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ANNUAL CYCLES OF SOIL AND WATER TEMPERATURES AT HUBBARD BROOK[1]

Abstract. Soil temperatures in the Hubbard Brook Experimental Forest in central New Hampshire decline very slowly from December to March and are restricted from falling below 0°C. by insulation of snow and organic matter. Soil in the hardwood forest on a moderate south slope warms rapidly in the spring leafless period after snowmelt and reaches a maximum temperature in early August that averages 17.5°C. near the surface and 12.5°C. at 91-cm. depth. The soil cools to nearly isothermal conditions at 11°C. in October. The mean annual cycle of soil temperature near the surface corresponds closely to that of air temperature under the canopy, except in winter. Stream temperatures are about the same as soil temperature at a depth of 31 cm. throughout the year. Windthrow mounds are cooler than uniform slopes in winter and warmer in summer. Simultaneous soil temperatures at different locations in the forest generally differ by no more than 2°C. at any given depth.

The Hubbard Brook Experimental Forest in central New Hampshire is the location of intensive investigations of the ecology of hardwood forest ecosystems and the effect of disturbance on them.

Soil and water temperatures in the undisturbed ecosystem are important baseline variables for many studies and have been measured routinely for more than 10 years. These temperatures affect the rates of many biological and geochemical processes in both the soil and stream parts of the ecosystem. Annual cycles of stream water temperature and of soil temperatures at several sites and depths for undisturbed forests are summarized in this paper.

Soil Temperatures Vs. Depth and Time

Soil temperatures in this study were all measured by thermistors in Colman fiberglass soil-moisture units. These sensors, which are quite stable and are accurate to about ± 1°C., were calibrated before placement in the soil.

Eleven years of data (1960-1970) are available for a location about 300 m. southwest of weir 4 at Hubbard Brook. This site will hereafter be referred to as location A (fig. 1). Location A is on a southeast-facing slope of

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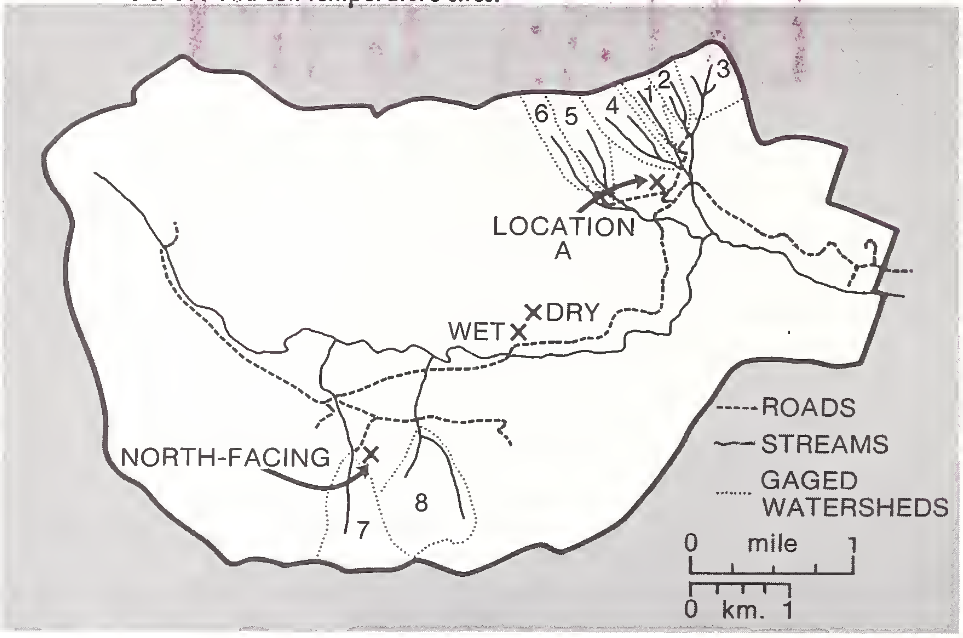
[1] This is contribution No. 56 of the Hubbard Brook Ecosystem Study. John Eaton, Cornell University, compiled much of the water temperature data.

Figure 1.—Map of Hubbard Brook Experimental Forest showing gaged watersheds and soil temperature sites.



