Final Report

Modeling two-inch soil temperatures using daily air temperature observations

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Introduction

The physical, chemical, and biological processes within soils are affected by temperature. However, soil temperatures are not routinely measured at most operational weather stations. The observation of these data is limited to a few widely spaced agricultural research sites. Thus, it is difficult to infer soil temperatures across the region. This presents problems in many Integrated Pest Management (IPM) applications that require soil temperature to track weed germination and insect development.

Method

A physical model described by Campbell (1985) that uses daily maximum and minimum air temperature as inputs to a physical model describing heat flow in the soil and heat exchange at the soil surface was used. The model operates on an hourly time step. Diurnal air temperatures are assumed to follow a sinusoidal pattern given by:

$$T_h = T_{avg} + A\,(\sin(0.261799(h-6)),$$

where A is the amplitude of the diurnal temperature cycle ($T_{max} - T_{min}$), T_{avg} is the average daily temperature ($0.5(T_{max} + T_{min})$) and T_h is the temperature at hour h.

At each depth node in the model the energy balance equation is:

$$K_i\left(\overline{T}_{i+1} - \overline{T}_i\right) - K_{i-1}\left(\overline{T}_i - \overline{T}_{i-1}\right) = C(T_i^{j+1} - T_i^{j})\left(z_{i+1} - z_i\right)/2\Delta t.$$

Here Δt is the time increment, C is the volumetric heat capacity of the soil, z is depth, i is the model node (increasing downward), K is thermal conductance, and j is time. The mean temperature within each model layer is specified as:

$$T = \eta T^{j+1} + (1-\eta)T^{j},$$

where $\eta = 0.5$ is used in the current implementation of the model.

Currently, the model is parameterized such that the deepest depth node, $Z_{max} = 2$ m, has a constant temperature of 10°C. The fraction of clay in the soil column, M_c, is set at 0.12; the bulk density, BD, is specified as 1.3 Mg m^{-3}; and the maximum volumetric water content of the soil, WV_{max}, is set at 0.3 $m^3\ m^{-3}$.

On a daily basis, the actual water content of the upper two inches of soil is adjusted based on antecedent evaporation and precipitation. Currently daily evaporation is fixed at 2.3 mm while observed rainfall is used to assess increases in soil water content. Thus, the heat capacity, C, and thermal conductivity, K, of the soil column are adjusted on a daily basis such that:

$$C = \left(\frac{2.4 \times 10^6 BD}{2.65 + 4.18 \times 10^6 WV}\right)\left(\frac{z_{i+1} - z_{i-1}}{2\Delta t}\right)$$

and

$$K = (\chi_1 + \chi_2)(WV - (\chi_1 - \chi_4))\exp\left(\frac{(-\chi_3 WV)^4}{z_{i+1} - z_i}\right).$$

The values of χ are functions of bulk density and clay content and given by Campbell (1985) as:

$$\chi_1 = 0.65 - 0.78BD + 0.6BD^2$$

$$\chi_2 = 1.06BD$$

$$\chi_3 = 1 + 2.6M_c^{-0.5}$$

$$\chi_4 = 0.3 + 0.1BD^2.$$

Validation

The model was validated using two-inch soil temperature observations from USDA Soil Climate Analysis Network (SCAN) sites at Geneva, NY; Mahantango Creek, PA; Powder Mill, MD; and Sunleaf Nursery, OH. Table 1 shows the average seasonal (April 1- October 31) difference between the model and observed soil temperatures.

TABLE 1. Daily (March 1 – October 31) difference (observed – model) between modeled and observed (USDA SCAN Network) 2-inch soil temperatures (°C) at four stations in the Northeastern U.S.

Station	Number of Seasons	Average Difference	Maximum Difference
Geneva, NY	12	-0.47	8.13
Mahantango Creek, PA	11	-0.99	7.59
Powder Mill, MD	8	0.06	4.81
Sunleaf Nursery, OH	3	0.29	10.75

In Figure 1, a representative scatterplot is shown for the 2011 growing season at Geneva. Except for the coldest temperatures, the model replicates the observed temperatures quite well. For observed temperatures below 0°C, the model underestimates temperatures presumably since it does not account for the latent heat release during the freezing process. For the application at hand, the accumulation of base 50°F growing degree-days, this shortfall is of little consequence.

