GeoStudio Example File
Comparison of Surface Energy Balance to n-factor

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Introduction

The ground surface temperature is influenced by many factors, including air temperature, snow depth, vegetation canopy, wind speed, and surface roughness. The use of n-factors, or the ratio of surface to air indexes during the thaw or freeze season, can offer a simplified method of modeling the temperature of the ground surface. The surface energy balance (SEB) boundary condition in TEMP/W uses a surface energy balance approach to model the thermal response of the ground surface to climate conditions. This example compares ground temperature response using the SEB and n-factor approaches, where the n-factor was calculated based on the resulting surface ground temperatures of the SEB analysis.

Background

The modeling of ground surface temperatures has been conducted in many fields of study. The use of an n-factor for a specific time period, generally seasonal, can help simplify the process of estimating surface temperatures based on air temperatures and the air freezing and thawing indices. The n-factor is described as the ratio of the summed degree-day at the ground surface to that of the air for the freezing and thawing seasons. The freezing season is typically defined as starting on the first day that the ground surface temperatures fall below 0°C, while the thawing season starts when ground surface temperatures rise back above 0°C (Karunaratne and Burn, 2004). The n-factors can be calculated by using the summed degree-days for the freezing and thawing seasons, for both the ground surface and air temperatures. The freezing (n_f) and thawing (n_t) n-factor are calculated using:

$$n_f = \frac{FDD_s}{FDD_a} \quad \text{Equation 1}$$

$$n_t = \frac{TDD_s}{TDD_a} \quad \text{Equation 2}$$

where FDD_s and FDD_a are the freezing degree-days of the ground surface and air (°C days), and TDD_s and TDD_a are the thawing degree-days of the ground surface and air (°C days), respectively (Karunaratne and Burn, 2004; Klene et al. 2001).

Caution is required when working with seasonal n-factors, as significant changes in the n-factor can occur over small distances, based on snow cover depth, vegetation, latitude, and topography (Klene et al. 2001). The SEB boundary condition requires a higher number of inputs, including air temperature, wind speed, radiation, vegetation height, evaporation rate, and snow depth. These inputs are used in the calculation of the ground heat flux based on the surface energy balance equation, which negates the need to measure ground temperatures and develop site-specific n-factors.

Numerical Simulation

The model domain consists of a 30 m-long one-dimensional column with a global element size of 0.05 m (Figure 1). A steady-state heat transfer analysis was used to define the initial conditions with upper and lower boundary conditions set equal to -5°C and 5°C, respectively. Two long-term transient analyses, or spin-up analyses, were used to remove the influence of the initial conditions using the Surface Energy Balance (SEB) and n-factor boundary conditions.

Climate data used in these analyses was that recorded at the Cold Lake, Alberta, weather station in 2004.

The results of these spin-up analyses were used as the initial pore-water pressure conditions in two transient heat transfer analyses for comparing ground temperature response with the SEB and n-factor approaches (Figure 2). Climate for the final two analyses was that recorded in Cold Lake between 2004 and 2011. Additional information on the SEB and n-factor boundary conditions is provided below. All transient heat transfer analyses included a 4×10^{-5} kJ/sec geothermal heat rate at the bottom of the column, which is consistent with the Government of Alberta Heat Flow Map (Bachu and Burwash, 1994). The spin-up analyses are not included in the GeoStudio example file to decrease the file size.

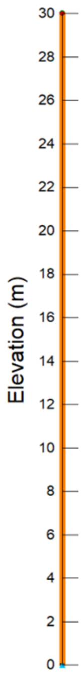

Figure 1. Problem configuration.

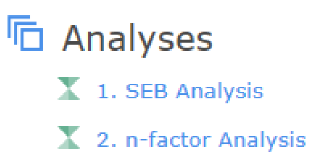

Figure 2. Analysis tree for the GeoStudio Project.

The Full Thermal Material Model is used to describe the native silty soil (Figure 3). The thermal conductivity was estimated using the sample silt material with unfrozen and frozen thermal conductivities of 180 and 220 kJ/days/m/°C, respectively. As shown in Figure 4, the thermal conductivity increases as the temperature decreases and the pore-water freezes. The unfrozen water content function, shown in Figure 5, was also estimated with the sample silt material. The unfrozen and frozen volumetric heat capacities are defined as 2,000 kJ/m³/°C and the *in situ* volumetric water content (VWC) is set to 0.4 m³/m³.

