GeoStudio Example File

Effect of Climate on Ground Temperature Response

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Introduction

The surface energy balance (SEB) boundary condition in TEMP/W is used to model the thermal response of the ground profile due to climatic conditions. This boundary condition requires a number of inputs including air temperature, wind speed, radiation, vegetation height, evaporation rate, and snow depth. These inputs are used to calculate the components of the surface energy balance equation, which in-turn is used to calculate a ground heat flux that is applied to the model domain as a boundary condition. Understanding the role of these climate inputs on the balance of energy at the ground surface, and therefore the thermal response of the ground, is necessary in order to interpret the results from an SEB problem. The objective of this example is to demonstrate the effect of climate on the ground temperature response.

Background

The energy conservation statement at the ground surface can be written as:

$$(q_{ns} - q_{nl}) = q_h + q_l + q_g \qquad \text{Equation 1}$$

where

q_{ns}	Net solar (shortwave) radiation [MJ m^{-2} day^{-1}]
q_{nl}	Net terrestrial (longwave) radiation [MJ m^{-2} day^{-1}]
$(q_{ns} - q_{nl})$	Net radiation [MJ m^{-2} day^{-1}]
q_h	Sensible heat flux [MJ m^{-2} day^{-1}]
q_l	Latent heat flux [MJ m^{-2} day^{-1}]
q_g	Ground heat flux [MJ m^{-2} day^{-1}]

The term on the left-side of Equation 1 represents the amount of energy delivered to the earth's surface from the atmosphere: it is the difference between the net shortwave and net longwave radiation (i.e. net radiation). This energy is utilized by a number of processes at the land surface including changing the air temperature via sensible heat flux (1st term on right), converting water into vapor (2nd term on right; evaporation), and changing the soil temperature (heating or cooling the ground). In a TEMP/W analysis, the third term on the right-side of the equation comprises the SEB boundary condition. In other words, the ground heat flux is solved from Equation 1 and applied to the model domain as the boundary condition.

Details of the SEB boundary condition can be found in the Engineering Book. Table 1 summarizes the relationship between the surface energy balance components and the climate inputs. The following numerical experiment aims to highlight these relationships.

Table 1. Relationship between surface energy fluxes and climate.

Energy Flux	Climate
Net Radiation	Incoming solar radiation, albedo, emissivity
Sensible Heat Flux	Air temperature, wind speed, vegetation height
Latent Heat Flux	Actual evaporation

Numerical Simulation

The model domain comprises a column of silt that is 5 m in height and 1 m wide. The silt is modeled using a full thermal model with a volumetric heat capacity and volumetric water content of 2000 kJ/m/°C and 0.4, respectively. The unfrozen and frozen thermal conductivity is 180 and 220 kJ/day/m/°C, respectively. The unfrozen volumetric water function was estimated using a silt material. The temperature at the bottom boundary was assumed constant for illustrative purposes; however, a more realistic boundary condition would have been a heat flux corresponding to the geothermal gradient. Moreover, the bottom boundary should likely be moved further far-field.

The climate data used in the analysis was taken from an Environment Canada weather station located in central Canada. The reader should carefully study the functions and note that the inputs for vegetation height, evaporation, and snow depth are optional. If these fields are undefined, the SEB boundary condition assumes that the inputs are zero for the duration of the analysis.

The incoming solar radiation was estimated for latitude 52° and the function was set to distribute the radiation sinusoidally over each day (Figure 1). This option computes the instantaneous solar radiation flux throughout the day given a cumulative daily solar radiation value (see Engineering Book).

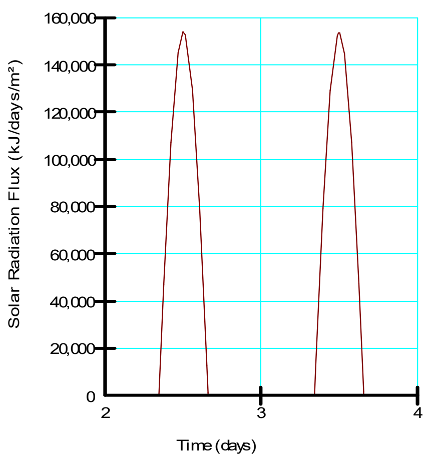

Figure 1. Example of sinusoidal solar radiation distribution for Day 3 and Day 4.

The GeoStudio project contains 10 analyses to model the effects of changing climatic inputs including increasing the wind speed, increasing the vegetation height, increasing the evaporation rate, and lowering the albedo. The cool-climate analyses explore the effect of increasing the snow depth and decreasing the snow conductivity on ground surface temperature response. A steady-state analysis was conducted to establish the initial conditions for both the warm-climate and cold-climate analyses. The transient analyses use two hour time steps, with the data from each step saved to file.

