) and in soil (64.5°F). So this season may be considered as cool to warm, even if a few hot days with a maximum temperature above 85°F are recorded.

In general, the temperatures in the Ottawa area are mostly suitable for cool-season crops, even if moderately tender crops with a relatively short growth period are grown. The growth of perennial crops generally stops from the end of July to the beginning of September, and a relatively high degree of hardiness is developed in the fall. Some of the crops that thrive are alfalfa, bluegrass, orchard-grass, timothy, oats, barley, rye, strawberries, raspberries, cabbage, beets, lettuce, carrots, tomatoes, kidney beans, and cucumbers.

Monthly Mean Maximum (Tmax) and Minimum (Tmin) Temperatures

Tmax is higher in the air than in the soil except in winter (Table 7). In the air, Tmax is moderate during the summer (76.6°F on the average), whereas it is low during the winter (22.4°F). In the soil, Tmax averages 74.9°F in summer at the 1-in. depth but only 66.5°F at 8 in., and it stays close to 32°F from December to March. Monthly Tmax and Tmin are not reported for depths lower than 8 in. because they are very close to the monthly means.

In contrast with Tmax, Tmin is always higher in the soil than in the air, particularly in winter. In January, for example, the difference between mean minimum T8 and Ta amounts to 28.1°F.

With respect to agriculture, Tmax is not high enough to impose frequent heat stresses on crops unless the soil is abnormally dry. However, Tmin constitutes a serious hazard during the cool period for crops lacking hardiness as may be the case after warm and wet falls.

TABLE 7. MEAN DAILY MAXIMUM AND MINIMUM TEMPERATURES (F), 1961–70

	Mean daily max.				Mean daily min.			
Month	Ta	T1	T4	T8	Ta	T1	T4	T8
September	68.2	65.6	62.4	61.2	49.0	57.8	58.9	59.9
October	56.9	53.2	51.7	51.3	39.5	47.5	49.2	50.4
November	40.8	40.1	40.5	41.4	29.0	38.3	39.8	41.2
Mean	55.3	53.0	51.5	51.3	39.2	47.9	49.3	50.5
December	24.6	33.2	34.0	35.1	12.2	32.9	34.0	35.0
January	20.0	30.7	31.4	32.3	4.1	30.4	31.3	32.2
February	22.6	31.3	31.5	32.2	4.7	31.2	31.4	32.1
Mean	22.4	31.7	32.3	33.2	7.0	31.5	32.2	33.1
March	34.9	32.3	32.0	32.4	19.3	32.0	32.0	32.4
April	51.4	44.5	40.1	38.3	33.1	38.1	37.5	37.2
May	64.6	60.6	55.5	53.3	43.2	51.7	51.4	51.7
Mean	50.3	45.8	42.5	41.3	31.9	40.6	40.3	40.4
June	75.2	72.9	66.6	63.8	53.9	62.6	61.5	61.6
July	78.8	77.9	71.6	68.8	58.8	67.3	66.6	66.8
August	75.8	73.8	69.1	66.9	56.5	64.7	64.9	65.6
Mean	76.6	74.9	69.1	66.5	56.4	65.2	64.3	64.7

Variability of Monthly Temperatures from Year to Year

Monthly temperatures at Ottawa, as indicated by the standard deviation (SD), vary markedly from year to year (Table 8), a characteristic common to humid continental climates. The variability of $\overline{T}a$ is the largest in winter and smallest in

TABLE 8. MONTHLY VARIATIONS OF TEMPERATURE (F) FROM YEAR TO YEAR AS INDICATED BY THE STANDARD DEVIATION (SD), 1961–70

	S	O	N	D	J	F	M	A	M	J	J	A
						Mean maximum						
Ta	3.5	3.8	3.0	4.7	4.7	4.0	2.7	2.9	3.6	2.3	1.9	2.4
T1	3.3	2.2	2.5	1.8	2.5	1.4	0.9	2.2	3.4	3.3	3.1	2.5
T4	2.9	2.4	2.3	1.4	2.3	1.1	0.7	3.3	2.2	2.0	2.0	2.1
T8	2.9	2.4	2.6	1.7	1.8	1.3	1.1	2.9	1.9	2.2	2.3	2.2
						Mean minimum						
Ta	3.1	2.5	3.2	5.1	5.6	5.3	3.4	1.7	3.0	1.7	2.3	2.0
T1	2.7	2.8	2.6	2.0	3.0	1.4	1.0	2.4	2.5	1.4	1.6	2.0
T4	2.6	2.2	2.1	1.3	2.4	1.1	0.7	2.5	2.2	1.5	1.9	2.0
T8	2.8	2.4	2.6	1.7	1.8	1.4	1.1	2.5	2.2	1.6	1.9	2.3
							Mean					
$\overline{T}a$	3.1	2.8	3.0	4.9	5.1	4.6	2.9	2.3	3.2	1.8	2.0	2.2
T1	2.9	2.3	2.5	1.9	2.7	1.4	0.9	2.2	2.9	2.2	2.0	1.8
T4	2.7	2.3	2.2	1.4	2.3	1.1	0.7	2.9	2.2	1.7	1.8	2.0
T8	2.8	2.4	2.6	1.7	1.8	1.3	1.1	2.7	2.0	1.8	2.0	2.2
T20	1.9	1.8	2.0	1.4	1.6	1.2	0.8	2.3	2.0	1.6	1.9	1.8
T39	1.8	2.1	2.3	2.1	2.1	1.8	1.2	1.8	1.9	1.3	1.4	1.4
T59	1.8	2.4	2.7	2.7	2.5	2.4	1.7	1.9	1.7	1.5	1.6	1.7

summer. SD amounts to 5.1°F in January and to 2°F in July. Tmax varies less than Tmin from November to March and generally more from April to October.