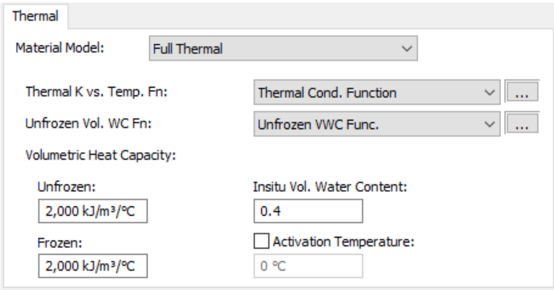

Figure 3. Full thermal material parameters.

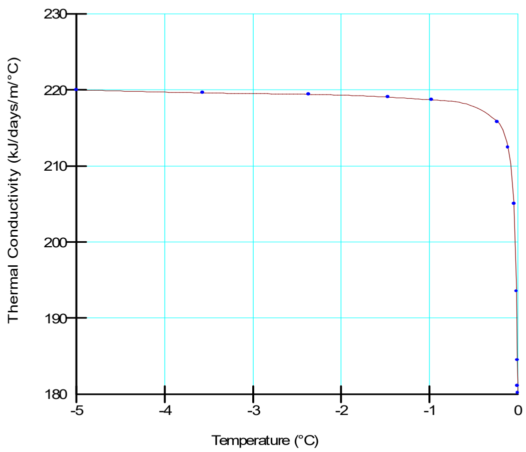

Figure 4. Thermal conductivity function.

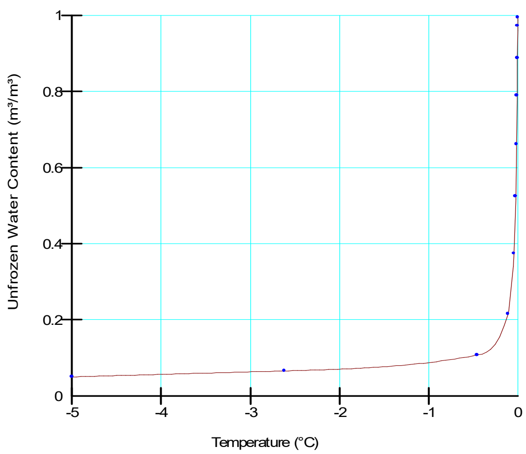

Figure 5. Unfrozen water content function.

In the SEB analyses, the SEB boundary condition was applied to the top node of the column. The annual air temperature (Figure 6), wind speed (Figure 7), solar radiation (Figure 8), evaporation (Figure 9), and snow depth (Figure 10) data was taken from the Cold Lake, Alberta, weather station. To account for the reflective properties of the snowpack, the surface albedo was set equal to 0.8 for the first 90 days, and 0.15 for the remainder of the year. The surface was assumed bare and the vegetation height was set equal to 0 m for the duration of the analyses. Snow properties were assumed constant, and the snow thermal conductivity was set equal to 10 kJ/day/m/°C.

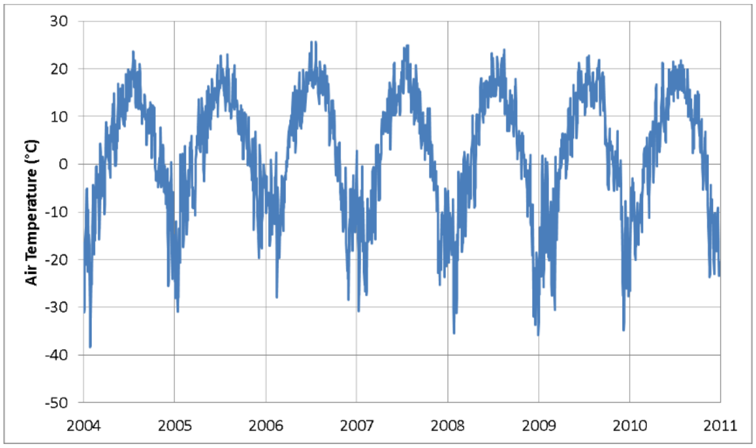

Figure 6. Air temperature function.

