The thermal regime in salt marsh peat at Barnstable, Massachusetts[1]

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ABSTRACT

The major features of the thermal regime in the peat of a salt marsh at Barnstable, Massachusetts, are described by the theory of heat flow in a homogeneous nonconvective medium subjected to an annual sinusoidal change in temperature having an amplitude of 12°C at the surface. The thermal diffusivity of the peat is 1.57×10^{-3} cm^2 sec^{-1}. Departures, attributed to meteorological effects, consist of a long term trend during the two-year period of observation, which may be approximated by a biennial sinusoidal component of 1°C amplitude, and of somewhat irregular perturbations occurring at intervals of about three months. The average effects attributed to the latter attenuate with depth at the rate expected for a component of one quarter year period. In the deeper layers of peat residuals remain after these components are eliminated from the observed data which are accounted for by the movement of ground water from the upland, a condition evidenced by the low chloride content of the peat at these depths. The mean temperature of the peat increases downward at a rate which indicates, when combined with the thermal diffusivity and volumetric heat capacity, that heat is moving upward through the peat layer at an average rate of 1.58×10^{-6} cal. cm^{-2} sec^{-1}. This value agrees with previous determinations of the geothermal heat flux. The march of temperature at the marsh surface agrees closely in amplitude and epoch with that of the air over the upland. The mean temperature of the marsh is 0.9° cooler than the air, an effect attributed to evaporation. The effect of spring tides which flood the marsh is examined and it is concluded that the principal effect is to keep the peat moist and thus increase evaporation.

Introduction

This study arose from the observation, made while sounding the depth of peat in a salt marsh, that a marked gradient in temperature occurred within a small distance below the surface. Because the marsh is flooded during approximately half the periods of high water, and since gradients in pressure may be produced within the peat with the fall of the tide it seemed possible that substantial quantities of such water moves through the peat in its return to the drainage creeks. Such movement should disturb the annual cycle of temperature change arising from the diffusion of heat within the peat. The thermal regime within the peat was consequently examined in the search for evidence of motion of the interstitial water.

The consistency of peat is such that a probe may be inserted and the *in situ* temperature measured with very little disturbance. Preliminary measurements showed that the temperature within the peat varied in a manner very close to the expectancy that it depended on thermal diffusion in a stagnant medium. It became evident that exact measurements were required if small anomalies were to be detected. Consequently better instrumentation was secured and systematic measurements made during a two-year period. The outcome was to provide a precise description of the thermal regime.

Procedure

Measurements were made during a two-year period in the Great Marshes at Barnstable,

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[1] Contribution No. 1446. The author is indebted to Dr. William S. Richardson, Mr. Charles H. Wilkins, and Dr. John W. Kanwisher for the design and construction of thermometric instrumentation, and to Mr. William Winsor and Mr. Charles L. Wheeler for local meteorological data.

Massachusetts, a salt marsh of the New England type described by AYERS (1959) and REDFIELD (1959). The position was located about 100 meters from the upland and at a similar distance east of Navigation Road, which extends across the marsh to Spring Creek. See Fig. 1. The elevation of the marsh surface is about 3 cm above mean high water and 2.86 m above mean low water, as determined by tide gauge in Spring Creek. The marsh is flooded by high course tides up to extreme depths of 60 cm. The surface vegetation consisted of the dwarf form of *Spartina alterniflora* 20 to 40 cm in height. A drainage ditch, 30 cm wide and 45 cm deep interrupted the marsh surface 15 m west of the area and a somewhat larger and deeper ditch was located 15 m east of it. The peat in the area was approximately 4.5 m deep, and was underlain by glacial deposits. Table 1 lists properties of peat cores obtained at various depths.

Temperature was measured with a thermistor mounted on a jointed ½ inch steel rod which could be thrust into the peat by hand. The thermistor was advanced by increments of about 15 cm and the temperature measured as soon as the readings became constant at the new depth. Each measurement was thus made in previously undisturbed soil. Probings at successive times were made at a distance of at least 1.5 m from any previous probing, the area examined thus expanding within a rectangle 18 × 24 m on a side.

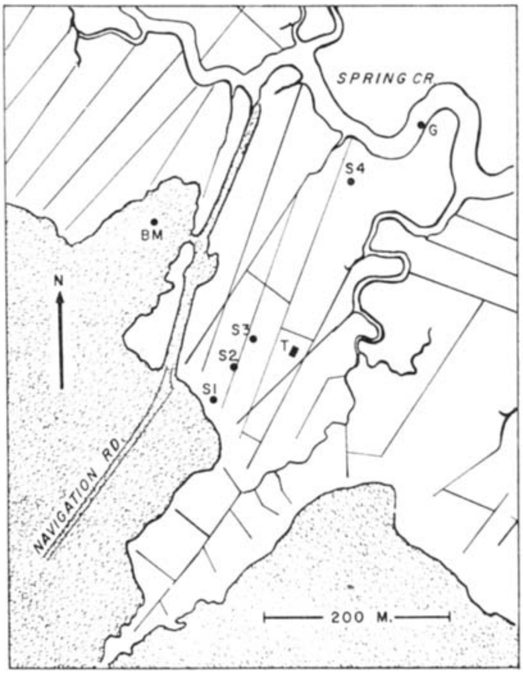

FIG. 1. Map of marsh at Navigation Road, West Barnstable, Mass. *BM*, Bench mark; *G*, tide gauge; *S1—S4*, stations where chloride was determined; *T*, site of temperature measurements.