Results and Discussion

Figure 2 compares the ground temperature response for the first three analyses that use the warm climate data. The domain starts at a temperature of 5°C with an air temperature that increases from 5°C to 7°C in a two day period. Each of the three cases exhibit a diurnal ground temperature fluctuation as the ground surface cools in the early morning, warms rapidly towards the peak sunshine hour, and then cools in the later afternoon and into the evening. This sinusoidal response is naturally governed by shape of the incoming solar radiation function, which peaks at 12 noon when using estimated radiation.

Increasing the wind speed caused the ground to be warmer during the early morning and evening periods compared to the base case. Although the ground surface is still exhibiting a cooling trend, increasing the wind speed enhances downward sensible heat flux because the air temperature is warmer than the ground temperature. The sensible heat flux reverses in the middle of the day when the ground was warmer than the air, causing a cooling effect compared to the base case.

The effect of sensible heat flux is highlighted by increasing the vegetation height (Figure 2). An increased vegetation height enhances sensible heat flux. Compared to the base case, the ground surface does not warm as much by mid-day because sensible heat flux is acting to balance more of the incoming net radiation, thereby decreasing the ground heat flux.

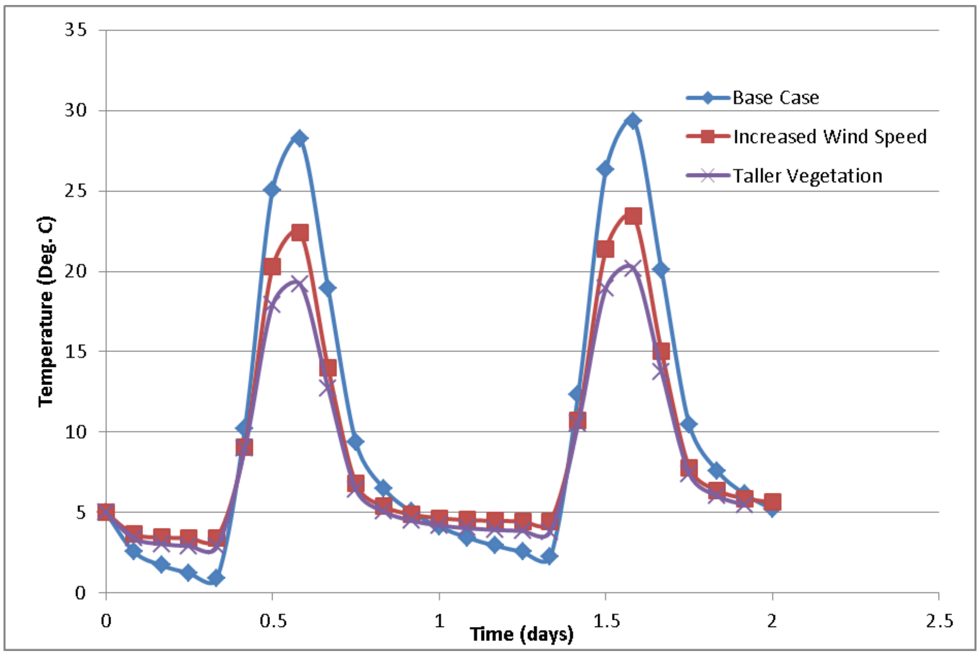

Figure 2. Effect of wind speed and evaporative flux.

Latent heat flux is the energy consumed in the process of converting liquid water to vapor via evaporation. An increased evaporation rate will therefore cause cooler ground temperatures compared to the base case (Figure 3). It should be noted in the file that evaporative flux occurs between 0.375 days and 0.75 days. In contrast, lowering the albedo causes the ground surface to be warmed compared to the base case because less incoming solar radiation is reflected back into the atmosphere, increasing the net shortwave radiation.