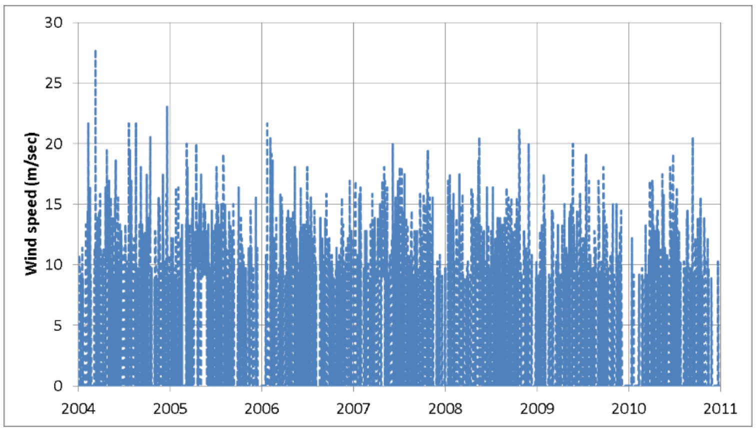

Figure 7. Wind speed function.

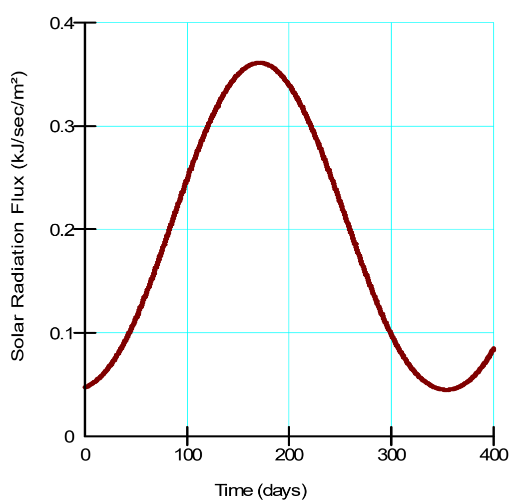

Figure 8. Estimated solar radiation function for Latitude 54°.

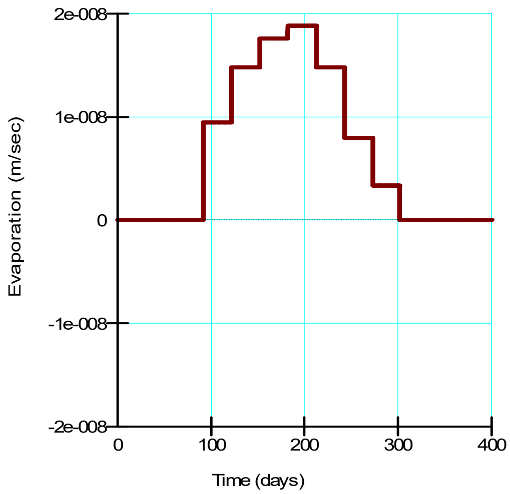

Figure 9. Estimated evaporation function.

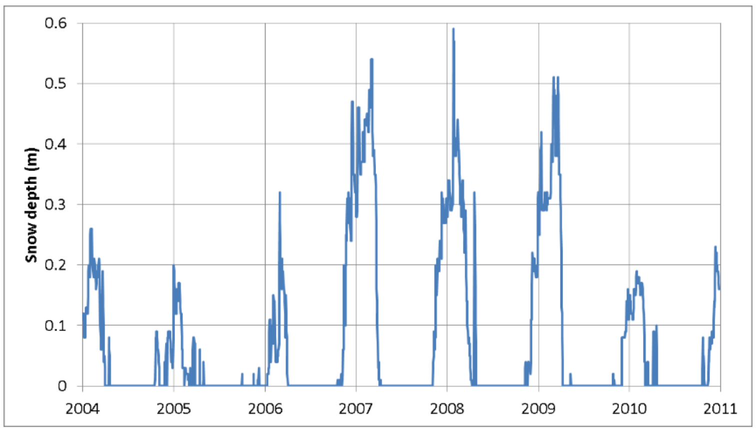

Figure 10. Snow depth function.