The thermistor was encased in a stainless steel tube 2 mm in diameter and 25 mm in length mounted on a fitting into which the end of the steel rod was screwed. The tube was filled with mercury to ensure rapid conduction. The lag was less than ½ minute when immersed in a stirred water bath. Two to five minutes, depending on the temperature gradient en-

TABLE 1. *Properties of peat.*

Depth cm	Composition Percentage by weight: Water	Ash	Organic matter	Specific gravity g/ml	Specific heat cal/g × °C	Chloride[a] %
3– 6	74.0	20.2	5.8	1.11	0.88	17.3
94–103	84.3	11.5	4.2	1.15	0.86	14.2
168–176	89.0	5.1	5.9	1.19	0.77	9.5
240–250	70.4	24.4	5.2	1.13	0.74	5.2
314–322	90.4	2.3	7.3	1.05	0.88	1.2
387–396	70.0	25.1	4.9	1.16	0.80	0.35
478–500	67.0	29.6	3.4	1.23	0.71	0.10
Mean	77.9	16.9	5.2	1.15	0.81	—

[a] (Wt. Cl ÷ loss in wt. by drying) × 1000.

countered, were requiredto obtain constant reading when the thermistor was advanced to a new position.

Temperatures could be read to ±0.005°C. Calibration was accurate to ±0.01°C and temperatures were recorded to the nearest 0.01°C. Depths were recorded to the nearest centimeter and time to the nearest day. Some error is to be expected from heat introduced by the instrument or conducted into the peat by the steel rod. As a control, measurements were made with a gang of thermistors mounted permanently in position on a 1.25″ wooden pole. Such measurements departed from those made with the steel rode to a degree which depended on the gradient in temperature and in a way which indicated that more heat was being conducted along such gradients by the wooden pole, which was permanently in place, than by the steel rod during the short period required for the measurements. Although the conduction of heat through a given gradient by steel is about 100 times that by the peat, the quantity of heat conducted along the rod in the time required to make a measurement is less than that moving through the peat in one half day. Thus the error introduced by the steel rod is probably not larger than that involved in the measurement of time. The permanently mounted thermistors were not used except in observations on the diurnal cycles of temperature near the surface where speed of observation was essential. Measurements were made on 37 days between August 1, 1958, and August 12, 1960, at intervals of about three weeks. Temperatures were recorded at intervals of about 15 cm between the surface and the substratum. To obtain a suitable body of data for analysis the measurements were reduced by interpolation to give values for the temperature at time intervals of 20° of the annual cycle (20.3 days), and at depth intervals of 30.5 cm. December 31, 1957, was taken as the origin of time.

Data on daily maximum and minimum air temperatures are available from U.S. Weather Bureau observations made at Sandwich, a position 13 km west of the marsh. To obtain a comparison of the march of regional air temperature with that of the marsh peat, twenty-day means of this data were determined, centering on the days for which the marsh data were reduced.

Theory

At the surface the temperature of the peat is determined primarily by climatic factors. These depend in the first instance on astronomical considerations, i.e., the seasonal variation in intensity of insolation with the declination of the sun and the alternation of day and night. Secondary effects may be expected which are associated with the movement of air masses of different temperature and moisture content and with the flooding of the marsh during spring tides. Within the peat the temperature is affected in the main by the diffusion of heat from and to the surface. It is also influenced by the gradient in temperature required to permit the escape of heat from within the earth. The quantity of heat involved is not large and usually its effects have been neglected in studies of soil temperatures. However, an average gradient sufficient to maintain this flux can be measured in the peat layer and its effects can be included in the analysis. All these factors depend on molecular diffusion. In addition the movement of water through the peat would modify the distribution of temperature.

Biological activity would produce heat within the peat mass. The soil below the immediate surface, however, is completely anaerobic. Its organic content does not appear to decrease with depth although the age of the peat increases with depth to about 3000 years (REDFIELD & RUBIN, 1962). The organic heat production below the surface zone is undoubtedly small and has been neglected in the present analysis.

There are thus three types of effects to be separated by analysis:

1. The gradient in mean temperature required for the escape of heat produced within the earth.
2. Regular recurring fluctuations occurring as harmonics of the annual cycle.
3. Irregular fluctuations arising from variable meteorological effects, tidal flooding, the advection of water, etc.

If it is assumed that the thermal diffusivity of the peat layer is uniform with depth the variation in mean temperature with depth may be expressed by

$$T_z = T_0 + \beta z, \qquad (1)$$

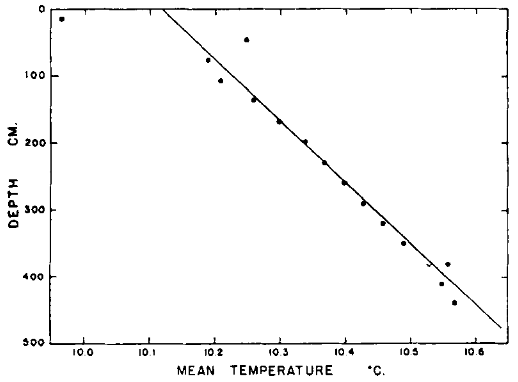

FIG. 2. Relation of mean temperature to depth. The line corresponds to $\bar{T}_0 = 10.12$°C, $\beta = 0.00108$°C cm^{-1}.

where $\bar{T}_0$ = mean temperature at the surface,
$\bar{T}_z$ = mean temperature at the depth, z, below the surface, and
β = the gradient in mean temperature with depth.

The temperature variation at the surface may be expressed as the sum of sinusoidal components, i, of frequencies $f_1, f_2 \ldots f_i \ldots$ and corresponding angular velocities $\omega_1, \omega_2, \ldots \omega_i \ldots$, as

$$T_{0,\,t} = \bar{T}_0 + \sum_i A_i \cos \omega_i (t - \varepsilon_i) \qquad (2)$$

each component having a characteristic amplitude A_i and epoch, ε_i.

If α is the thermal diffusivity of the peat each component will become attenuated with depth by $e^{-\sqrt{\omega_i/2\alpha}}$ and the phase lag will increase by $z\sqrt{\omega_i/2\alpha}$. The variation in temperature at any depth and time is given by

$$T_{z,\,t} = \bar{T}_0 + \beta z + \sum_i A_i e^{-z\sqrt{\omega_i/2\alpha}} \cos(\omega_i t - \omega_i \varepsilon_i - z\sqrt{\omega_1/2\alpha}). \qquad (3)$$

Analysis

It may be noted that each component, i, moves downward as a highly damped progressive wave having a velocity of $\sqrt{2\alpha\omega_i}$. The value of the thermal diffusivity, α, may be determined either from the attenuation coefficient or the phase lag. Moreover, the attenuation increases with the frequency and as a result the variation in temperature due to short period perturbations becomes insignificant at a small distance below the surface. The present observations were not made at close enough intervals to provide information on the diurnal and other short period fluctuations of the surface temperature. Since the effects of such fluctuations become insignificant below one meter, values of the thermal diffusivity of the peat have been determined from measurements below this depth and the effective trend in temperature at the surface has been calculated from its value.