The monthly variability of Ts from year to year is generally smaller than that of Ta. The difference is greatest during the months with substantial ground snow cover (November to March). In February, SD is 4.6°F for $\overline{T}a$ and 1.1°F for Ts at the 4-in. depth. In April and in summer, the variability of Ts and Ta is more comparable.

Because a crop should succeed 8 or 9 years out of 10 to be profitable, the annual variability of temperature just like the means should be considered in the selection of crops and other management decisions.

Monthly Changes of Temperature

Monthly changes of temperature given in Table 9 are the differences in temperature between the current and previous months. Changes of $\overline{T}a$ are positive from February to July, the greatest being for March and April (13.4°F and 15.1°F). The greatest positive changes occur later in the soil ($\overline{T}s$) than in the air, that is, in May (12.3°F) and in June (9.4°F). The greatest negative changes are in December for $\overline{T}a$ (16.5°F) and in November for $\overline{T}s$ (8.7°F).

TABLE 9. MONTHLY CHANGES OF MEAN, MEAN MAXIMUM, AND MEAN MINIMUM TEMPERATURES (F), 1961–70

	S	O	N	D	J	F	M	A	M	J	J	A
						Mean maximum						
Ta	−7.6	−11.3	−16.1	−16.2	−4.6	2.6	12.3	16.5	13.2	10.6	3.6	−3.0
T1	−8.2	−12.4	−13.1	−6.9	−2.5	0.6	1.0	12.2	16.1	12.3	5.0	−4.1
T4	−6.7	−10.7	−11.2	−6.5	−2.6	0.1	0.5	8.1	15.4	11.1	5.0	−2.5
T8	−5.7	−9.9	−9.9	−6.3	−2.8	−0.1	0.2	5.9	15.0	10.5	5.0	−1.9
						Mean minimum						
Ta	−7.5	−9.5	−10.5	−16.8	−8.1	0.6	14.6	13.8	10.1	10.7	4.9	−2.3
T1	−6.9	−10.3	−9.2	−5.4	−2.5	0.8	0.8	6.1	13.6	11.1	4.7	−2.6
T4	−6.0	−9.7	−9.4	−5.8	−2.7	0.1	0.6	5.5	13.9	10.1	5.1	−1.7
T8	−5.7	−9.5	−9.2	−6.2	−2.8	−0.1	0.3	4.8	14.5	9.9	5.2	−1.2
						Mean						
$\overline{T}a$	−7.6	−10.4	−13.3	−16.5	−6.3	1.6	13.4	15.1	11.7	10.6	4.3	−2.6
T1	−7.6	−11.3	−11.2	−6.2	−2.4	0.6	1.0	9.1	14.8	11.6	4.9	−3.3
T4	−6.4	−10.1	−10.4	−6.1	−2.6	0.0	0.6	6.8	14.7	10.5	5.1	−2.1
T8	−5.7	−9.7	−9.6	−6.2	−2.9	0.0	0.2	5.4	14.7	10.2	5.1	−1.5
T20	−4.0	−8.1	−8.8	−6.0	−3.0	−1.0	−0.1	3.9	12.4	9.4	5.3	0.0
T39	−1.7	−5.3	−6.8	−5.9	−3.3	−1.7	−0.8	1.6	8.6	7.8	5.6	1.9
T59	−0.3	−3.2	−4.8	−5.4	−3.6	−1.8	−1.1	−0.1	5.8	6.2	5.4	2.9
$\overline{T}s$	−4.2	−8.1	−8.7	−6.1	−3.0	−0.8	−0.1	4.2	12.3	9.4	5.3	−0.2

Even if the changes of Tmax and Tmin for any months are both positive or negative, the size of the changes may differ considerably. The changes for October, November, April, and May are significantly larger for Tmax than for Tmin, both in soil and air. In fall, the sharp reduction of Qt causes Tmax to drop more rapidly than Tmin. The decrease of Tmin is reduced by the heat released from the soil. In spring, the abundant Qt induces Tmax to increase faster than Tmin; the cooling by ground radiation at night is only slightly compensated by the low heat reserves in the soil.

Increase in temperature in spring helps the early germination and growth of plants at a time when the soil moisture is normally adequate. Decrease in temperature in fall combined with shorter days leads to the cessation of growth and the relatively fast hardening of perennial plants.

Monthly Soil Temperature Gradients

Soil temperature gradients (Table 10) indicate the vertical temperature variations by 4 in. of depth. Gradients are positive or negative depending on whether the temperature is increasing or decreasing with depth. Steepest positive gradients occur from November to January, whereas steepest negative gradients occur in June and July when solar radiation is greatest and the top soil is drying.