The n-factor boundary condition was applied to the top node of the n-factor analyses. The same air temperature data was taken from the Cold Lake weather station as above (Figure 6). Seasonal n-factors were computed from the average daily air and surface temperatures computed in the final year of the SEB spin-up analysis. The freezing and thawing n-factors, computed with equations 1 and 2, were determined to be equal to 0.44 and 1.41, respectively.

It should be noted that using the SEB numerical results to calculate the n-factors is somewhat paradoxical. However, the purpose of this example is to demonstrate how both approaches can be handled in TEMP/W and to highlight some of the differences. Realistically, site-specific surface temperature data would be required to determine the n-factors.

Results and Discussion

Figure 11 compares the ground surface temperatures obtained with the SEB and n-factor approaches. As expected, the simulated surface temperatures in the SEB analysis are generally milder than those reached using the n-factor approach. The n-factor approach also displays greater fluctuations that can be attributed to its direct link to air temperature. This is particularly evident during the winter months, when the snow pack is fairly deep and its insulating effect is most prevalent.

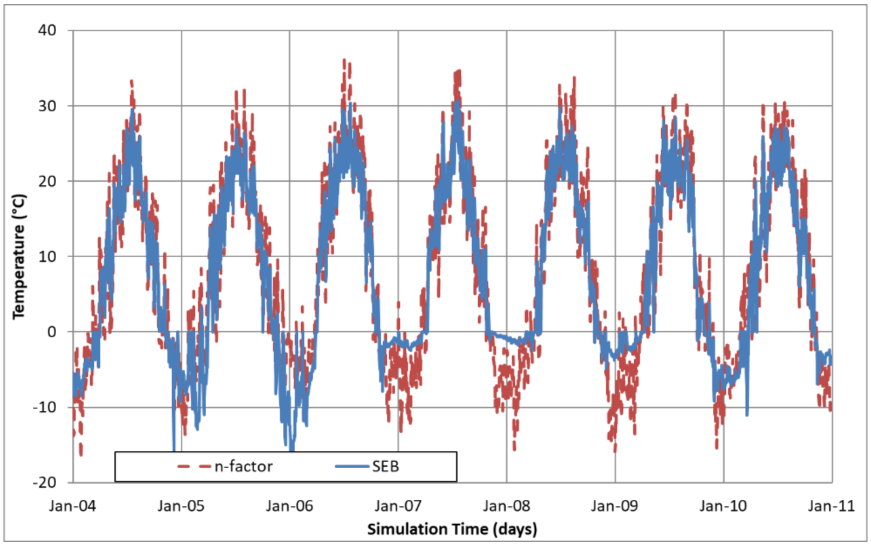

Figure 11. Ground surface temperature results for the SEB and n-factor analyses.

Figure 12 compares the cumulative energy transfer over the 7 year-period. The cumulative energy transfer of the n-factor analysis is shown to be fairly consistent from year to year whereas that of the SEB analysis is more dynamic. This is consistent with the fact that the SEB ground heat flux is a function of a number of climate inputs, while that of the n-factor depends only on air temperature. Moreover, the presence of the snowpack is again evident in the SEB analysis in which the amount of energy extracted during the 2007, 2008, and 2009 winters is less significant than that of the n-factor analysis.