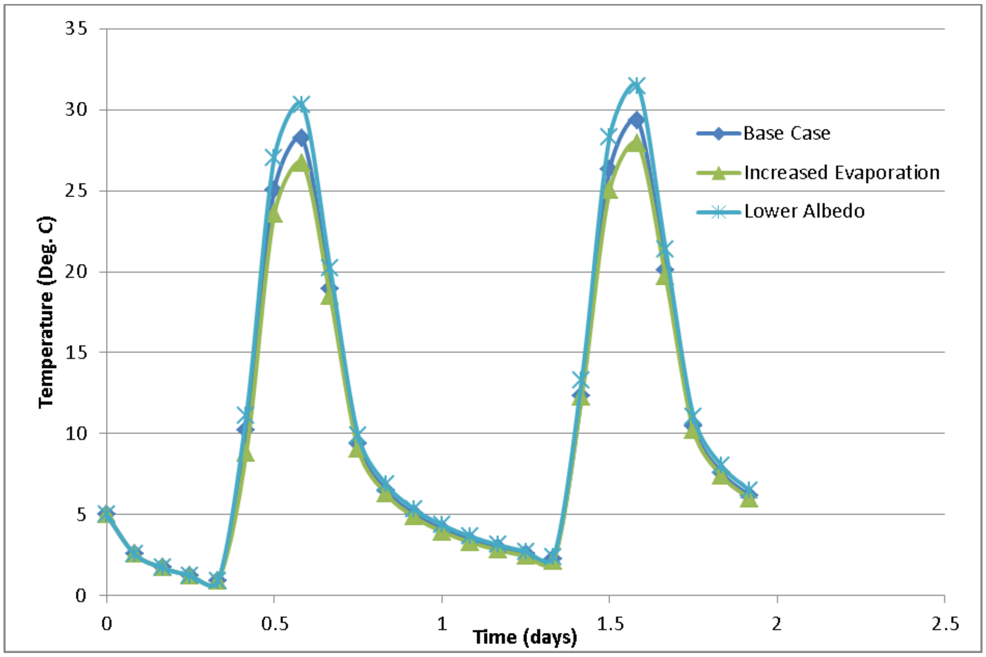

Figure 3. Effect of evaporation and albedo on ground surface temperature.

Figure 4 presents the results from the cold climate analyses. The air temperature is lower than the ground surface temperature causing sensible heat flux to remove energy from the surface. For the base case, the ground surface temperature again reflects the diurnal fluctuation in solar radiation as the ground warms slightly during the day when the incoming net radiation exceeds the outgoing sensible heat flux. The overall trend is cooling of the ground surface as the snow/ground heat flux is negative to balance the energy equation. Increasing the snow depth and decreasing the snow thermal conductivity both have an insulating effect on the ground surface. Although the snow/ground heat flux remains negative (i.e. removal of energy), the flux rate is not large enough to balance the upwards flow of heat from the base of the domain, causing a slight warming of the ground surface.

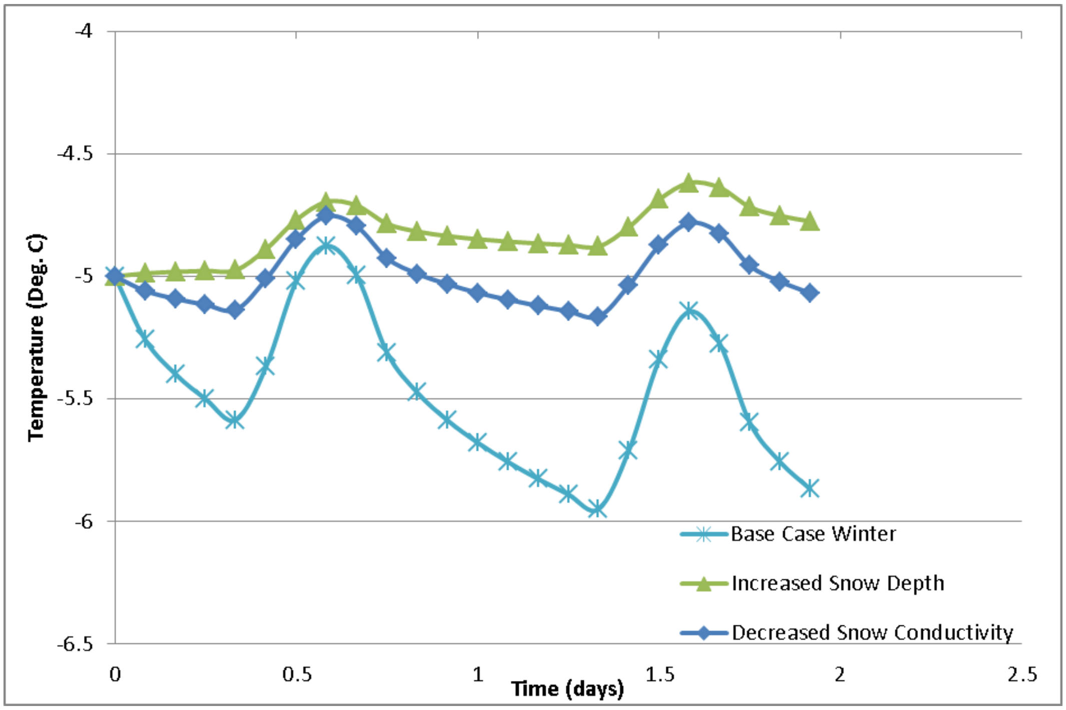

Figure 4. Effect of snow depth and snow thermal conductivity.