TABLE 10. MONTHLY SOIL TEMPERATURE GRADIENT PER 4-IN. DEPTH WITHIN VARIOUS LAYERS OF THE SOIL PROFILE (F), 1961–70

	Layers (in.)					
Month	1–4	4–8	8–20	20–39	39–59	1–39
September	−1.5	0.0	0.0	−0.4	−0.2	−0.3
October	0.1	0.4	0.5	0.1	0.3	0.3
November	1.2	1.2	0.8	0.5	0.7	0.7
December	1.3	1.1	0.8	0.6	0.7	0.7
January	1.1	0.8	0.8	0.5	0.7	0.7
February	0.4	0.6	0.5	0.4	0.7	0.4
March	−0.4	0.4	0.4	0.2	0.6	0.2
April	−3.3	−1.0	−0.1	−0.2	0.3	−0.5
May	−3.5	−1.0	−0.9	−1.0	−0.3	−1.1
June	−4.9	−1.3	−1.2	−1.3	−0.6	−1.5
July	−4.7	−1.3	−1.1	−1.3	−0.6	−1.4
August	−3.1	−0.7	−0.6	−0.9	−0.4	−0.9

Temperature gradients for every month are illustrated in Figure 2. Negative gradients in summer are steeper than positive ones in winter. Temperature gradients result in the reduction of annual temperature amplitude with depth. The slight curvature of the graph lines for April and September reflects the reversal of the temperature gradient during these months. Taking into account the gradients

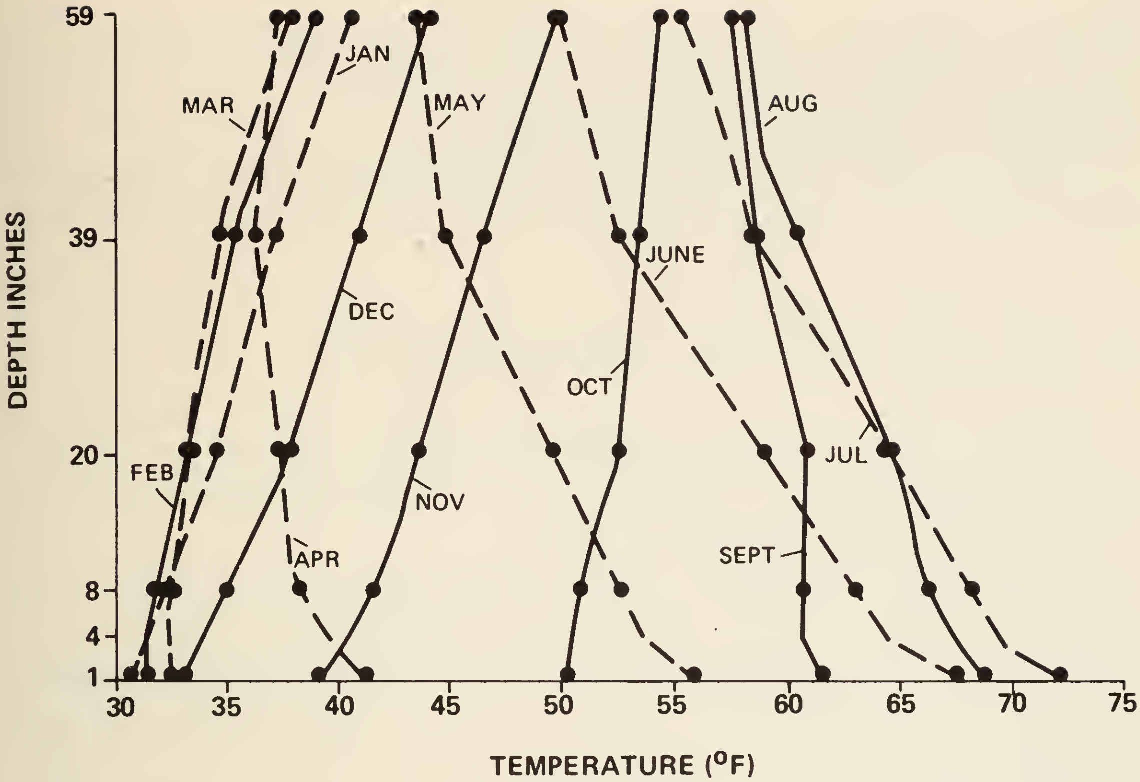

Fig. 2 Monthly soil temperature profiles.

through the top 20-in. layer, the monthly Ts is above 60°F, between 40°F and 60°F, and below 40°F for 4 months for each of these temperatures.

In late spring and summer, the elongation of plant roots is largely controlled by the gradual warming of soil at depth, that is, by the temperature gradient. The positive gradient prevailing in fall and winter favors the survival of plant roots.

DAILY TEMPERATURES

Daily Cycles of Soil and Air Temperatures

The maximum and minimun reached by Ts lag behind those of Ta. For the maximum (Chang 1968) the lags are about 3 hr at 4 in., 12 hr at 12 in., and 33 hr at 24 in. (Chang 1968). At lower depths the daily lag can be ignored because the differences between the maximums and minimums are too small.