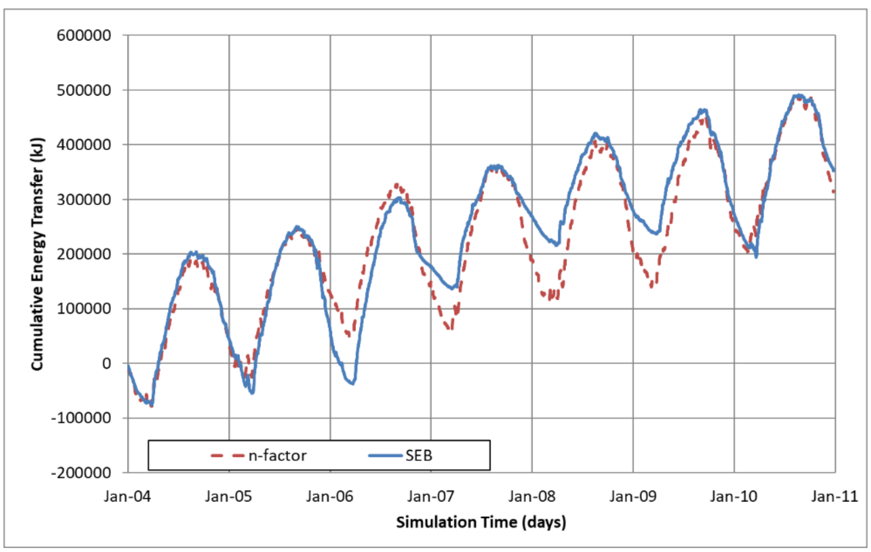

Figure 12. Cumulative energy transfer results for the surface node in the SEB and n-factor analyses.

Figure 13 and Figure 14 present the ground surface temperatures for 2005 and 2007, respectively. As shown in Figure 10, the snow depth in 2005 was much smaller than in 2007. As expected, the snow accumulation acts as a buffer to the changing air temperatures, which is not correctly accounted for by the seasonal n-factor approach. There are also significant differences during the summer months in which the SEB approach responds to daily variations in net radiation, wind speed, and air temperatures, not only air temperature as in the n-factor approach.

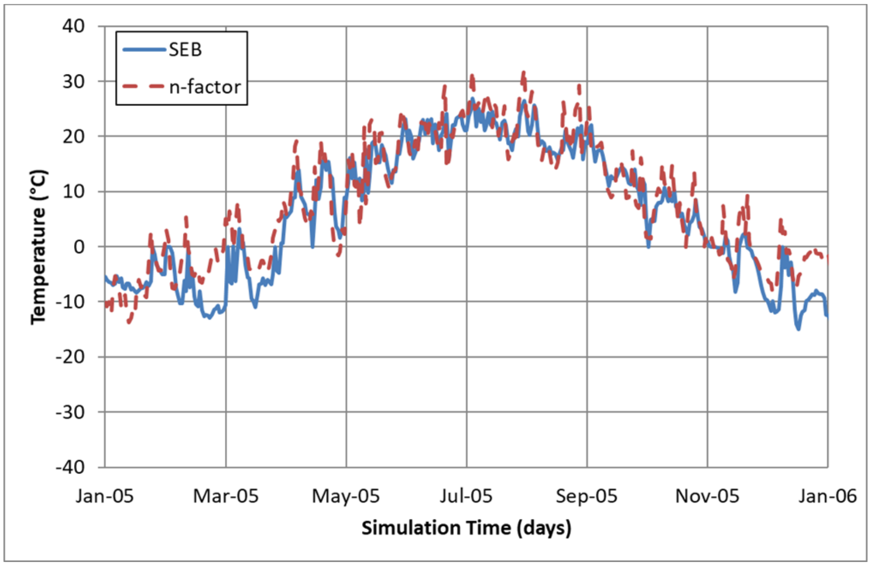

Figure 13. Ground surface temperatures for the SEB and n-factor analyses in 2005.