THE ANNUAL COMPONENT

Since the classic paper of THOMPSON (1861) the first harmonic of equation (3), describing the distribution of temperature within a solid of infinite depth and extent, bounded by a plane surface subjected to a sinusoidal change in temperature, has been applied repeatedly to determine the thermal diffusivity of the surface layers of the earth, and the resulting annual regime of temperature, particularly in the interest of agriculture (CARSLAW & JAEGER, 1947; GEIGER, 1959; PEARCE & GOLD, 1959; CARSON, 1961).

A Fourier analysis of the reduced data for the annual component of temperature at each depth was made from the reduced data for the two years. The results are plotted in Figs. 2, 3, and 4. The amplitude and epoch of the annual component, f_1, and of the thermal properties of the peat, derived from graphical analysis of these figures, are given in Table 2. Since ω_1 is

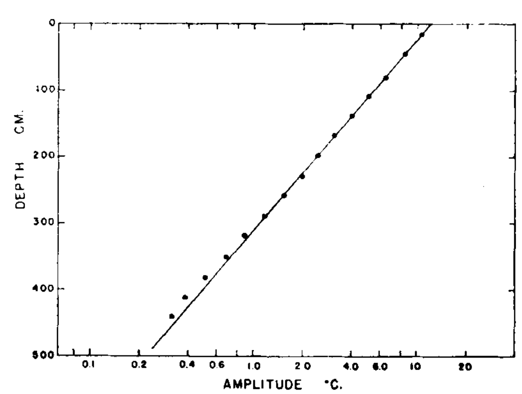

FIG. 3. Relation of amplitude of annual component to depth. The line corresponds to $A_1 = 12.02$°C. $\alpha = 1.57 \times 10^{-3}$ cm^2 sec^{-1}.

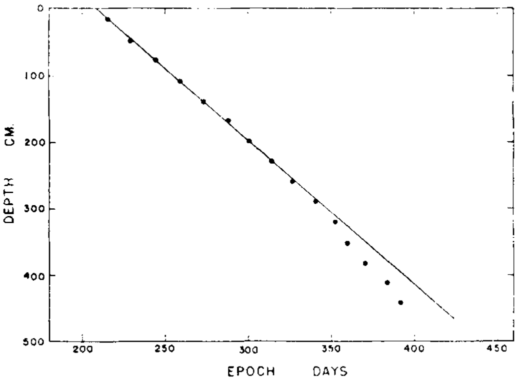

FIG. 4. Relation of epoch of annual component to depth. The line corresponds to $\alpha = 1.57 \times 10^{-3}$ cm^2 sec^{-1}, $\varepsilon_1 = 209$ days.

equivalent to 0.986° day the equation for the temperature regime resulting from the geothermal gradient and the annual component may be written

$$T_{1(z,\,t)} = 10.12 + 0.00108z + 12.02e^{-0.00796z} \cos 0.986\,(t - 209 - 0.463z). \qquad (4)$$

The linear distribution of the data shown in Figs. 2, 3, and 4 appears to justify the conclusion that the peat layer may be treated as a homogeneous medium in spite of the variations in composition shown in Table 1. However, at depths below 300 cm the data depart from the straight line relation from which the diffusivity of the peat was determined. These and other departures to be discussed below show that the equation for the annual component does not describe the thermal regime completely. Since the departures are relatively small equation (4) provides a first approximation of the temperature of the peat during the annual temperature cycle.

HIGHER HARMONICS

Fourier analyses of the reduced data for higher harmonics of the annual cycle of temperature change yielded components with amplitudes recorded in Table 2. The results obtained when the two years are examined separately do not agree well and the attenuation and phase lag with depth are very irregular. It is concluded that they do not represent phenomena recurring regularly but are mathematical artefacts arising from irregular fluctuations in surface temperature.

DIFFERENCE IN TEMPERATURES FOR THE TWO YEARS

The winter of 1958–59 was notably colder than that of 1959–60. Corresponding differences in the peat temperatures were observed. The differences are conveniently expressed as residuals, R_0, remaining when the values of $T_{1(z,\,t)}$ calculated from equation (4) are subtracted from the reduced data, i.e.,

TABLE 2. *Results of Fourier analysis of temperatures of salt marsh peat.*

Component	i	$\frac{1}{2}$	1	2	3	4
Frequency, years^{-1}	f_i	$\frac{1}{2}$	1	2	3	4
Angular velocity, sec^{-1}	ω_i	1×10^{-7}	2×10^{-7}	4×10^{-7}	6×10^{-7}	8×10^{-7}
Mean surface temperature, °C	$\overline{T}_0$		10.12			
Gradient in mean surface temperature, °C cm^{-1}	β		1.08×10^{-3}			
Amplitude, °C	A_i	1.00	12.02	0.38	0.36	0.80
Epoch, days	ε_i	713	209			
Attenuation coefficient, cm^{-1}	$\sqrt{\omega_i/2\alpha}$	5.63×10^{-3}	7.96×10^{-3}			
Phase lag coefficient, days cm^{-1}	$1/\omega_1\sqrt{\omega_1/2\alpha}$	0.654	0.463			
Wave length, cm		1100	788			
Thermal diffusivity, cm^2 sec^{-1}	α		1.57×10^{-3}			