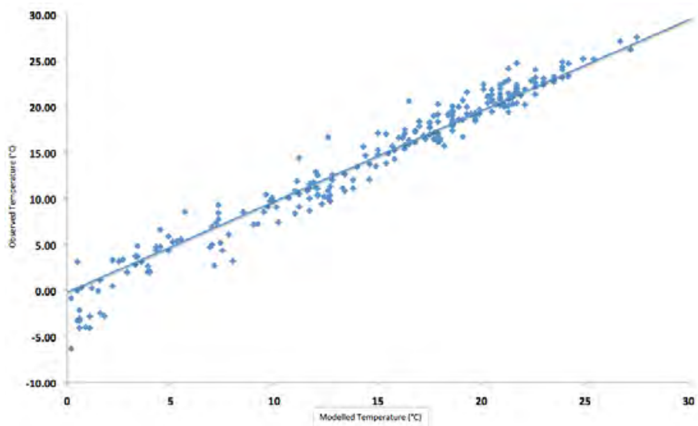

Figure 1. Scatterplot of observed and modeled 2-inch soil temperatures (°C) during 2011 at Geneva, NY.

Figure 2 shows the accumulation of base-50 GDD at Geneva, NY; Powder Mill, MD and Mahantango Creek, PA during the 2011 growing season. At Geneva, the model and observations track each other closely, with a difference (observation – model) of no more than 36 GDD during any point in the season. At the other sites, GDD differences of as much as -70 and -170 GDD were found at Powder Mill and Mahantango Creek. At Powder Mill, data for 2011 end in early August, with the greatest GDD difference occurring in June. At Mahantango Creek, the largest GDD difference occurs at the end of October and thus represents an accumulation through the season as can be seen in Figure 2.

Table 2 shows that the results presented in Figure 2 are typical of the other seasons as well. At Geneva, the average difference in GDD accumulations over the 11 seasons with available data are typically positive (observations > model), and relatively small, with the largest differences occurring later in the season, owing to the accumulation of bias through the season. At the other sites, the differences are similar over the 11 seasons at Mahantango and 8 seasons at Powder Mill. In terms of days, rather than GDD, the accumulation of 100, 200, 400, 600 and 800 GDD based on the observations and model typically occur within three days of each other at Geneva. Here, the soil temperature and air temperature observations (which drive the model) are collocated. At Mahantango Creek, the difference in accumulation period is similar, while at Powder Mill this difference averages a week.

It should be noted that at these two sites, the soil and air temperature data are obtained from different stations.