The daily cycles of Ts (4-in. depth) and Ta are illustrated in Figure 3. Four typical clear days in the months of January, April, July, and October are considered. The lag of the maximum of Ts behind Ta is about 3 hr in April and 2 hr in both July and October. This feature is not present in January because Ts remains close to 32°F due to the insulation of snow and the heat released by the freezing of water. The lag of Ts for the minimum is more difficult to determine than for the maximum because the decrease of Ts is less pronounced than its increase. In addition, the diurnal cycle of Ts is much smoother than that of Ta, largely due to the greater thermal diffusivity of air than that of soil.

These differences in the daily cycles of soil and air temperatures may have some implications in the metabolism of plant roots and stems and their interrelationships.

Course of Daily Soil and Air Temperatures During the Month

Courses of daily soil (Ts) and air (Ta) temperatures during the month are illustrated in Figure 4. Ts is represented by T4. Daily maximums and minimums were plotted and linked by a straight line. Four representative months of 1970 are considered: October, January, April, and July.

In October, the influence of changing air masses on Ts and Ta is striking, producing alternate warmer and colder periods. Notwithstanding this feature, temperature shows an overall decrease due to the gradual reduction of solar radiation. Because of the soil heat reserves and the smaller temperature changes in soil than in air, Ts fluctuations are generally closer to the maximums than to the minimums of Ta.

In January, except for the end of the month, Ts exceeds Ta. Contrasted with the strong fluctuations of Ta, those of Ts are weak. The effects of the strong fluctuations of Ta on Ts are minimized by the snow cover (6 to 7 in.).

In April, Ts is constant up to the 16th of the month, that is until the complete disappearance of the snow cover. Afterwards, it rises at an increasing rate to the end of the month.

In July, Ts and Ta are fluctuating the most due to the strong solar radiation. The range of Ts fluctuations falls midway between those of Ta.

Crops like tomatoes and potatoes require such temperature fluctuations for their metabolic processes and a normal development (Threshow 1970).

Daily Range of Temperature

The daily range of temperature is the difference between the highest and lowest temperatures recorded during a period of 24 hr, commonly from 8 a.m. on one day to 8 a.m. the next day. Table 11 shows for each month and year the mean daily range (MR), the 10-year averages of yearly largest range (AL), and the largest range for the whole period (L).

Both in soil and air, MR is wider during the warmer part of the year (April to October) than during the colder period (November to March). The daily range decreases with soil depth. At the 20-in. depth and deeper, MR is insignificant, varying from 0.0 to 0.3°F. The largest daily ranges (L) recorded during the 10-year period were 45°F for Ta, 14°F for T4, 4°F for T20, and 3°F for T39.

In general, the plants adapt to the normal ranges of temperature prevailing in the Ottawa area. However, extreme diurnal and interdiurnal ranges may damage them, particularly during the period from fall to spring.