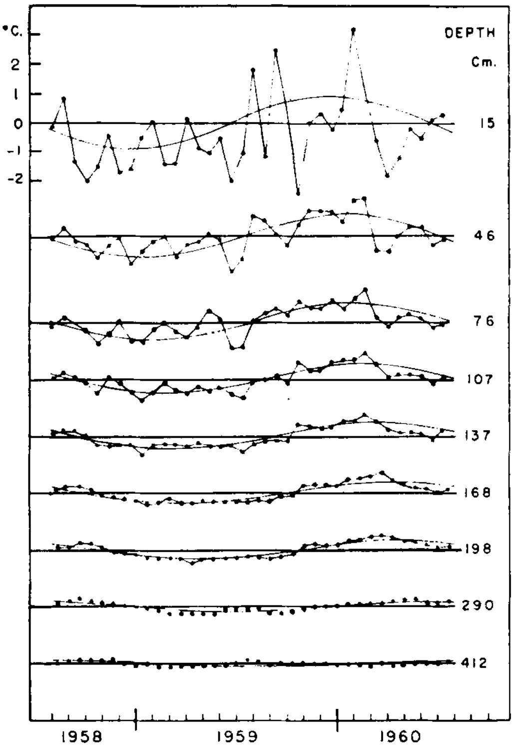

FIG. 5. Residuals, R_0, obtained after subtracting the temperatures calculated for the annual component from the reduced temperature data. The curves represent the portion of the residue attributable to a biennial component.

$R_0 = T_{z,t}$ observed $- T_{1(z,\,t)}$ calculated from equation (4).

The values of R_0 obtained at different depths throughout the two-year period are shown in Fig. 5. These residuals, which may be attributed tentatively to meteorological influences resulting from variations in the weather, fluctuate irregularly with a period of about three months. The mean values about which the residuals fluctuate exhibit a definite trend, becoming negative during the winter of 1958–59 and positive the following winter. This trend suggested that a biennial component might be used to characterize the differences in the two years and to separate the short term fluctuations from the long term trend in climate. A Fourier analysis for a component of a two-year period, $f_{1/2}$, was consequently made from the reduced data.

The results of this analysis are shown in Figs. 6 and 7. The straight lines in these figures are drawn from the theoretical expectancy when the value of α is that determined from the annual component. The characteristics of the biennial component are given in Table 2. The variation in temperature due to this component are given by

$$T_{\frac{1}{2}(z,\,t)} = 1.00e^{-0.00563z}\ 0.493(t - 713 - 0.654z). \quad (5)$$

This expression is introduced merely to separate

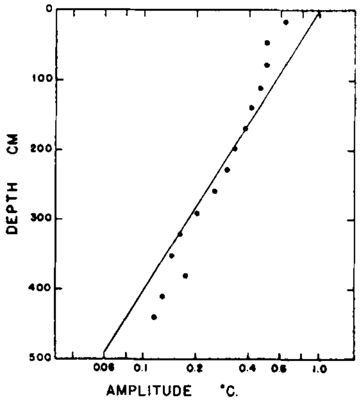

Fig. 6

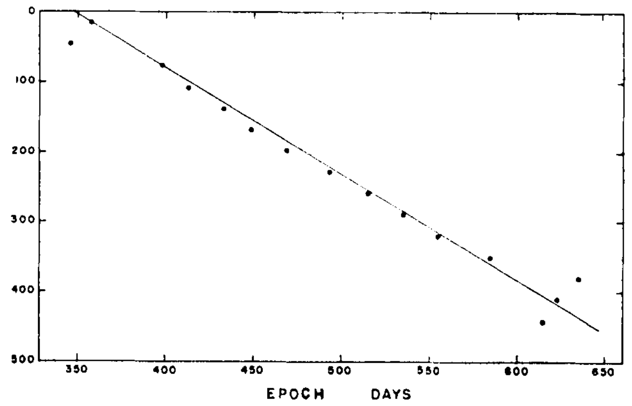

Fig. 7

FIG. 6. Relation of amplitude of biennial component to depth. The line corresponds to $A_{\frac{1}{2}} = 1.0$°C, $\alpha = 1.57 \times 10^{-3}$ cm^2 sec^{-1}.

FIG. 7. Relation of epoch of biennial component to depth. The line corresponds to $\varepsilon_{\frac{1}{2}} = 713$ days, $\alpha = 1.57 \times 10^{-3}$ cm^2 sec^{-1}.

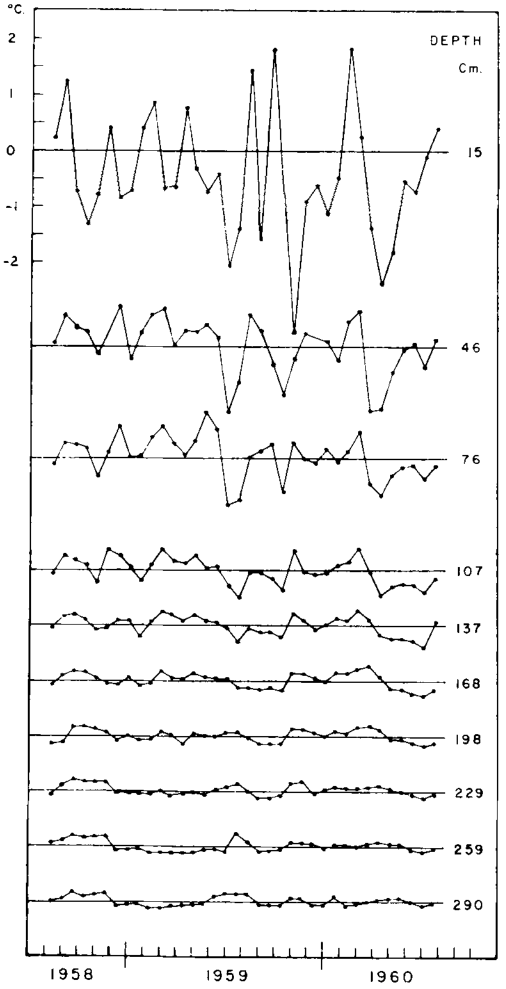

Fig. 8. Residuals, R_1, obtained by subtacting temperatures calculated for the annual and biennial components from the reduced temperature data.

the long term variations in climate during the period of observation from irregular fluctuations of shorter period. It should not be expected to apply to such fluctuations at any other time.