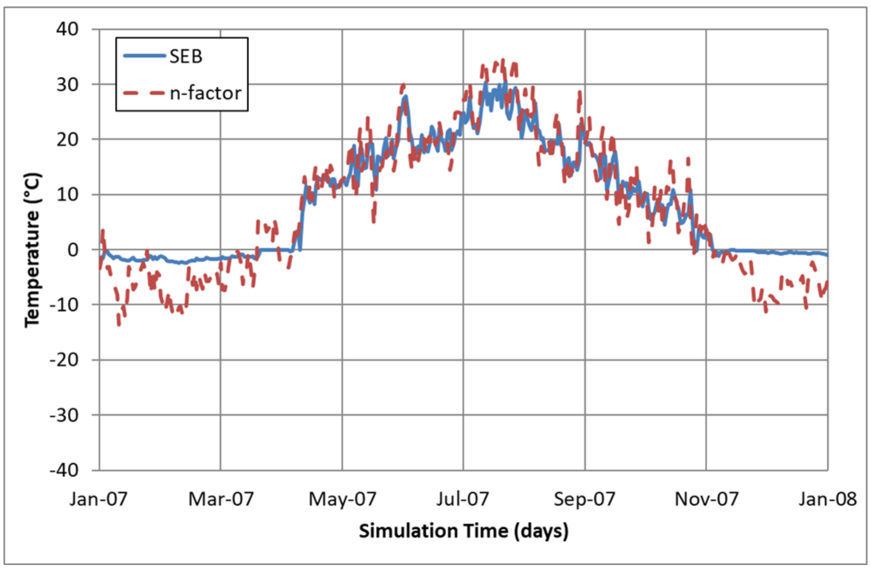

Figure 14. Ground surface temperatures for the SEB and n-factor analyses in 2007.

These differences in surface temperature also have an effect on temperatures at depth. As shown in Figure 15 and Figure 16, the n-factor approach generally leads to higher summertime soil temperatures. In wintertime, however, the n-factor approach generally leads to colder temperatures as it does not correctly account for the changing characteristics of the snowpack.

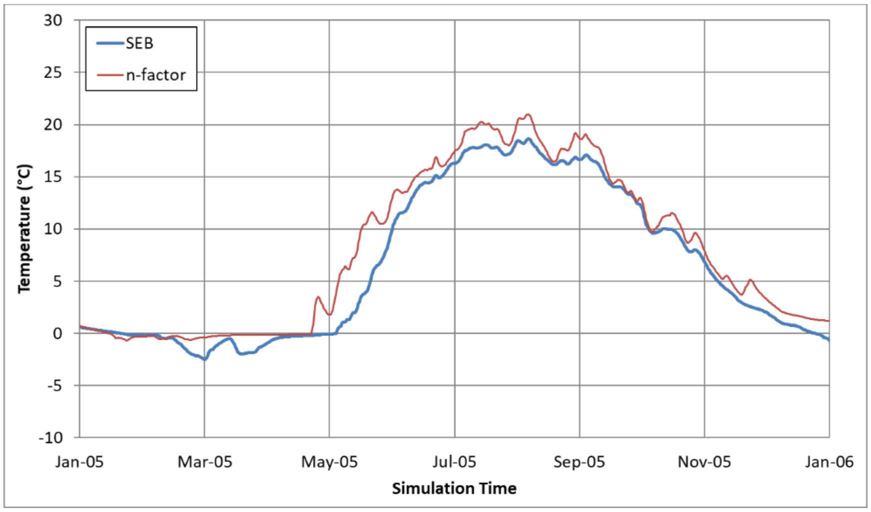

Figure 15. Soil temperatures at a depth of 1 m for the SEB and n-factor analyses in 2005.

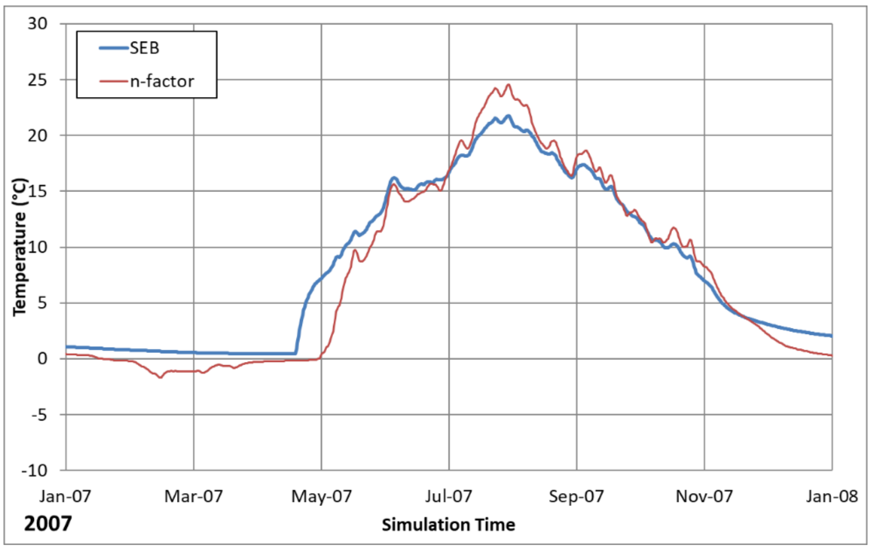

Figure 16. Soil temperatures at a depth of 1 m for the SEB and n-factor analyses in 2007.