11° at an elevation of 450 m. in a typical northern hardwood forest, which consists primarily of beech (*Fagus grandifolia*), yellow birch (*Betula alleghaniensis*), and sugar maple (*Acer saccharum*) about 60 years old with scattered older trees. The soil at this location is Berkshire fine sandy loam, a member of the coarse loamy, mixed, frigid family of Typic Haplorthods.

Sensors at location A were placed vertically in two stacks or profiles 3 m. apart and at seven depths in each stack — 2.5, 7.5, 15, 30, 46, 61, and 91 cm. These depths were measured from the top of the F layer, which was just below the surface litter. The sensors at 2.5 cm. depth were in humus. Temperature data from the two sensors at each depth rarely differed by more than 1°C., so they were averaged for this study.

Measurements at location A were obtained at 1- or 2-week intervals, for a total of about 360 dates over the 11-year period. The time of day at which measurements were taken varied. All the data were plotted by depth and date, and all years were superimposed. A curve was fitted by eye through the points; I took this to be the annual cycle of mean daily soil temperature at that depth (fig. 2). Two other smoothed curves were drawn as envelopes around the data points for each depth (fig. 3). These included virtually all of the data points, so I have designated the difference between these curves on a given date as the range for that date.

Temperature at the soil surface in winter is normally held at the freezing point because of a continuous cover of snow from late December through early April. Heat flow out of the soil normally maintains a slow rate of melt, and thus the temperature is 0°C. at the soil-snow interface (*Federer 1965*).

At Hubbard Brook, soil frost occurs infrequently because it is limited to locations, such as the tops of windthrow mounds, where there is little organic cover. It occasionally spreads through much of the forest when snow cover is abnormally thin or late (*Hart, Leonard, and Pierce 1962; Sartz 1957*). Often this frost disappears by spring because of heat from greater depths in the soil.

Soil temperature in winter increases with increasing depth on any given date (fig. 2). The temperature at each depth declines gradually through the winter (fig. 2). At

Figure 2.—Annual cycle of mean daily soil temperature for 11 years of data at Hubbard Brook location A, a gentle south-facing slope at 450 m. elevation. Depths are measured from the top of the F horizon.

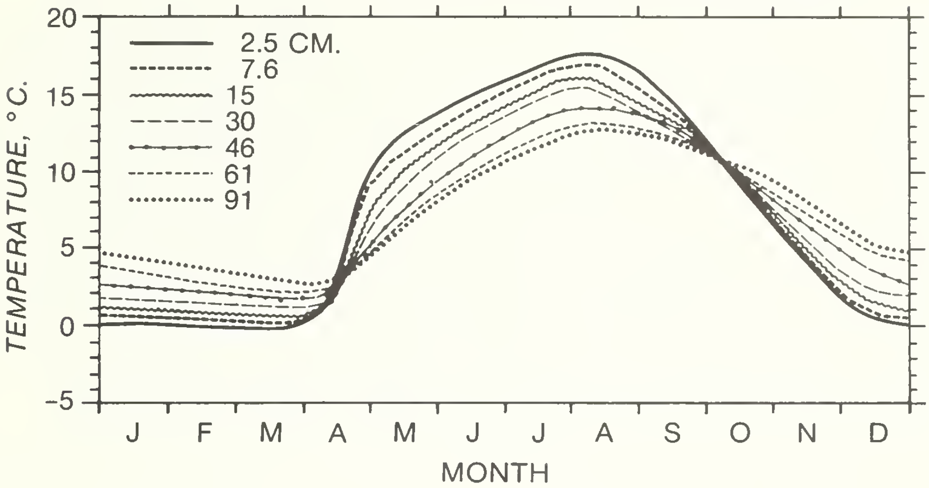
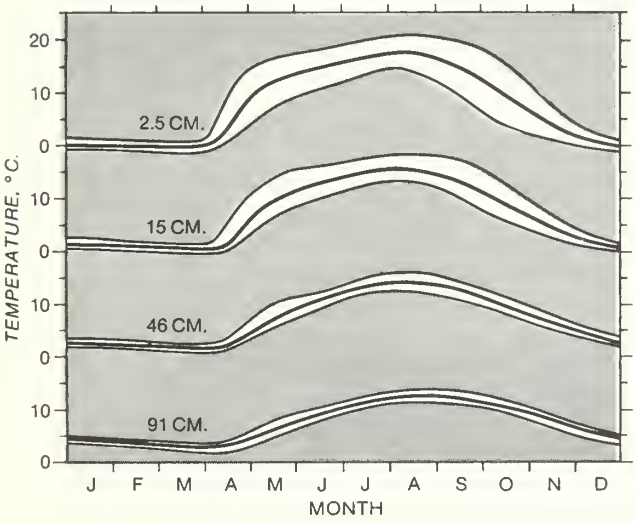


Figure 3. — Range of measured soil temperatures from 1960 to 1970 for 4 depths about the mean values shown in Figure 2.