Short term perturbations arising at the marsh surface

Residuals, R_1, which express the perturbations of temperature remaining after the annual and biennial components are eliminated are given by

$R_1 = T_{(z,t)}$ observed $-[T_{1(z,t)} + T_{\frac{1}{2}(z,t)}]$ calculated from equations (4) and (5).

They are shown in Fig. 8. The perturbations retain their identity down to a depth of about 200 cm. They exhibit a phase lag and undergo attenuation with depth. This is the behavior to be expected if they arise at the surface. The period of fluctuation is about one quarter year.

In addition to the effects of the surface temperature the R_1 residuals contain increments due to errors in measurements and computation and any other factors not attributable to the annual and bienniel harmonic components of the surface temperature cycle. The magnitude of these combined effects may be expressed statistically by the dispersion of the R_1 residuals. Fig. 9 shows the standard deviation, σ, of the values of R_1 at each depth. The standard deviation decreases rapidly with depth down to 200 cm, as the perturbations arising at the surface become attenuated. Below this level the standard deviation is constant at $\sigma = 0.09$°C. This value may be attributed to effects remaining after those arising at the surface have been eliminated.

The dispersion of the values of R_1 may be separated into two components, the standard deviation of fluctuations arising at the surface, σ_1, and those due to other factors, σ_2, by the

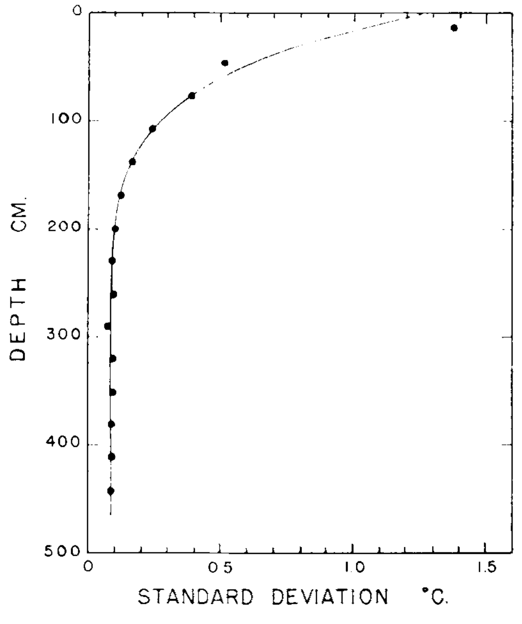

Fig. 9. Change with depth of the standard deviation of residuals, R_1, obtained after eliminating the annual and biennial components.

relation $\sigma^2 = \sigma_1^2 + \sigma_2^2$. When this is done the attenuation with depth of σ_1, proceeds approximately according to the relation $\sigma_1 = 1.25e^{-0.01059z}$ which is that of a sinusoidal wave of amplitude 1.25°C and period of one quarter year. The curve drawn through the points in Fig. 9 is calculated from these relations.

It is suggested that the perturbations of the annual march of temperature of the peat which recur at intervals of about one quarter year are related to meteorological effects such as the change of radiant heat flux accompanying the semiannual passage of the general position of the polar front across the point of observation, etc. The effects of the migration of the polar front will not follow a regular sinusoidal cycle, since the changes will occur more abruptly as the general position of the front crosses the position in spring and fall. The departures in temperature from that produced by the regular sinusoidal cycle of insolation gives rise to temperature effects which appear as harmonics of the annual cycle. In a similar way the year to year variation in temperatures may be attributed to the varying depth and duration within which the point of observation lies on either side of the polar front.[1]

PERTURBATIONS APPEARING WITHIN THE DEPTHS OF THE MARSH

Although the dispersion of the values of R_1, at depths greater than 200 cm is constant, the distribution of the values is not random. See Fig. 10. Below 300 cm the values vary in an annual cycle which is approximately in phase with the surface temperatures, but in opposite phase with the temperatures at these depths. There is some indication of these perturbations at depths between 200 and 300 cm during 1958–59 but not during the following year.

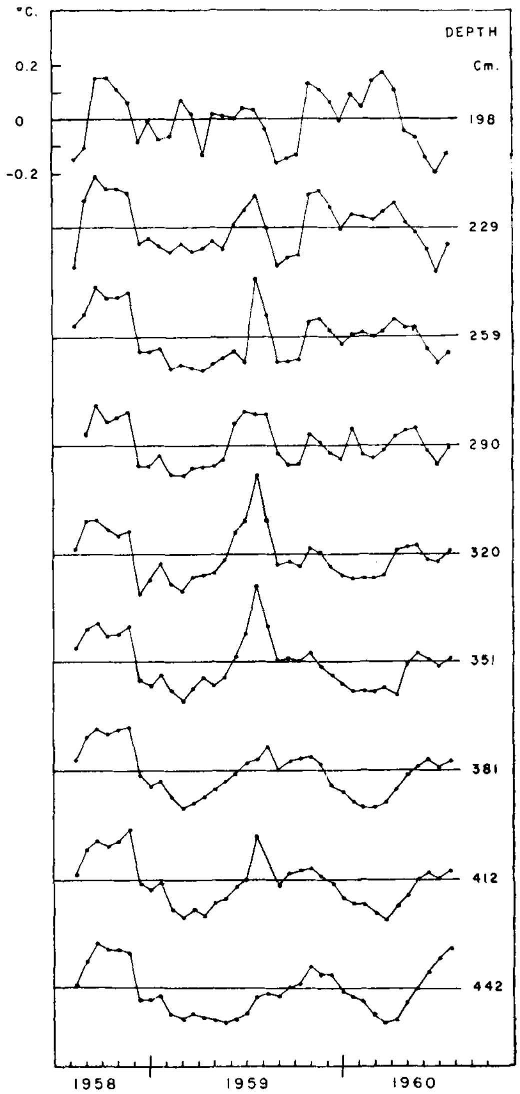

FIG. 10. Residuals, R_1, in the deeper layers of peat. Note expanded temperature scale.

