Soil Temperature Variations With Time and Depth

Soil temperature fluctuates annually and daily affected mainly by variations in air temperature and solar radiation. The annual variation of daily average soil temperature at different depths can be estimated using a sinusoidal function (Hillel, 1982; Marshall and Holmes, 1988; Wu and Nofziger, 1999). This program estimates daily soil temperatures and displays these values as functions of time or depth for user defined input parameters.

Model Description

The annual variation of daily average soil temperature at different depths is described with the following sinusoidal function (Hillel, 1982):

$$T(z,t) = T_a + A_0 e^{-z/d} \sin\left[\frac{2\pi(t - t_0)}{365} - \frac{z}{d} - \frac{\pi}{2}\right]$$

where T(z,t) is the soil temperature at time t (d) and depth z (m), T_a is the average soil temperature (^oC), A_0 is the annual amplitude of the surface soil temperature (^oC), d is the damping depth (m) of annual fluctuation and t_0 is the time lag (days) from an arbitrary starting date (taken as January 1 in this software) to the occurrence of the minimum temperature in a year. The damping depth is given by $d = (2D_h/\omega)^{1/2}$, where D_h is the thermal diffusivity and $\omega = 2\pi/365\ d^{-1}$.

Assumptions and Simplifications

The sinusoidal temperature model was derived by solving the following partial differential equation (Hillel, 1982 ; Marshall and Holmes, 1988):

$$\frac{\partial T(z,t)}{\partial t} = D_h \frac{\partial^2 T(z,t)}{\partial z^2}$$

where T(z,t) is the soil temperature at time t and depth z and D_h is the thermal diffusivity.

The following assumptions are employed in the derivation of the temperature model:

1. A sinusoidal temperature variation at the soil surface z = 0. That is

$$T(0,t) = T_a + A_0 \sin\left[\frac{2\pi(t - t_0)}{365}\right]$$

   where T_a is the average soil temperature, A_0 is the amplitude of the annual temperature function, t_0 a time lag from an arbitrary starting date (selected as January 1 in this software) to the occurrence of the minimum temperature in a year.

2. At infinite depth, the soil temperature is constant and is equal to the average soil temperature.
3. The thermal diffusivity is constant throughout the soil profile and throughout the year.

Frequently Asked Questions

1. *How well does the model predict soil temperatures?* Figure 1 compares measured and predicted soil temperatures at 4 depths for a site (located at 36.87 degrees North and 115.57 degrees East) in Hebei Province, China (Wu and Nofziger, 1999). The parameters in the model in this case were obtained from measured soil surface temperatures, clay content and average water content of each layer. Clearly the model does a good job predicting the mean daily temperatures.