91-cm. depth soil temperature is about 4.5°C. on January 1 and 3°C. on April 1. The winter temperatures are very consistent year after year, only deviating about 1°C. from the mean for a given date and depth (fig. 3).

As soon as the snow cover disappears in April, the soil warms rapidly but erratically at the surface and becomes nearly isothermal on the average in mid-April, but there is much year-to-year variablity. This variability shows up as a spring bulge in the range of temperatures for a given depth (fig. 3).

Soil temperature at 2.5 cm. may deviate as much as 5°C. from the long-term mean of 9°C. on May 1 (fig. 3). On clear days in April and May, the sun is quite high in the sky at midday; and solar radiation readily penetrates the leafless canopy, supplying large amounts of heat to the soil. On the other hand, cloudy days provide little heat; and the soil surface may temporarily be cooler than at greater depths. Thus the variability is caused primarily by variation in weather from day to day, but differences in seasonal warming from year to year and variability in the time of day at which the measurements were taken also play a role. The range declines in June as leaves develop in the canopy and a more uniform radiation regime is produced at the soil surface. It increases again in the autumn after leaf-fall (fig. 3).

By mid-May, soil temperature decreases with depth at least down to 91 cm. Soil temperatures continue to rise gradually until early August, reaching peak mean values of 17.5°C. at 2.5 cm., and 12.5°C. at 91 cm. (fig. 2). Thereafter, the surface cools most rapidly; and in about mid-October, the soil to a depth of 91 cm. is nearly isothermal at about 11°C. Further cooling then occurs until it is halted by snow accumulation in December.

Air Temperature and Soil Temperature

Air temperature was measured at location A from 1960 through 1970 with a thermograph in a standard instrument shelter (1.5 m. above the ground). Mean daily air temperature is defined here as the average of the daily maximum and minimum temperatures. An annual curve of mean daily temperature was drawn by eye through plotted air temperatures for the 10th, 20th, and last day of each month for the 11 years (fig. 4). Comparison of the mean daily air temperature and of soil temperature at 2.5 cm. clearly shows the insulating effort of the snow cover (fig. 4).

In January, the soil temperature is practically fixed at 0°C. although the mean daily air temperature drops to −12°C. From late March until late October, the soil temperature at 2.5 cm. is within 2°C. of the mean air temperature. In the spring, the soil surface warms more rapidly than the air; and in the fall, it cools less rapidly.

Water Temperature and Soil Temperature

The temperature of water in streams flowing through undisturbed hardwood forest was measured continually with 7-day Bourdon-tube recorders in some watersheds and weekly with thermometers in other watersheds. Recorder data from just above weir 1 for June 1965 through May 1968 (*Likens et al. 1970*), and just above weir 4 in 1969, and thermometer data from above weir 3 and weir 4 for June 1965 through May 1968 were analyzed for this study.

Water temperatures in the uppermost 50 m. of stream channel may be 5 to 7°C. higher than temperatures at the weirs in summer (*McConnochie and Likens 1969*). Diurnal cycles of water temperature are usually small (*Likens et al. 1970*), so the mean daily temperatures from the recorder and the instantaneous thermometer data were combined.

When all data points were plotted by day of the year, there were no evident differences

Figure 4.—Annual cycle of mean daily air temperature and range of daily values at 10-day intervals from 1960 to 1970 at 1.5 m. above the forest floor on a gentle south-facing slope at 450-m. elevation. Annual cycle of mean daily soil temperature at 2.5-cm. depth (dashed line) is superimposed.