The perturbations do not show attenuation or phase lag with depth and thus do not appear to be propagated from the surface. They cannot be attributed to errors in estimating the constants of the annual component of temperature change at the surface since such errors must be very large to produce the observed effects after attenuation. They occur at the same depths at which it was noted that the relations of attenuation and phase lag of the annual component depart from the linear relation shown in Figs. 3 and 4. These departures cannot arise from a change in the diffusivity of the peat at the depths in question because such change would have to be in an opposite sense to account for the two respective functions. They could be accounted for by an independent source of temperature variation at these depths if this source tended to decrease both the amplitude and phase lag of the temperature wave descending from the surface. These conditions are

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[1] This explanation was suggested to me by Dr. William S. von Arx.

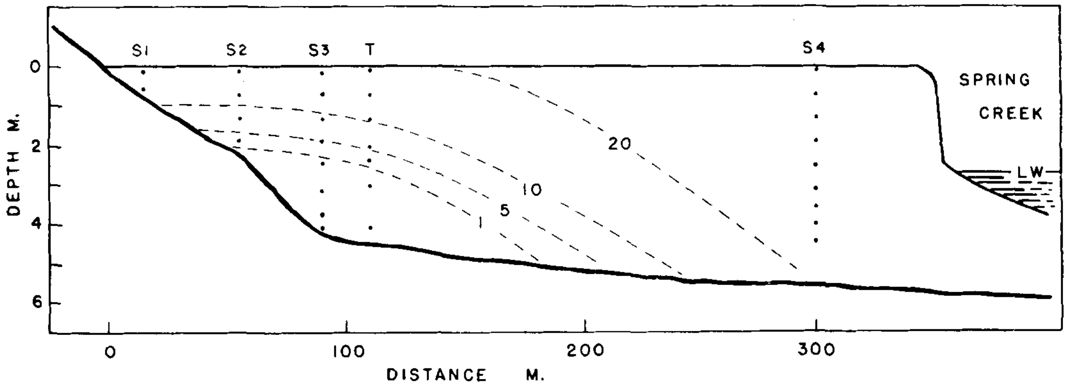

FIG. 11. Distribution of chloride in the interstitial water of peat in a section across the marsh. See Fig. 1 for positions. Contours, chloride in parts per thousand.

fulfilled by the perturbations under discussion. Some process appears to be operating in the deeper layers of peat which disturbs the distribution of heat resulting from the climatic fluctuation of temperature at the surface.

PERTURBATIONS ARISING FROM THE ADVECTION OF WATER

The concentration of chloride in the interstitial waters of the peat (see Table 1) provides evidence that there is a substantial movement of fresh water through the deeper layers of the peat mass. The chloride decreases with depth and below 300 cm is reduced to less than 1‰. Its distribution in a section across the marsh from the upland to Spring Creek indicates that ground water emerges from the upland below the high water level and flows through the deeper layers of peat above the substratum of sandy or silty clay which underlies the peat deposit (see Fig. 11). Its effects are not apparent at a position 300 m from the upland, which suggests that the ground water is drained off by a collateral creek which parallels the section across the marsh (see Fig. 1).

The coincidence in depth of the effects of the movement of ground water and of the anomalous temperatures of the peat suggest strongly that the latter are produced by a seasonal variation in the temperature of the ground water. It is apparent that the horizontal advection is rapid relative to any vertical movement which might transport salt or heat to the lower layers of peat. The phase relations are such that at 380 cm, for example, about 160 days must be allowed for the phase lag in the diffusion of heat to this depth. The phase lag in the anomaly, R_1, relative to the temperature at the surface is about 400 days. Consequently the time required for the advection of ground water from the upland to cover a distance of at least 100 m is 240 days.

The cyclic fluctuations in the values of R_1 in the deeper layers of peat extend upward to lesser depth levels and are somewhat greater in 1958–59 than in the following year. This observation might be explained by a more pronounced movement of ground water, resulting from heavier rainfall during the earlier year. Rainfall records made at Hatchville, Massachusetts, a point 20 km from the marsh, show substantially heavier rainfall during six months periods prior to and during the first year of observation than in the following year. The measurements are:

January–June 1958	85.2 cm
July–December 1958	61.6
January–June 1959	64.5
July–December 1959	58.2
January–June 1960	53.6

The vertical movement of the water table in salt marshes has been studied by CHAPMAN (1938, 1940, 1960). Small diurnal movements related to the daily tidal cycle were observed, but only within short distances of the creeks. Cyclic movements related to spring and neap tides could be traced over the whole extent of the marsh. The probable effect of such vertical motions would be to increase the rate of vertical diffusion of heat and thus to increase the apparent value of the coefficient of thermal diffusivity. It will be shown below that the thermal diffusivity of the peat does not appear to differ significantly from that expected from its water content. However, one can conclude from this only that any such effects are small. The thermal regime near the surface of the marsh, where water movement is apt to be most evident, is so complex, owing to the diurnal temperature cycle and its variation from day to day that temperature measurements are not an effective means of detecting the motion of the interstitial water at such levels.

The diurnal cycle and its variation

The temperature at the surface of the marsh fluctuates greatly as the result of the daily cycle of insolation and irradiation and of its variation with the weather. The long term march of temperature within the peat mass is of course due to the integration of inequalities in these short term perturbations. The intervals of observation in the present study were too great to provide information on the latter. Because these perturbations in temperature attenuate rapidly with depth they become negligible a short distance below the surface.

The diurnal temperature changes occurring on a clear day are shown in Fig. 12. Although the temperature vaired through 8°C at the surface, the variation in temperature was reduced to 0.15° at a depth of 30 cm. The envelopes of the curves are drawn to correspond with the attenuation of a diurnal sinusoidal wave of 3.2°C amplitude in a medium in which the thermal diffusivity is that of the marsh peat. Thus although the diurnal temperature fluctuation is not strictly sinusoidal its attenuation as it penetrates the peat follows closely that of a sinusoidal wave.