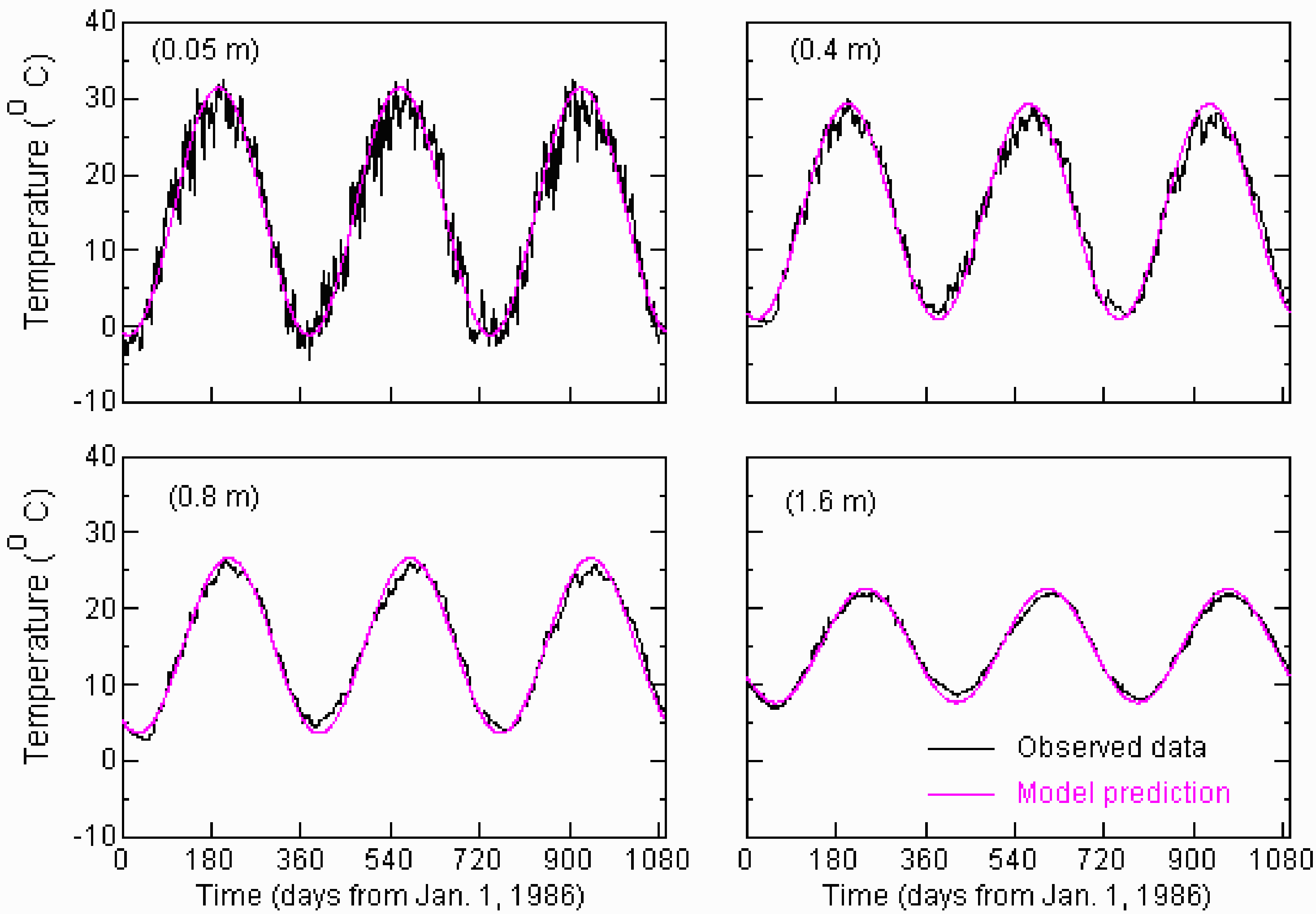

Figure 1. Measured mean and predicted soil temperatures at four depths based on measured soil surface temperatures.

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2. *Can I use air temperatures to estimate soil temperatures?* Figure 2 compares the measured and predicted soil temperatures for the same site when model parameters are obtained from air temperatures instead of measured soil surface temperatures (Wu and Nofziger, 1999). The model consistently underestimates soil temperatures by about 2 degrees Celsius. These data and those of others suggests that good estimates of temperatures under bare soils can be obtained using by simply increasing the maximum and minimum air temperatures by 2 degrees when defining the model parameters. The correction for soils that are not bare will likely be less since those soil temperatures are somewhat less due to shading from the plants.