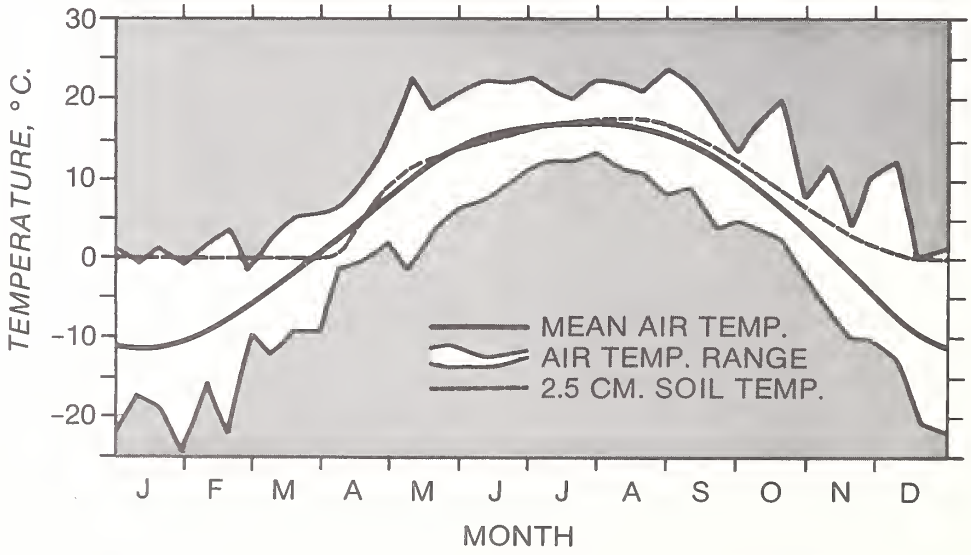
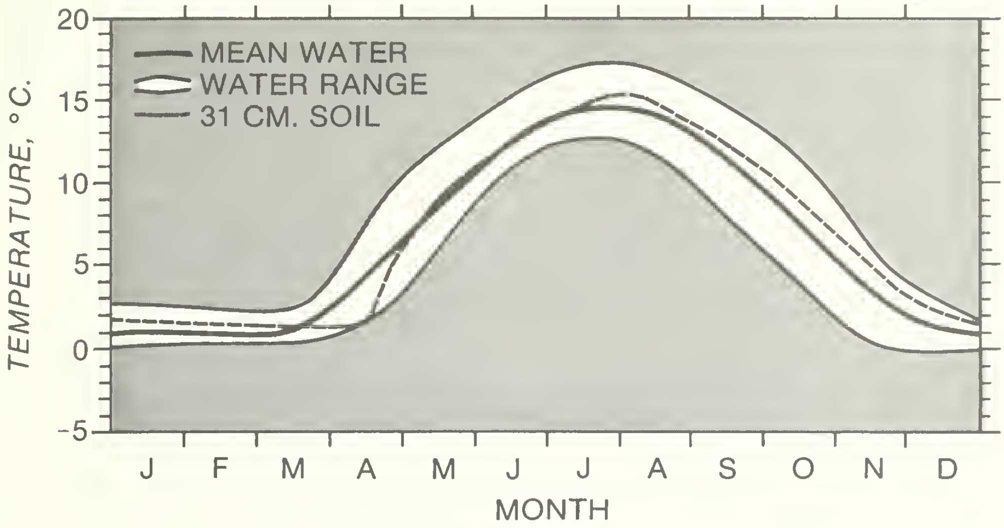


Figure 5.—Annual cycle and range of mean daily water temperature in several Hubbard Brook streams and range of temperatures. Annual cycle of soil temperature at 31 cm. (dashed line) is superimposed.