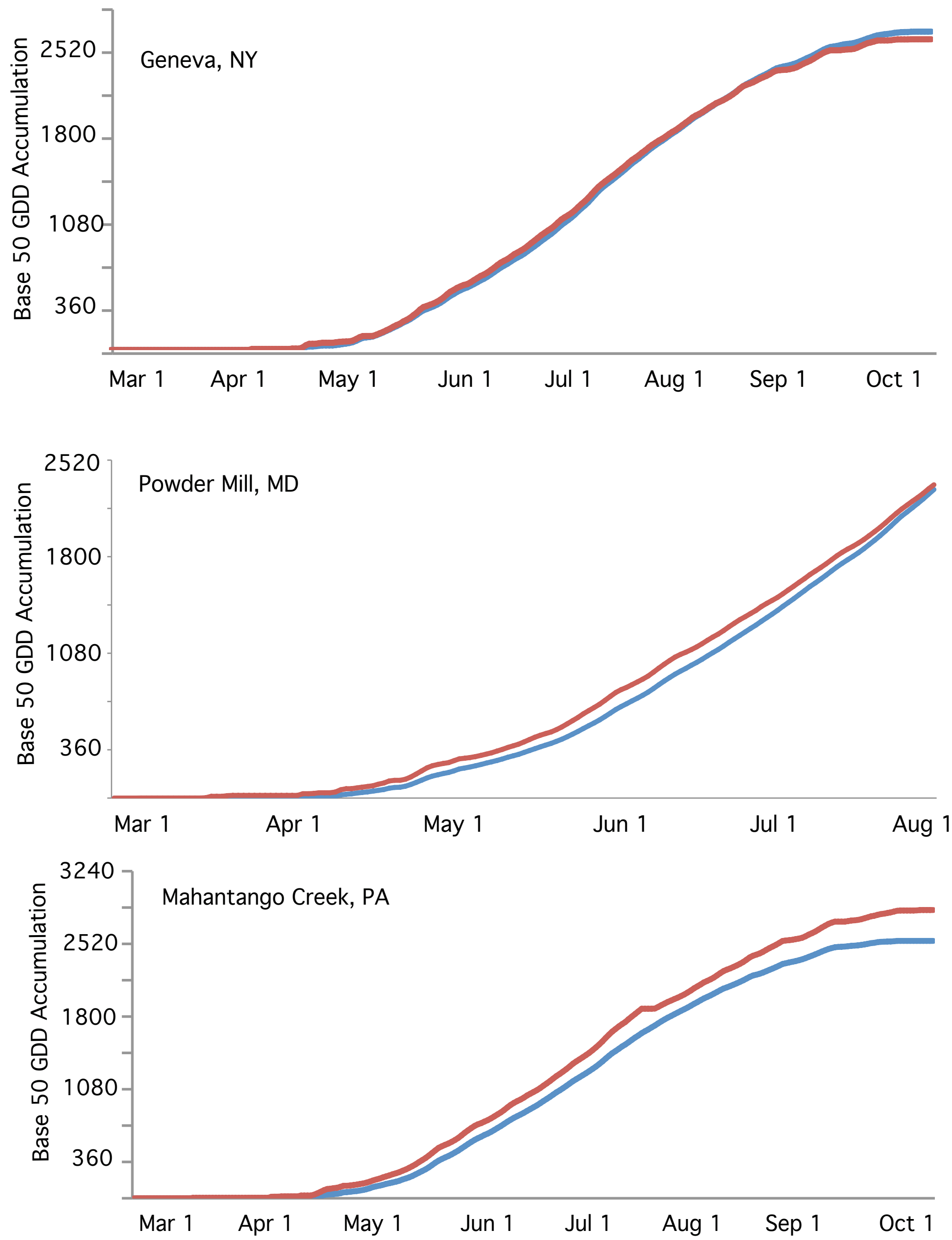

Figure 2. Seasonal base-50°F GDD accumulation during 2011 at Geneva, NY; Powder Mill, MD; and Mahantango Creek, PA based on observed (blue) and modeled (red) two-inch soil temperatures.

Table 2. Summary of average difference and standard deviation between base-50 (°F) GDD computed using observed and modeled 2-inch soil temperature. Values are given for the base-50°F GDD accumulation on April 30, May 31 and June 30 (uppermost rows) and the date of occurrence (days) of the listed GDD accumulation thresholds.

	Geneva	Mahantango	Powder Mill
Apr 30 GDD	29±11	-15±25	-82±42
May 31 GDD	37±31	38±84	-142±148
Jun 30 GDD	65±64	85±1129	-170±153
100 GDD	7±8	3±7	10±10
200 GDD	3±3	-1±8	12±9
400 GDD	3±3	-2±5	9±7
600 GDD	4±3	-3±6	7±7
800 GDD	4±4	-3±5	8±8

Conclusion

A physical soil temperature model proposed by Campbell (1985) has been modified to provide operational estimates of 2-inch soil temperature growing degree days. The model uses commonly observed daily meteorological observations, and thus can be applied to over 100 stations in New York and several hundred stations across the Northeast. The model is able to simulate the observed 2-inch soil temperatures at Geneva over 11 seasons with an average error of approximately 0.5°C (0.9°F). The largest errors in daily soil temperatures are associated with the coldest temperatures and appear to result from soil freezing processes that are not modeled. These errors are of little consequence to the desired application of these data, since such days do not contribute to the seasonal accumulation of base-50°F GDD.

In terms of GDD accumulation, the modeled values are with 30-60 GDD of the observed values during the early growing season at Geneva, with larger average differences at Powder Mill and Mahantango Creek, where the soil and air temperature that drive the model are observed at different locations. In terms of the timing of certain fixed GDD accumulation thresholds, the modeled and observed values typically occur within three days of each other.

These results indicate that the model that we have developed will provide a useful tool for monitoring soil-based degree-days. Similarly, the modeled values will be useful in driving models of insect emergence that rely on soil-based degree day accumulations and thus will benefit ongoing weather-related IPM applications.