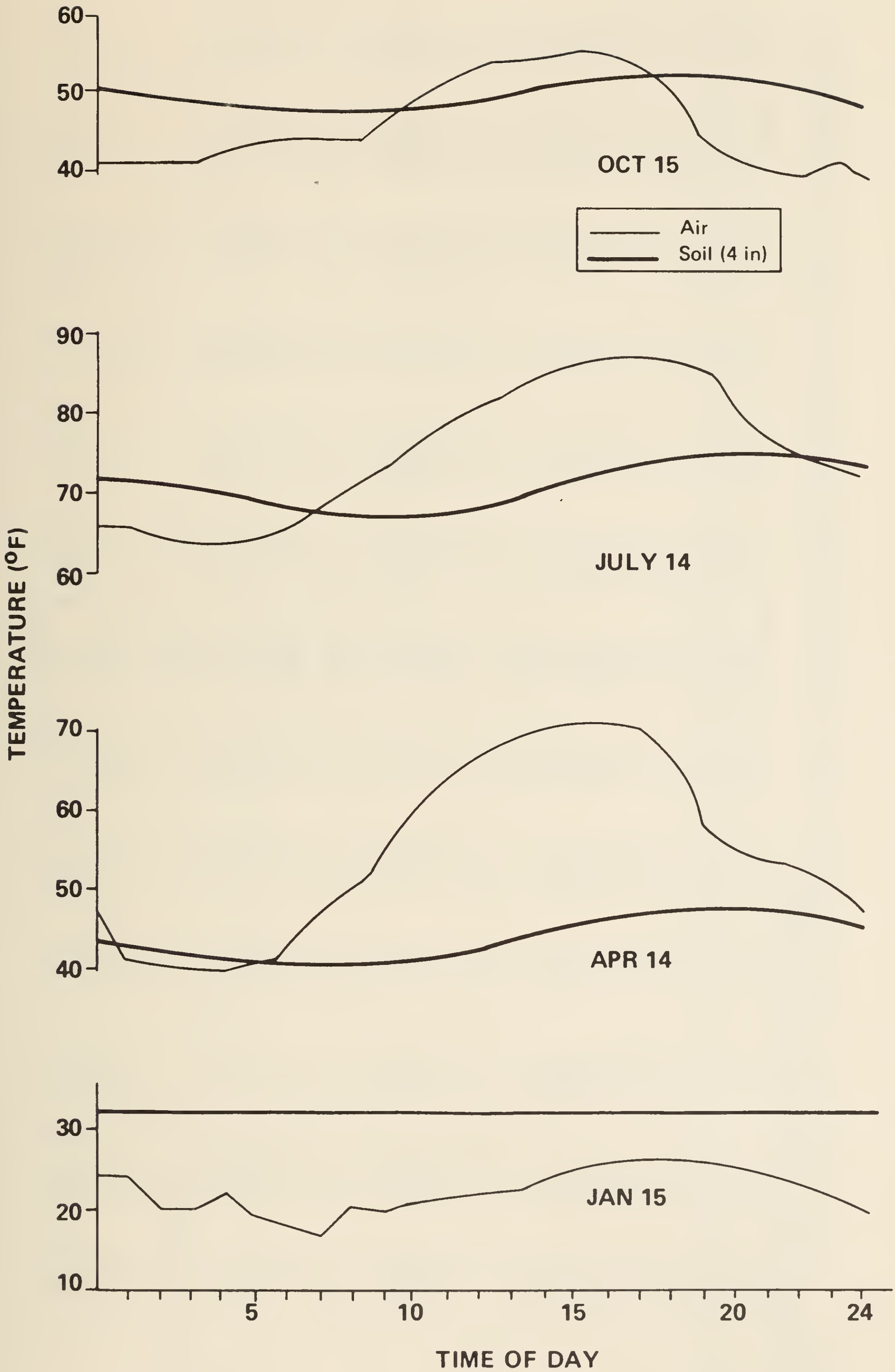

Fig. 3 Daily cycles of soil and air temperatures at Ottawa during four representative sunny days of 1970.

TABLE 11. DAILY RANGE OF TEMPERATURE (F), 1961–70: MEAN (MR); AVERAGE OF YEARLY LARGEST (AL); AND LARGEST FOR THE WHOLE PERIOD (L)

Range	S	O	N	D	J	F	M	A	M	J	J	A	Y
							Ta						
MR	19.2	17.4	11.8	12.4	15.8	17.9	15.6	18.3	21.3	21.3	19.9	19.4	17.5
AL	33.4	32.9	27.5	31.3	35.9	35.5	31.9	35.2	34.5	34.5	30.5	31.4	39.6
L	38.0	37.0	35.0	42.0	45.0	41.0	43.0	40.0	37.0	38.0	35.0	35.0	45.0
							T1						
MR	7.7	5.7	1.8	0.3	0.4	0.1	0.4	6.4	8.9	10.3	10.6	9.1	5.1
AL	14.2	11.6	7.1	2.2	1.7	1.0	2.0	15.6	15.6	17.8	18.1	16.0	19.9
L	20.0	17.0	13.0	5.0	5.0	2.0	8.0	22.0	21.0	27.0	26.0	30.0	30.0
							T4						
MR	3.5	2.5	0.7	0.1	0.1	0.1	0.0	2.6	4.0	5.1	5.0	4.2	2.3
AL	6.7	5.9	3.1	1.2	1.0	0.8	0.8	6.9	7.5	8.5	8.8	7.4	9.5
L	10.0	11.0	7.0	4.0	2.0	1.0	2.0	14.0	9.0	10.0	12.0	8.0	14.0
							T8						
MR	1.3	0.9	0.2	0.1	0.1	0.1	0.1	1.1	1.7	2.3	2.1	1.4	0.9
AL	2.8	3.2	4.2	1.0	0.8	0.6	0.8	3.6	3.9	4.3	4.0	3.7	6.3
L	5.0	10.0	4.0	2.0	2.0	1.0	1.0	10.0	7.0	9.0	10.0	8.0	10.0

TABLE 11. (concluded)

Range	S	O	N	D	J	F	M	A	M	J	J	A	Y
							T20						
MR	0.3	0.2	0.1	0.1	0.0	0.0	0.1	0.0	0.1	0.2	0.3	0.3	0.1
AL	1.2	1.6	1.2	1.0	1.0	1.0	0.8	1.0	1.2	1.0	1.0	1.0	2.0
L	2.0	4.0	2.0	1.0	1.0	1.0	1.0	1.0	2.0	1.0	1.0	1.0	4.0
							T39						
MR	0.1	0.1	0.1	0.0	0.1	0.0	0.1	0.0	0.1	0.1	0.1	0.1	0.1
AL	1.2	1.6	1.0	1.0	1.0	0.6	0.8	0.8	1.0	1.0	1.0	0.8	1.6
L	2.0	3.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	3.0
							T59						
MR	0.1	0.0	0.1	0.0	0.0	0.0	0.1	0.0	0.1	0.1	0.1	0.0	0.1
AL	1.0	1.6	1.0	1.0	0.8	1.0	0.8	1.0	1.0	1.0	1.0	1.0	1.6
L	1.0	4.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	4.0

TABLE 12. EXTREME DAILY TEMPERATURES FOR MONTHS AND YEAR (F), 1961–70): TEN-YEAR AVERAGE (MH AND ML); AND HIGHEST AND LOWEST FOR THE WHOLE PERIOD (H AND L)

