

Thermal Properties of Soil

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In his 1822 *Analytical Theory of Heat*,¹ Joseph Fourier stated, “The problem of terrestrial temperatures presents one of the most beautiful applications of the theory of heat.” He continued, “The theory of heat will always attract the attention of mathematicians, by the rigorous exactness of its elements and the analytical difficulties peculiar to it, and above all by the extent and usefulness of its applications; for all its consequences concern at the same time general physics, the operations of the arts, domestic uses and civil economy.”

The study of heat flow and the thermal properties of various materials, soil in particular, is still an active area of applied physics research. As Fourier indicated, these properties are important because of their many applications to our food, shelter, and well-being. Seeds generally require a certain temperature threshold to germinate and develop. Soil scientists are concerned with various tillage techniques, their effects on the soil’s thermal properties, and the effects on different crops. The thermal properties of frozen soils are essential to the accurate prediction of snowmelt run-off and flood potential.

Soil provides an easily accessible physical system. Temperature studies in soil lend themselves to a number of interesting observations. These observations can be performed throughout a range of levels of sophistication, from primary grades through fundamental research.

Grade-school children might measure and compare the temperatures at different depths in the soil. The air temperature and the temperature on or below the soil surface could be compared. The insulating effect to changes in tem-

perature can be observed only a few centimeters below the soil surface. More advanced students might measure and plot temperature versus time of day and/or depth beneath the soil surface. If temperatures at several depths in the soil are monitored, the damping and propagation of the temperature wave in the soil can be observed.

Temperatures can be measured using a variety of instruments spanning a great range of cost and complexity. Glass thermometers containing alcohol or mercury are still common in many classrooms and laboratories; however, safer digital thermometers are replacing glass thermometers for many applications. Many companies supply interfaced temperature sensors for computers. (See for example the temperature sensors offered by Vernier Software and PASCO scientific.) Any of these devices could be used directly to measure the temperatures at various depths in the soil. For the electronically literate, solid-state devices (such as the LM-35), thermocouples, or thermistors can be used to measure temperatures. These components could be incorporated into a computer-controlled probe to measure temperature as a function of time and depth.

Temperature as a Function of Time of Day and Depth

Air and soil temperatures generally exhibit a diurnal cycle. Figure 1 displays the hourly air temperature for Oct. 30, 1999, a generally clear day in west-central Minnesota. The air-temperature data were acquired using a commercial thermocouple probe and data logger. The ther-

thermocouples have an accuracy of $\pm 0.1^\circ\text{C}$. A sine wave fit to the air-temperature data is also shown. One can observe that the variation in the air temperature is approximately sinusoidal, but that obvious differences exist. The maximum and minimum of the air temperature do not occur half of an oscillation (12 hours) apart. The minimum temperature occurred at 8 a.m. and the maximum temperature occurred at 4 p.m. (Taking air-temperature data versus time and fitting it to a sine wave would be a useful exercise for physics students.)

Figure 2 presents the hourly air temperature and the soil temperature at various depths beneath the surface versus time. A custom-made thermocouple temperature probe was used to acquire the soil temperature below the soil surface. On the probe a thermocouple was placed from depths of 1.0 cm to 20.0 cm at one-centimeter intervals. Only part of the data is plotted. The reduction in amplitude of the diurnal temperature cycle and the phase shift of the temperature maximum and minimum with depth are easily observable from the data.

If the thermal characteristics of the soil (conductivity and diffusivity) are considered constant with depth and time of day, and soil temperature is modeled as a sine wave solution to the heat equation, the amplitude of the diurnal soil temperature wave is expected to decrease exponentially with increasing depth in the soil. (For a more complete discussion of the solution to the heat equation in soil, see Campbell and Norman² or Monteith.³) This exponential decrease has a characteristic length known as the damping depth, D . The damping depth is the depth at which the amplitude of the diurnal temperature wave is $1/e$ times the amplitude of the diurnal temperature wave at the surface.

$$A(d) = A(0)e^{-d/D}$$

$A(d)$ is the amplitude of the temperature wave at depth d , and $A(0)$ is the amplitude of the temperature wave at the surface. Since the actual waves are not perfect sine waves, Fig. 3 plots half

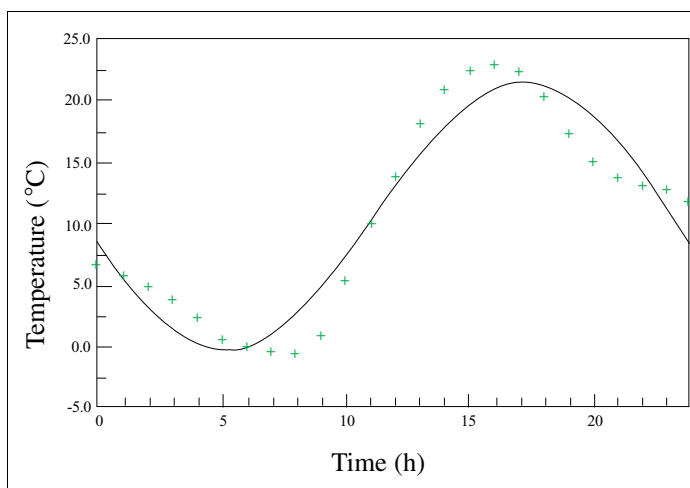


Fig. 1. Hourly air temperature (+) and a sine wave fit to the air temperature vs time of day for Oct. 30, 1999, in Morris, Minn.