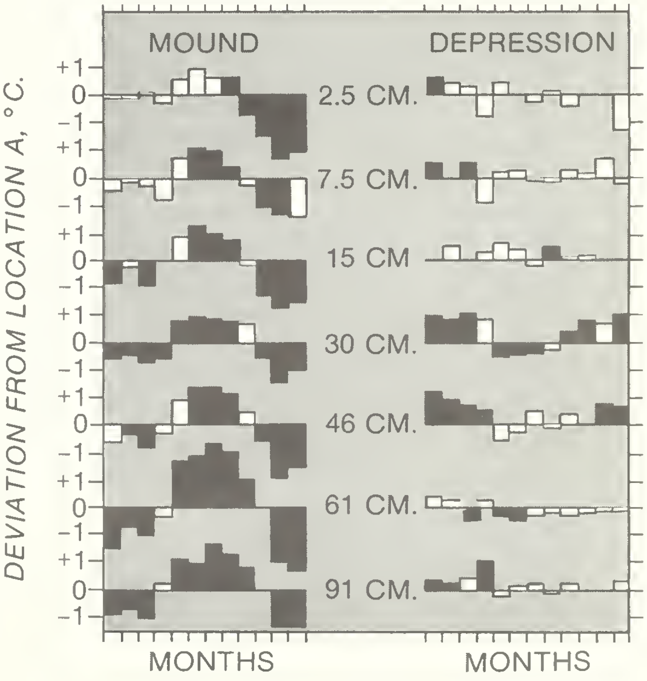
among the streams; thus data from all streams were combined. A curve of the annual cycle of mean daily temperature was drawn through the points, and envelope curves were drawn to show the range (fig. 5). Winter stream temperatures are normally 1°C., but range from 0 to 2.5°C. depending on snow cover over the stream channel — higher temperatures occur with more snow for insulation.

Throughout the year, mean stream temperature usually deviates less than 1°C. from the mean soil temperature at 31 cm. for location A. The stream seems to warm more rapidly in April, but the soil soon catches up. The stream warms to a peak of about 15°C. by the end of July. The range of water temperatures from May through November is about ± 3°C. from the mean and seems to increase slightly in the leafless periods as does the soil temperature range near the surface.

Microrelief and Soil Temperature

The ground surface at Hubbard Brook is very uneven; it is pock-marked by windthrow mounds and depressions and strewn with boulders. These factors alter the soil temperature regime from the uniform slope case of location A discussed so far. We have no

Figure 6.—Mean monthly deviation of soil temperatures in windthrow mounds and depressions from temperature at location A for the same depths and time. Solid bars indicate that the paired means are significantly different, based on a t-test at the 5 percent level.



specific information on the effect of rocks; but because their thermal conductivity is several times that of soil, they can be expected to make the temperature profile more isothermal.

We have measured temperature profiles in the top of two windthrow mounds (one profile each) and the bottom of an adjacent depression (two profiles) near location A. The two mound profiles were averaged, and the two depression profiles were averaged for this study; and the differences at each depth from the temperature at the same depth and time for location A were evaluated. Location A is on a uniform slope.

Three years of data (1960-62) clearly show that the mounds cool faster in the fall and are colder through the winter (fig. 6). This is due to a thinner organic layer and thinner snow cover and leads to a greater incidence of soil frost on the mounds (*Hart, Leonard and Pierce 1962*). The mounds also tend to be several degrees warmer in summer due to the thinness of their insulating organic cover. Depression temperatures deviate less than mounds from the uniform slope values (fig. 6). They may be about 1°C. warmer in winter at some depths because of thicker organic and snow layers. Summer temperatures in depressions are not consistently different from soil temperature at the same depth on a uniform slope.

Soil Temperatures at Other Sites

Soil temperatures have been measured with Colman units at three other sites on the Hubbard Brook Experimental Forest since 1969. One of these is near weir 7 on a 10° northwest-facing slope (here designated "north-facing") at 610 m. elevation (fig. 1). Two profiles were obtained at this location about 10 m. apart on uniform slopes, but data at the same depths were averaged for this analysis. The soil is a Becket fine sandy loam, a member of the coarse loamy, mixed, frigid family of Typic Fragiorthods.

The other two sites are close to each other near the center of the Experimental Forest at 470 m. elevation (fig. 1). The "wet" site is in a level area of poorly drained soil, a Peru slightly stony loam, a member of the coarse loamy, mixed, frigid family of Aquic Fragiorthods. A perched water table is near the surface much of the year. The nearby "dry" site is on a 15° south-facing slope and is Berkshire fine sandy loam. Only one profile was measured at each of these sites. Data for these sites was collected on the same date but not necessarily at the same time of day as at location A.