Figure 5 presents the results of the warm climate case solved with the solar radiation constant throughout the day. This was accomplished by toggling-off the option to distribute the radiation sinusoidally over the day. The ground temperature does not fluctuate throughout the day compared to the base case. Although the diurnal response is dampened, the average daily ground temperature is about the same as the base case because the cumulative energy from the net radiation function is the same for both cases. It is also interesting to note that using 12 hour time steps with a sinusoidal distribution yields the same response as using the constant cumulative daily radiation. This is because of the symmetry of the sinusoidal function around noon: the cumulative radiation from 0 to 12 hours plus that between 12 and 24 is equivalent to the cumulative daily radiation.

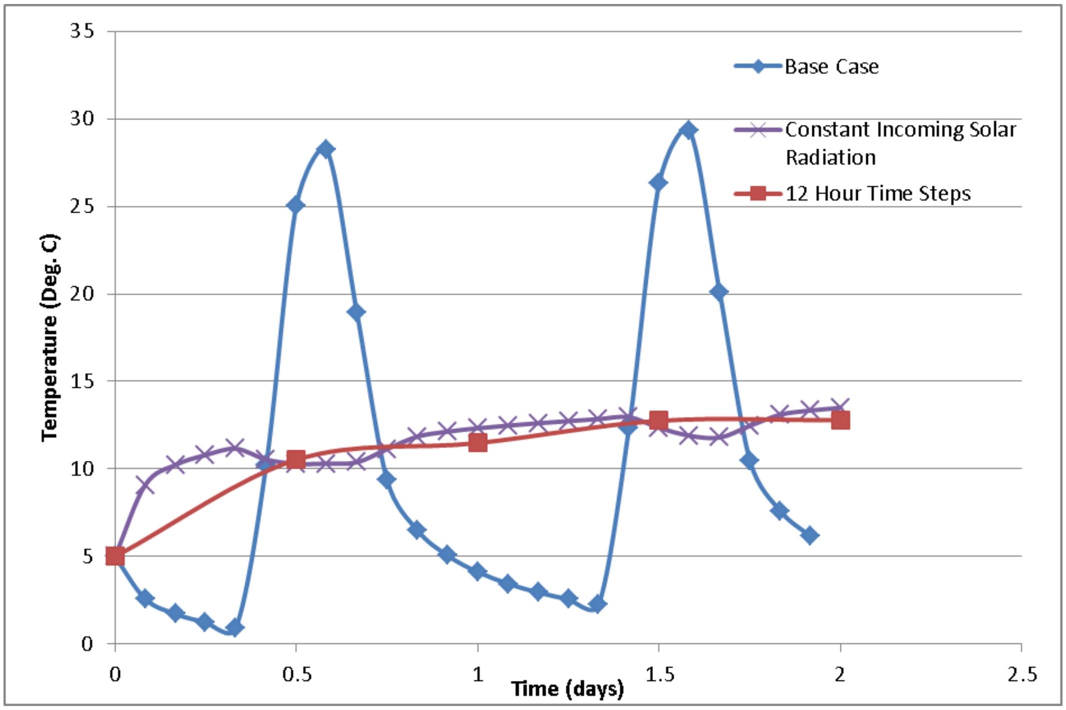

Figure 5. Base case solved with constant solar radiation function.

Summary and Conclusions

The surface energy balance boundary condition in TEMP/W represents the ground heat flux, or residual energy, of the surface energy balance equation. The ground heat flux is therefore highly dependent on climatic inputs. This example demonstrates the effect of varying the primary inputs on the ground temperature response. Increasing the vegetation height or wind speed enhances sensible heat flux and therefore has a pronounced effect on ground surface cooling or warming, depending on direction of the ground-air temperature differential. The albedo embodies the surface reflectivity and therefore governs the net incoming solar radiation. An increased albedo causes the net radiation to increase, which in turn causes warmer ground temperatures.

Snow cover acts to insulate the ground surface during the winter months. The diurnal temperature fluctuations are therefore dampened compared to fluctuations in air temperature. An increase in snow depth or reduction in snow conductivity further reduces the negative snow/ground heat flux, which has an insulating effect on the ground surface.