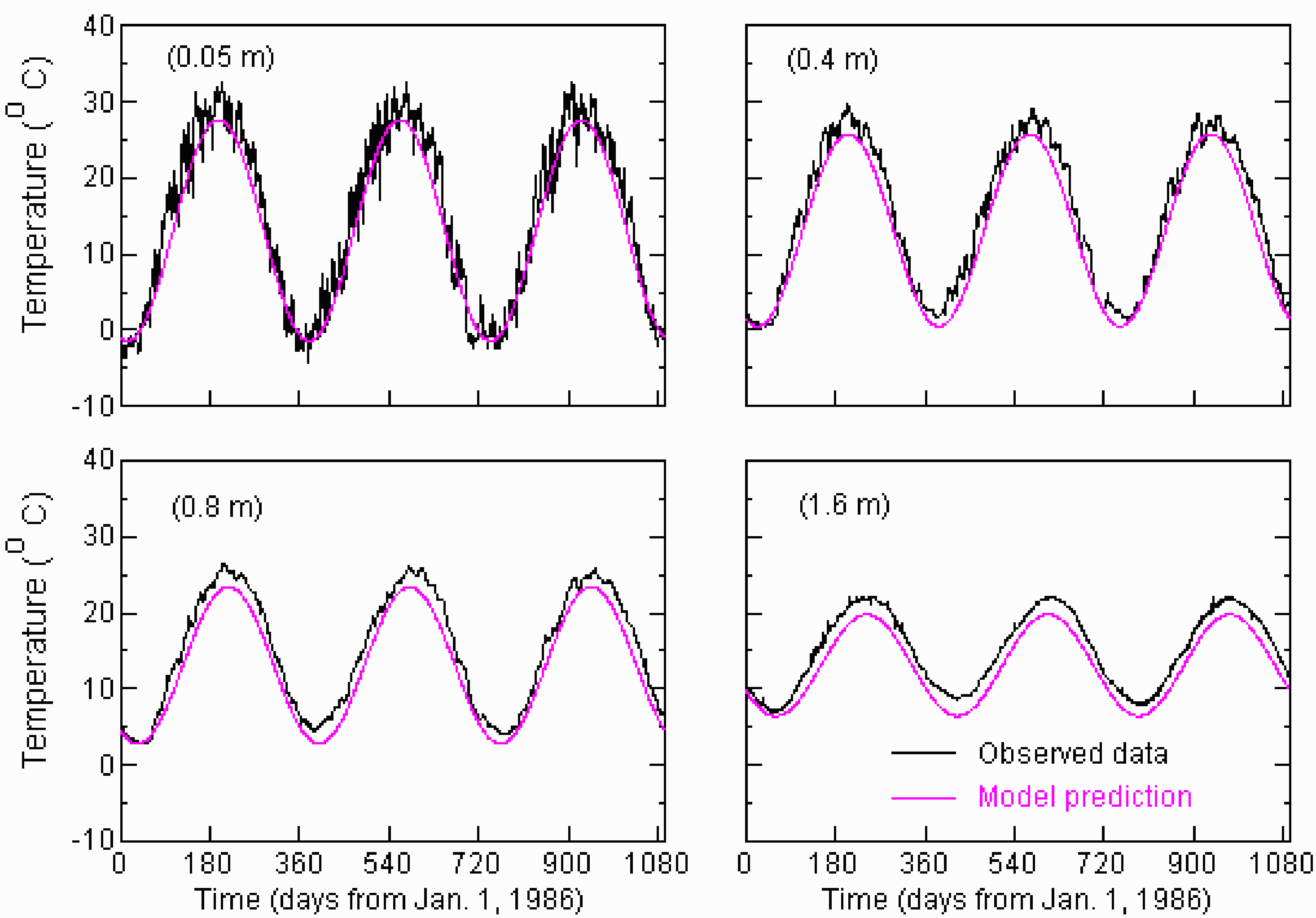

Figure 2. Comparison of measured and predicted soil temperatures at four depths based upon air temperatures at the site.

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3. *What is the effect of soil wetness on soil temperature distributions?* The thermal diffusivity of the soil is the ratio of the thermal conductivity of the soil to the volumetric heat capacity of the soil. The conductivity and volumetric heat capacity increase with water content so the diffusivity is also dependent upon soil water content. For mineral soils, the thermal diffusivity increases with water content at low water contents and then gradually decreases with increasing water contents at high water contents. This is illustrated in the Figure 3 for three clay contents and for three bulk density values. The volumetric heat capacity fot the three bulk densities is shown in Figure 4.