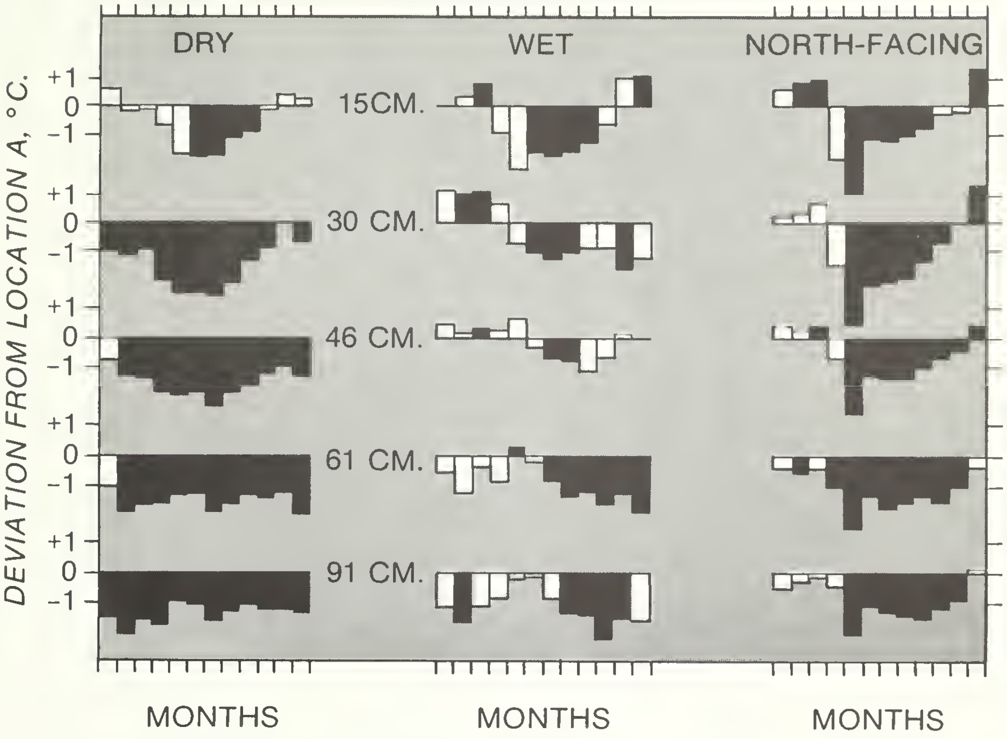
The best way to analyze these data was to average by months the differences in temperature from location A for the same depth and times (fig. 7). Although the depths had the same value as those for location A, they were not strictly comparable because depths were measured from the top of mineral soil for these sites rather than from the top of the F layer as at location A. This difference in the zero reference level may be about 6 cm.

The north-facing slope differs little from the south-facing location A in winter, but it warms more slowly in spring because of lower radiation and delayed snowmelt on the north-facing slope (fig. 7). Through the summer, this site is about 1.5°C. cooler than the south-facing slope. Figure 2 indicates that less than half of this difference can be attributed to the 6-cm. discrepancy in depths of measurement.

The dry site is 1 to 2°C. cooler than location A for all seasons and depths except 15 cm. (fig. 7). This is somewhat surprising because both sites have practically the same slope, elevation, and aspect. However the dry site is only 35 m. elevation above the Hubbard Brook valley floor, and it may be more subject to cold nocturnal drainage wind than is location A. The wet site is generally warmer than the dry site except in summer at 15 cm.; more detailed study of heat capacities and conductivities would be necessary to explain the differences. The wet site is cooler than location A in summer at all depths; and in fall, it is cooler at 61 and 91 cm.

None of the three sites differs on the average by more than 2.5°C. from location A except during snowmelt, which occurs in May on the north-facing slope. These differences, although small, are consistent and indicate that in some parts of the Hubbard Brook basin, soil temperature may average 1 to 2°C.

Figure 7.—Mean monthly deviation of soil temperatures at three sites from temperatures at location A for the same depths and date. Solid bars indicate that the paired means are significantly different based on a t-test at the 10 percent level.



cooler than at location A, especially in summer.

Soil temperatures for any date and depth on the south-facing watersheds of Hubbard Brook can be estimated from fig. 2, which provides long-term means by date and depth. Fig. 3 shows the possible deviations of the estimate from the actual temperature due to variation among days and years. Variation from site to site may contribute another 2 or 3°C. to the deviations of any estimate from the actual temperature.

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