	S	O	N	D	J	F	M	A	M	J	J	A	Y
							High						
Ta–MH	82.9	76.3	59.2	45.2	40.3	39.9	54.3	73.4	83.7	89.7	90.8	87.8	92.2
H	88.0	80.0	74.0	50.0	50.0	44.0	66.0	84.0	92.0	94.0	96.0	92.0	96.0
T1–MH	74.8	62.9	49.7	36.5	32.2	32.6	33.8	58.6	71.0	82.5	86.1	82.0	86.5
H	84.0	66.0	56.0	41.0	34.0	34.0	38.0	67.0	80.0	95.0	94.0	93.0	95.0
T4–MH	69.0	59.5	48.1	37.1	32.5	32.3	32.3	51.2	63.9	72.9	76.9	74.5	77.5
H	78.0	63.0	53.0	41.0	34.0	34.0	33.0	57.0	69.0	78.0	80.0	79.0	80.0
T8–MH	67.7	57.8	48.1	37.7	33.3	32.8	32.9	48.3	60.4	69.2	73.2	71.8	74.0
H	75.0	62.0	53.0	41.0	35.0	35.0	35.0	56.0	65.0	76.0	78.0	77.0	78.0
T20–MH	64.6	56.3	48.1	40.0	35.5	34.4	33.7	44.7	55.3	63.5	67.4	66.9	68.2
H	69.0	60.0	53.0	43.0	39.0	38.0	35.0	49.0	57.0	68.0	70.0	70.0	70.0
T39–MH	60.2	55.9	49.7	42.9	38.5	36.1	35.0	40.4	48.6	55.9	60.4	61.1	61.7
H	65.0	60.0	54.0	48.0	43.0	41.0	37.0	44.0	51.0	58.0	62.0	63.0	65.0
T59–MH	58.5	56.5	52.3	46.8	41.8	40.0	38.2	39.4	46.8	52.4	56.9	58.4	58.7
H	62.0	60.0	55.0	50.0	46.0	44.0	40.0	42.0	48.0	54.0	59.0	60.0	62.0

TABLE 12. (concluded)

	S	O	N	D	J	F	M	A	M	J	J	A	Y
							Low						
Ta–ML	32.9	24.5	10.9	−11.7	−18.0	−20.0	−1.5	17.7	29.9	42.1	46.3	44.1	−22.5
L	29.0	20.0	−1.0	−20.0	−27.0	−28.0	−11.0	9.0	22.0	36.0	43.0	38.0	−28.0
T1–ML	48.4	38.1	33.4	30.3	27.5	29.3	30.5	31.7	42.8	54.6	60.0	57.6	26.1
L	42.0	33.0	31.0	24.0	16.0	25.0	24.0	28.0	36.0	51.0	57.0	51.0	16.0
T4–ML	50.8	41.2	35.3	32.4	29.3	30.2	30.9	31.9	43.9	54.4	61.6	59.4	28.2
L	47.0	39.0	33.0	29.0	20.0	27.0	28.0	30.0	40.0	50.0	59.0	56.0	20.0
T8–ML	52.5	42.7	36.3	33.8	30.8	31.8	31.9	32.3	44.9	55.4	62.4	61.0	30.2
L	48.0	39.0	34.0	32.0	23.0	28.0	30.0	31.0	41.0	51.0	61.0	58.0	23.0
T20–ML	55.7	47.1	39.5	36.0	33.7	33.1	33.0	33.1	44.1	54.5	61.7	61.9	32.7
L	53.0	45.0	37.0	34.0	29.0	31.0	31.0	32.0	39.0	53.0	59.0	59.0	29.0
T39–ML	55.8	49.7	43.0	38.6	36.1	34.9	34.3	40.5	48.6	56.2	59.0	55.8	34.2
L	54.0	47.0	41.0	36.0	32.0	32.0	32.0	36.0	47.0	53.0	55.0	54.0	32.0
T59–ML	56.4	52.3	46.9	42.1	39.1	38.1	37.2	36.6	40.0	46.4	52.6	57.0	36.5
L	54.0	48.0	42.0	38.0	35.0	34.0	33.0	33.0	36.0	44.0	49.0	52.0	33.0

Extreme Daily Temperatures

Ottawa is exposed to extreme temperatures that are particularly severe in winter. Ten-year averages of the highest and lowest daily temperatures for each month and year are given in Table 12, as well as the extremes for the whole period.

The 10-year averages of the highest Ta during the summer months vary around 90°F. They range from 59 to 83°F in fall, from 54 to 84°F in spring, and from 40 to 45°F in winter. Those for Ts are considerably lower except at the 1-in. depth (86.1°F in July). The highest temperatures recorded during the 10-year period are 96°F for Ta, 95°F for T1, 70°F for T20, and only 65°F for T39.

Lowest air temperatures during months, averaged for 10 years, range from 46.3°F in July to -20°F in February. They vary from 61.6°F (July) to 29.3°F (January) for T4, and from 59°F (July) to 34.3°F (March) for T39. Lowest daily temperatures during the 10 years are -28°F for Ta, 16°F for T1, 29°F for T20, and 32°F for T39. Frosts were recorded in the air each month except June, July, and August over the 10-year period and at all depths in the soil except at 59 in. during the cold period.