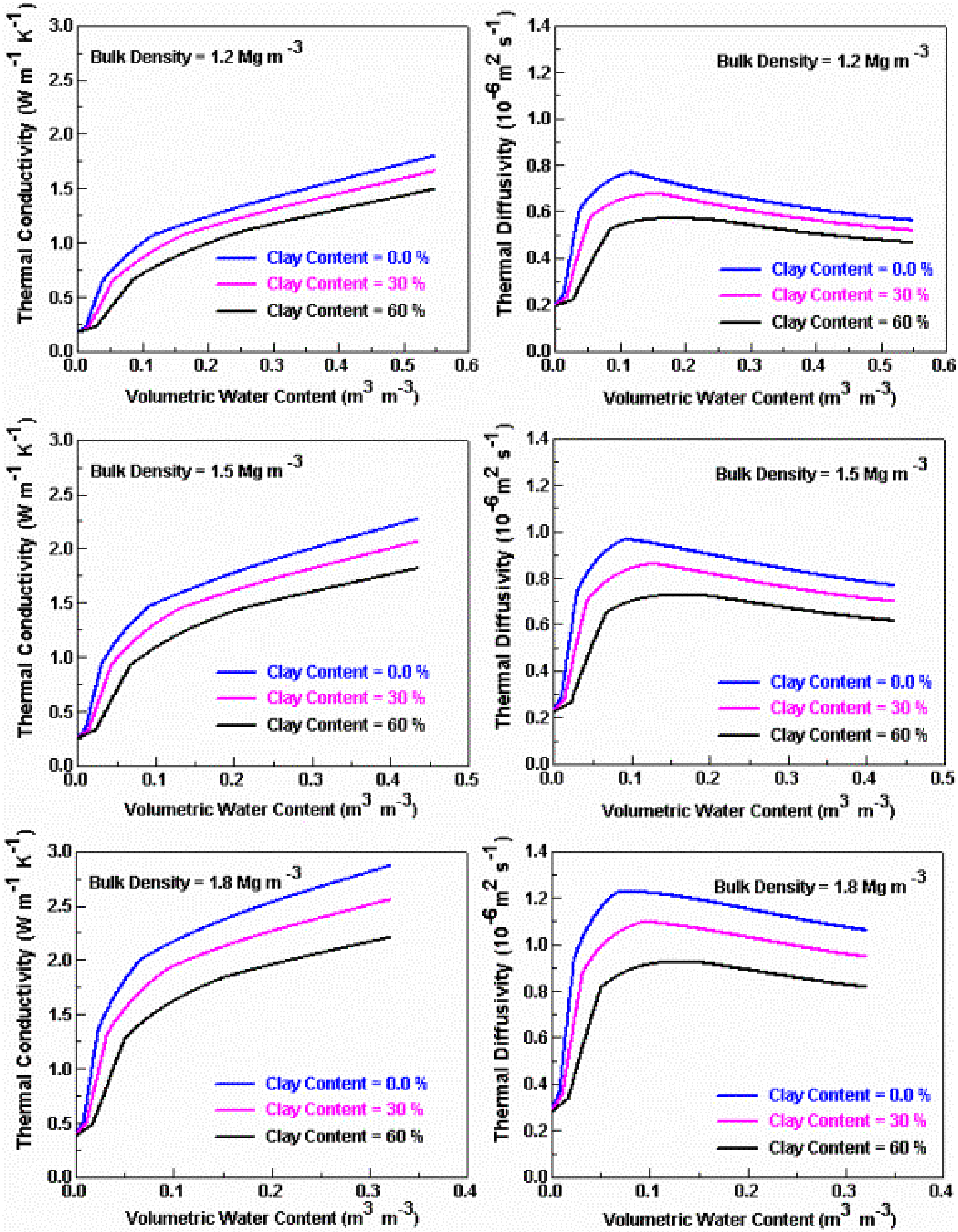
Thermal Conductivity (W m^{-1} K^{-1})
Bulk Density = 1.2 Mg m^{-3}
Clay Content = 0.0 %
Clay Content = 30 %
Clay Content = 60 %
Volumetric Water Content (m^3 m^{-3})
Thermal Diffusivity (10^{-6}m^2 s^{-1})
Bulk Density = 1.2 Mg m^{-3}
Clay Content = 0.0 %
Clay Content = 30 %
Clay Content = 60 %
Volumetric Water Content (m^3 m^{-3})
Thermal Conductivity (W m^{-1} K^{-1})
Bulk Density = 1.5 Mg m^{-3}
Clay Content = 0.0 %
Clay Content = 30 %
Clay Content = 60 %
Volumetric Water Content (m^3 m^{-3})
Thermal Diffusivity (10^{-6}m^2 s^{-1})
Bulk Density = 1.5 Mg m^{-3}
Clay Content = 0.0 %
Clay Content = 30 %
Clay Content = 60 %
Volumetric Water Content (m^3 m^{-3})
Thermal Conductivity (W m^{-1} K^{-1})
Bulk Density = 1.8 Mg m^{-3}
Clay Content = 0.0 %
Clay Content = 30 %
Clay Content = 60 %
Volumetric Water Content (m^3 m^{-3})
Thermal Diffusivity (10^{-6}m^2 s^{-1})
Bulk Density = 1.8 Mg m^{-3}
Clay Content = 0.0 %
Clay Content = 30 %
Clay Content = 60 %
Volumetric Water Content (m^3 m^{-3})

Figure 3. Variation of thermal conductivity and diffusivity with soil water content, clay content, and bulk density for mineral soils.