The diurnal temperature cycle varies greatly from day to day as the result of changes in weather associated with the passage of fronts. These fluctuations are very irregular but in a general way recur at intervals of about one week with amplitudes of 4 or 5°C. Some idea may be given of the depths to which such perturbations would remain significant from the following estimates of the depths at which sinusoidal waves of different periods would be reduced to 1 per cent of the amplitude at the surface, and of the time required for this attenuation to take place, in a medium with the thermal diffusivity of the marsh.

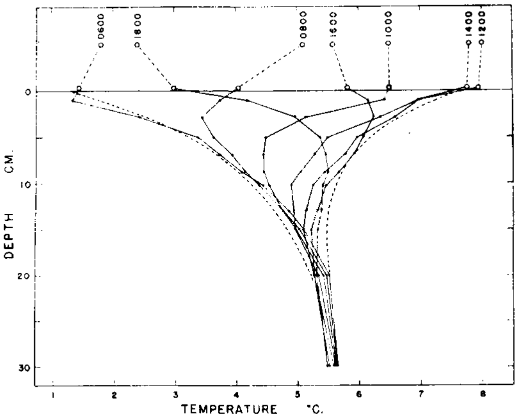

Fig. 12. Distribution of temperature in peat and in air at marsh surface and 50 cm above surface on April 13, 1959.

Period	Depth	Time
1 day	30 cm	0.5 days
4 days	60 cm	2.1 days
8 days	85 cm	4.2 days

The most precise measurements of the long term cycles of temperature in the peat may be made at depths below 100 cm where the perturbations due to the daily cycle and its variations become insignificant, and above 300 cm, where attenuation has not reduced the thermal waves too greatly.

The coefficients of thermal diffusivity and heat conductivity

The thermal diffusivity, $\alpha = 1.57 \times 10^{-3}$ cm^2 sec^{-1}, has been determined from the analysis of the annual cycle where the greater precision obtains. The same value was found by attenuation and phase lag. The value so obtained was found to determine satisfactorily the attenuation and phase lag of the biennial component and also the attenuation of the diurnal perturbation. The corresponding value for the coefficient of heat conductivity, K, is given by $K = \alpha \varrho s$ where ϱ and s are the specific gravity and specific heat of the material. The average values of the specific gravity and specific heat of the marsh peat, found by rather crude measurements are 1.15 and 0.81 respectively. Consequently $K \simeq 1.46 \times 10^{-3}$ cal. cm^{-1} sec^{-1}.

The most similar soil with which the data on the heat conductivity can be compared is the sediment of the deep ocean bottom. From measurements by Ratcliffe (1960) the relation of heat conductivity to water content was obtained by Bullard & Day (1961) to be:

$$\text{Thermal resistivity} = K^{-1} = (161 \pm 14) + (6.51 \pm 0.30)\ W$$

at 4°C, where W is the water content expressed as percentage wet weight. The thermal conductivity increases 0.25 per cent per °C (Ratcliffe, 1960). Correcting to the mean temperature of the marsh (10°C) and taking $W = 77.9$ per cent (see Table 1) this equation also gives $K = 1.46 \times 10^{-3}$ cal. cm^{-1} sec^{-1}. The value of K for the marsh thus agrees with that predicted by the equation of sea-bottom sediments.

THE HEAT FLUX FROM THE EARTH

The gradient in mean temperature with depth may be interpreted as due to a source of heat within the earth. The flux of heat, F, may be estimated from the relation $F = \beta K$. The analysis for the annual component yielded the values $\beta = 0.00108°$ cm^{-1} and $K = 1.46 \times 10^{-3}$ cal. cm^{-1} sec^{-1}. Consequently the flux of heat appears to be at a rate of 1.58×10^{-6} cal. cm^{-2} sec^{-1}. This value is close to the average of 1.61×10^{-6} cal. cm^{-2} sec^{-1} given by Lee & MacDonald (1963) for 813 measurements distributed over the earth as a whole. The agreement appears to justify the conclusion that the gradient in mean temperature in the peat arises from heat produced within the earth.

Thermal relations of soil and air

It is generally considered that the variations in the temperature of the ground and of the air near the ground depend primarily on the balance of insolation and irradiation at the earth's surface, from which the deeper layers of the ground and the lower layers of the atmosphere are warmed or cooled as the temperature of the surface changes (Geiger, 1959). Advection of air and evaporation from the ground, among other factors, enter into the relation. Within the ground the thermal diffusivity and heat capacity determine the rate at which heat is exchanged with the surface and minimize to varying degree the fluctuations of temperature at the surface. While no attempt has been made to measure the various factors involved some information can be presented on the results of such interchange.

Measurements of the temperatures of the marsh were usually made in the early morning when the air temperatures were rising rapidly. It was usually observed that the temperature of the free air 50 cm above the surface was several degrees warmer than that under the surface cover of grass, or of the peat at a depth of 3 cm. Such relations are shown in Fig. 12 where it may be seen that the temperature change at the surface and within the peat lags behind that of the overlying air when the temperature is changing rapidly. It was occasionally observed that following unusually cold nights the air above the marsh was colder than that at the peat surface. These relations suggest that the upper layers of the cover of marsh gress, rather than the actual peat surface, are the primary sites of absorption and radiation.

The distribution of heat between the atmosphere and the soil depends on their relative thermal properties. The high heat capacity of the soil permits it to minimize to varying degree the fluctuations in temperature which result from the changing balance of insolation, radiation, etc. The thermal properties of the salt marsh peat are compared with those of water and with an upland soil in Table 3. Because of its saturated condition and high water content the peat resembles water more closely than does upland soil.