To further emphasize the differences between the two approaches, Figure 17 presents monthly temperature profiles during 2007. Differences between the SEB and n-factor approaches can be seen at depth. Seasonal frost depth is limited to 0.80 m in the SEB analysis, and extends down to 1.65 m in the n-factor analysis. The n-factor approach is also shown to lead to greater soil temperature extremes.

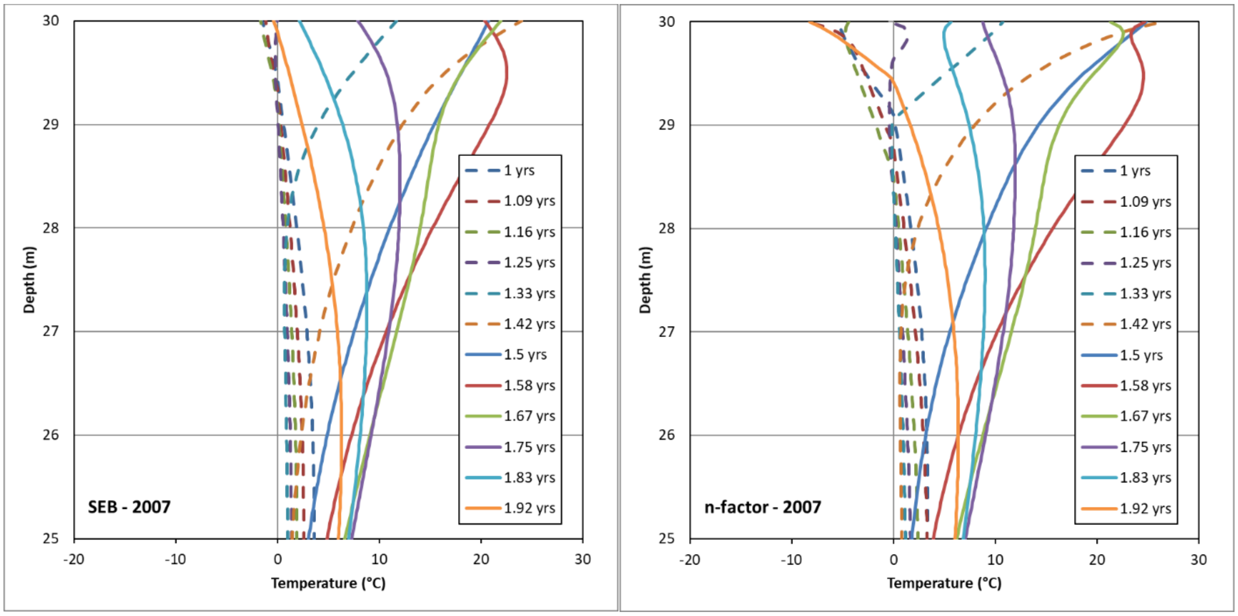

Figure 17. Temperature versus depth for the SEB and n-factor analyses in 2007.

Summary and Conclusions

TEMP/W analyses were used to explore the thermal response of a soil column to different surface boundary conditions: the surface energy balance (SEB) and n-factor. The n-factor approach generally resulted in more dynamic temperature changes, especially during the winter months. The freezing front was also generally deeper in the n-factor analysis, especially during years with greater snow cover. Although data extensive, the SEB boundary condition is a more rigorous approach that can be used on many different sites without field data calibration. Although herein considered constant, the n-factor is inherently variable as it changes with changes in ground conditions and climate.

References

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Klene, A.E., Nelson, F.E., Shiklomanov, N.I., and Hinkel, K.M. 2001. The n-factor in natural landscapes: variability of air and soil-surface temperatures, Kuparuk River Basin, Alaska, USA. Arctic, Antarctic, and Alpine Research 33 (2): 140-148.