Extremely high temperatures may sometimes damage plants. In summer during severe droughts they cause excessive transpiration and in fall they delay hardening. High temperatures in winter make the plants less resistant to sharp temperature drops and in early spring they may induce premature growth. However, extremely low temperatures are more hazardous in the Ottawa area and are an important limiting factor in the selection and distribution of crops.

SUMMARY

Soil and air temperatures at Ottawa during a 10-year period (1961–70) are analyzed and compared.

The main controlling factors of soil and air temperatures are solar radiation, air advection, thermal properties, type of soil, water content of soil, and ground snow cover. Average annual cycles of soil and air temperatures are similar to the cycle of solar radiation; however, the extreme values of soil temperature for the upper 39-in. layer lag behind those of air temperature by 3 to 6 weeks and the latter behind extreme values of solar radiation.

The mean annual soil temperature for the upper 39-in. layer is 5°F higher than for air temperature. The variability from year to year is generally greater in the soil than in the air.

Based on the highest and lowest daily temperatures, the mean annual range amounts to 114.7°F in the air, whereas it decreases from 60.4°F at the 1-in. depth in the soil to 22.2°F at 59 in.

The annual maximum depth of frost, as indicated by the lowest daily temperatures, varied from 2 to 39 in. during the 10-year period.

Mean soil temperature exceeds mean air temperature from September to March and is lower from April to August. Mean monthly maximum temperatures are higher in the air than in the soil except in winter. Mean monthly minimum temperatures are consistently higher in soil. The variability of monthly soil temperature from year to year is generally lower than that of air temperature.

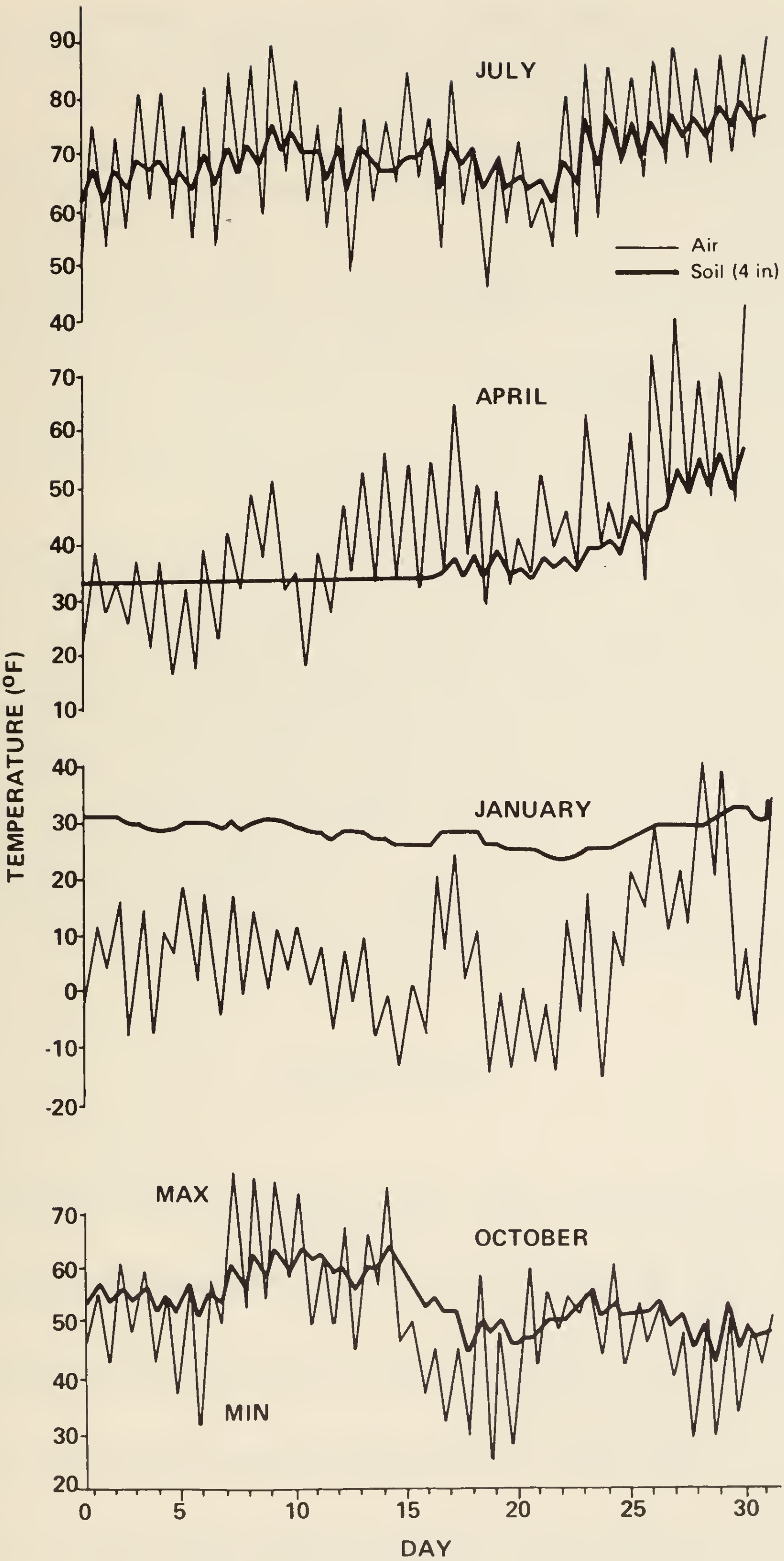

Fig. 4 Course of daily soil and air temperatures at Ottawa during four representative months of 1970.