The capacity of an area of the earth's surface to absorb and give off heat during a periodic change in surface temperature is referred to as its heat budget. It is defined as the quantity of heat entering a unit area during the half period between the times of minimum and maximum surface temperature in response to a sinusoidal change in surface temperature, and is given by $2\ AK\sqrt{1/\alpha\omega_1}$. The relative values of the heat budget for different soils during the same cycle of surface temperature change is proportional to the ratio of their characteristic terms, $K\sqrt{1/\alpha}$. Using the constants given in Table 4 for the marsh and the upland soil the ratio is 0.87. It is estimated that the annual

TABLE 3. *Thermal properties of water, peat and soil.*

	Thermal diffusivity cm^2 sec^{-1}	Thermal conductivity cal. cm^{-1} °C^{-1} · sec^{-1}	Volumetric heat capacity cal. cm^{-3} · °C^{-1}
Water	1.35×10^{-3}	1.35×10^{-3}	1.0
Marsh Peat	1.57	1.46	0.93
Upland Soil[a]	3.06	2.34	0.77

[a] From data for soil at Ottawa, Canada (Pearce & Gould, 1959).

heat budget for the marsh is 1980 cal. cm^{-2}. The corresponding value for the upland soil under the same conditions would be 2270 cal. cm^{-2}. The diurnal heat budget of the marsh for April 13, 1959 when the amplitude of the surface temperature change was 3.14°C was approximately 27 cal. cm^{-2}. The corresponding value for the upland soil, under the same conditions, would be 31 cal. cm^{-2}. The marsh is thus slightly less able to buffer the effects of disturbances in the heat balance which occur at its surface and these perturbations may be expected to have a greater effect on its temperature than is the case with upland soils.

With natural waters the comparison is quite different. For water the thermal diffusivity given is that for the motionless fluid. In nature, however, surface waters are subject to eddy motion which transports heat vertically at rates compared to which thermal diffusivity is negligible. Consequently the heat budgets of standing waters are much greater than those of soils. For Ashumet Pond, Falmouth, Mass., a small lake exposed to a climate similar to that at Sandwich, measurements by STOMMEL (1952) indicate that the annual heat budget is at least 10,800 cal. cm^{-2} or five times that of the marsh. For the Atlantic Ocean at 40° N 70° W BRYAN & SCHROEDER (1960) estimate the annual heat budget to be 54,000 cal. cm^{-2}.

The marsh was not visited frequently enough to obtain useful observations on the seasonal cycle of air temperatures. Air temperature records from Sandwich, Mass., a position 13 km west of the marsh were analyzed for the annual and biennial components in order to compare the marsh data with the general regional trend in air temperature. The results given in Table 4 show a close correspondence in the amplitudes and epochs of the components. The differences in the epochs and in the amplitude of the biennial component are probably not significant. The difference of 0.5°C in the amplitude of the annual component is about that to be expected from the relative thermal properties of marsh peat and upland soil, if it may be assumed that the air temperature at Sandwich is the same as that of the local soil. Evaporation from the moist marsh surface would probably be adequate to account for the difference of 0.9°C in mean temperature.

THE EFFECT OF THE FLOODING OF THE MARSH BY TIDE WATER

A tide gauge operated in Spring Creek during June and July 1958 indicated that during a

TABLE 4. *Comparison of the thermal characteristics of salt marsh peat and the air for the period August 1, 1958, to August 1, 1960.*

		Annual component		Biennial component	
	Mean temp. °C	Amplitude °C	Epoch days	Amplitude °C	Epoch days[a]
Air	11.01	11.55	207	1.4	700
Peat	10.12	12.02	209	1.00	733

[a] Since Dec. 31, 1957.

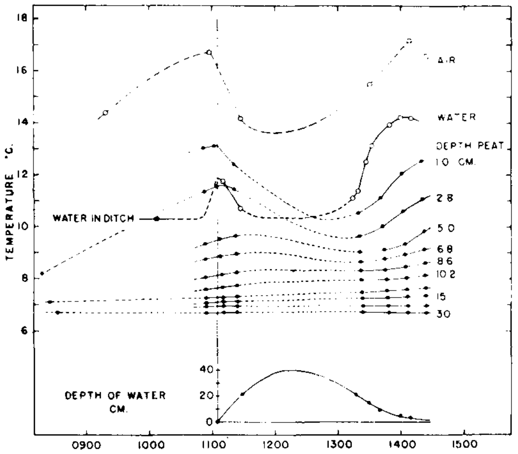

FIG. 13. Effect of flooding by a spring tide on the temperatures of the peat, and of the air 50 cm above the surface. April 24, 1959.

lunar cycle approximately half the tides rose to the elevation of the marsh surface. The number of tides flooding to a given depth decreased linearly with the depth of flooding. The highest tide rose to an elevation of 43 cm above the marsh level and remained above it for 2.5 hours. The average elevation of flooding tides above marsh was 22 cm and the average duration was 1.8 hours. The movement of water across the marsh to and from the creeks is somewhat delayed, particularly during the ebb. It is estimated that tide water covers the marsh for about 3 per cent of the time.

The effect of flooding the marsh was observed on April 24, 1959 when the water rose to a depth of 40 cm and covered its surface for about 3.5 hours (see Fig. 13). Prior to the flooding the temperature of the water in the nearby ditch was 2.4°C cooler than the marsh surface. By the time the water reached the position of measurement its temperature had risen 1.1° but was still 1.3° cooler than the marsh surface. During the next twenty minutes the temperature of the water dropped to its original value as it deepened. During this period the temperature of the subsurface peat decreased but the effect did not extend more than 3 or 4 cm below the surface. Rising water caused the observations to be suspended. When they were resumed the water had become warmer than the peat as a result of its exposure to insolation as a thin layer. As the water drained away the temperatures of the water and the subsurface peat rose steadily. While the observations indicate that an active interchange of heat between the water and the peat took place it did not extend very deeply. The net result was to leave the marsh surface about 0.5°C cooler whereas it might have been expected to have warmed by a like amount had it not been submerged. This would amount to a difference of not more than 2 or 3 cal. cm^{-2} in heat content—a small fraction of the diurnal heat budget.

When the marsh is flooded at night it is probable that the water is frequently warmer than the marsh surface. Consequently the effects of the alternate tides should tend to annul one another. The perturbations caused by the spring tides are probably small compared to those arising from the day to day variations in the diurnal thermal regime which result from the weather cycle. Their major effect is probably to keep the marsh surface moist and to thus promote heat loss by evaporation.

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