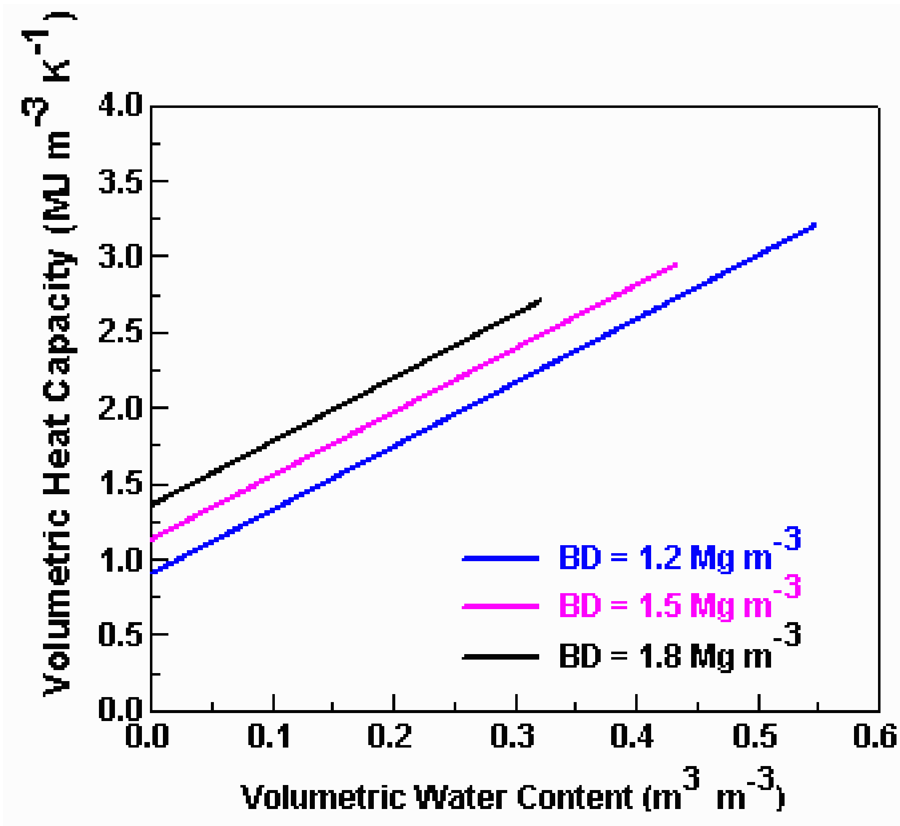

Figure 4. Volumetric heat capacity for three bulk densities for soils whose thermal conductivity and diffusivity are shown in Figure 3.

The impact of water content upon estimated soil temperature can be observed by viewing results for this range of thermal diffusivities. Figure 3 is based on research cited by of deVries (1963, 1975) and Farouki (1986). Heat transport involves soils as a mixture of mineral particles (primarily quartz and clay), organic matter, water, and air. For a mineral soils, contributions of organic matter and air to specific heat capacity and thermal conductivity of the composite soil system are usually negligible. Thermal diffusivity values change by approximately 30% or less for water contents greater than 0.05 $m^3 m^{-3}$.

Glossary

Amplitude: Amplitude is a parameter characterizing the annual variation of soil temperature around an average value. If the variation in temperature within a day is averaged out over many years, the annual amplitude is one-half the difference between this annual averaged maximum and annual averaged minimum temperatures within a year.

Damping depth: Damping depth is a constant characterizing the decrease in amplitude with an increase in distance from the soil surface. It is defined as $(2D_h/\omega)^{1/2}$, where D_h is the thermal diffusivity and ω is the frequency of a temperature fluctuation. For annual fluctuation $\omega = 2\pi/365\ d^{-1}$.

Thermal diffusivity: Thermal diffusivity is the change in temperature produced in a unit volume by the quantity of heat flowing through the volume in unit time under a unit temperature gradient. It can be calculated from thermal conductivity and volumetric heat capacity.

Time lag: Time lag is the number of days from an arbitrary starting date to the occurrence of the minimum temperature in a year.

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