In the air, the greatest monthly changes of mean temperature are in March (13.4°F), April (15.1°F), November (−13.3°F), and December (−16.5°F), whereas in the soil, they occur in May (12.3°F), June (9.4°F), October (−8.1°F), and November (−8.7°F).

Steepest positive soil temperature gradients (warmer with depth) are from November to January and steepest negative gradients (colder with depth) are from May to August.

During the day, the maximum Ts at the 4-in. depth lags behind the Ta by 2 to 3 hr. The courses of daily temperatures during any given month show smaller fluctuations for soil than air. The mean daily range of temperature in both soil and air is wider during the warmest months (April to October) than during the coldest months (November to March).

Extreme temperatures are more remarkable in air than in soil. The highest and lowest temperatures for the 10-year period were 96 and −28°F respectively in the air, and 80 and 20°F at the 4-in. depth in the soil.

Temperatures in the Ottawa area limit the choice, the growth, and the survival of crops because they result in relatively short frost-free periods, moderately warm summers, cold winters, and variations from year to year. Hence, this temperature regime is mainly suitable for cool-weather crops. Relatively tender crops can be grown, if their period of growth is short enough. However, the progressive warming of soil from the surface down in spring permits earlier growth of annual crops and prevents premature growth of perennial plants. Generally, the summer is free from excessively high temperatures that can damage crops. The slow cooling of soil in fall compared with that of air favors the establishment of late-summer and early-fall plantings as well as the accumulation of food reserves in the roots of perennial crops. Because of a persistent snow cover, soil temperature remains generally close to 32°F in winter, so that low plants (even only moderately hardy) can escape the injury from the low air temperatures of the winter.

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CONVERSION FACTORS FOR METRIC SYSTEM

Imperial units	Approximate conversion factor	Results in:	
LINEAR			
inch	x 25	**millimetre**	**(mm)**
foot	x 30	**centimetre**	**(cm)**
yard	x 0.9	**metre**	**(m)**
mile	x 1.6	**kilometre**	**(km)**
AREA			
square inch	x 6.5	**square centimetre**	**(cm^2)**
square foot	x 0.09	**square metre**	**(m^2)**
acre	x 0.40	**hectare**	**(ha)**
VOLUME			
cubic inch	x 16	**cubic centimetre**	**(cm^3)**
cubic foot	x 28	**cubic decimetre**	**(dm^3)**
cubic yard	x 0.8	**cubic metre**	**(m^3)**
fluid ounce	x 28	**millilitre**	**(mℓ)**
pint	x 0.57	**litre**	**(ℓ)**
quart	x 1.1	**litre**	**(ℓ)**
gallon	x 4.5	**litre**	**(ℓ)**
bushel	x 0.36	**hectolitre**	**(hℓ)**
WEIGHT			
ounce	x 28	**gram**	**(g)**
pound	x 0.45	**kilogram**	**(kg)**
short ton (2000 lb)	x 0.9	**tonne**	**(t)**
TEMPERATURE			
degree fahrenheit	°F-32 x 0.56 (or °F-32 x 5/9)	**degree Celsius**	**(°C)**
PRESSURE			
pounds per square inch	x 6.9	**kilopascal**	**(kPa)**
POWER			
horsepower	x 746	**watt**	**(W)**
	x 0.75	**kilowatt**	**(kW)**
SPEED			
feet per second	x 0.30	**metres per second**	**(m/s)**
miles per hour	x 1.6	**kilometres per hour**	**(km/h)**
AGRICULTURE			
bushels per acre	x 0.90	**hectolitres per hectare**	**(hℓ/ha)**
gallons per acre	x 11.23	**litres per hectare**	**(ℓ/ha)**
quarts per acre	x 2.8	**litres per hectare**	**(ℓ/ha)**
pints per acre	x 1.4	**litres per hectare**	**(ℓ/ha)**
fluid ounces per acre	x 70	**millilitres per hectare**	**(mℓ/ha)**
tons per acre	x 2.24	**tonnes per hectare**	**(t/ha)**
pounds per acre	x 1.12	**kilograms per hectare**	**(kg/ha)**
ounces per acre	x 70	**grams per hectare**	**(g/ha)**
plants per acre	x 2.47	**plants per hectare**	**(plants/ha)**

Examples: 2 miles x 1.6 = 3.2 km; 15 bu/ac x 0.90 = 13.5 hℓ/ha

INFORMATION
Edifice Sir John Carling Building
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Ottawa, Ontario
K1A 0C7

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Ottawa

IF UNDELIVERED, RETURN TO SENDER EN CAS DE NON-LIVRAISON, RETOURNER À L'EXPÉDITEUR