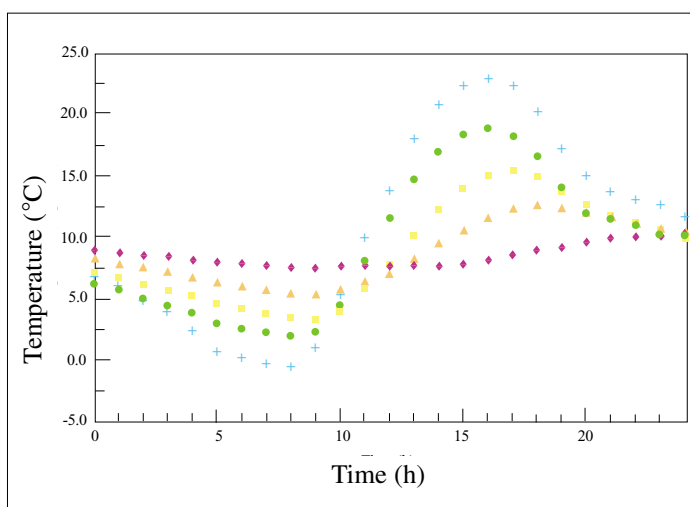


Fig. 2. Hourly air temperature (+) and temperatures at depths of 1.0 cm (●), 5.0 cm (■), 10.0 cm (▲), and 20.0 cm (◆) vs time of day for Oct. 30, 1999, in Morris, Minn.

of the difference between the maximum temperature, T_{\max} , and minimum temperature, T_{\min} , versus depth below the soil surface. An exponential fit curve is shown on the figure. The approximate damping depth is an output of the fit curve. This depth is an approximation because of the nonsinusoidal nature of the actual data. For the data displayed, the damping depth is 10.0 ± 0.1 cm. This depth indicates the approximate distance to which diurnal temperature variations occur in the soil. Several damping depths

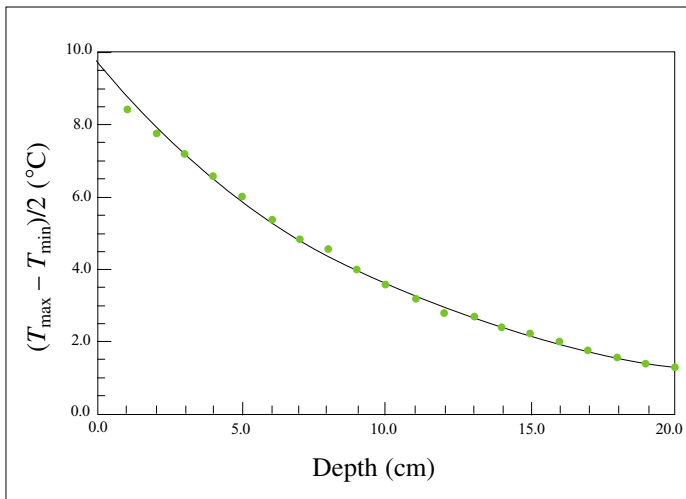


Fig. 3. $(T_{\max} - T_{\min})/2$ vs depth and an exponential fit to these data to determine the damping depth.

below the surface, the soil does not change temperature on a daily basis — the diurnal temperature variation is damped out. In regions that undergo a considerable seasonal temperature variation, an annual damping depth can also be determined. Data such as these could be used as an example of a damped decay along with more common examples such as the voltage versus time of a discharging capacitor or the rate of decay of a sample of radioactive material.

This velocity of the temperature wave, v_T , into the soil can also be calculated. v_T is an example of a phase velocity. No object is moving with this velocity. It represents the velocity of the temperature maximum into the soil. This velocity can be calculated by measuring the time be-

tween the temperature maxima at various depths into the soil.

$$v_T = (\text{depth difference})/(\text{time between maximum temperature at the depths}).$$

For the data shown

$$v_T = 19.0 \pm 0.1 \text{ cm}/7.0 \pm 0.5 \text{ h} = 2.7 \pm 0.3 \text{ cm/h}.$$

Theoretically the minima could be used for this calculation, but in practice the penetration of the minimum temperature is less well defined and more difficult to use. Using data with a greater time resolution could reduce the uncertainty in the time of the maxima. This value for the velocity of the temperature wave into the soil is in the range quoted for soils.³

Similar data could be used to study temperature changes in soil or other porous materials. A variety of conditions, wet, dry, or frozen, could be created to investigate the effects of these changes on the damping depth and velocity of the temperature wave.

References

1. Jean Baptiste Joseph Fourier, *Analytical Theory of Heat*, translated by Alexander Freeman (Encyclopedia Britannica, Inc., Chicago, 1952).
2. G.S. Campbell and J.M. Norman, *An Introduction to Environmental Biophysics*, 2nd ed. (Springer, New York, 1998).
3. J.L. Monteith, *Principles of Environmental Physics* (American Elsevier Publishing Co., New York, 1973).

A Discouraging Way to Start

etcetera... Editor:

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In the biographical sketch of the author of a recent article,¹ we read:

"Thomas P. Ray told his high school career advisor that he wanted to become an astronomer. Her reply: 'That's a great idea, but what real job would you like?' Today he is gainfully employed as a professor at the Dublin Institute for Advanced Studies, having also worked at the University of Sussex, and the Max Planck Institute for Astronomy in Heidelberg, Germany..."

1. Thomas P. Ray, "Fountains of Youth: Early Days in the Life of a Star," *Sci. Am.* **283**, 43–47 (August 2000).