# Influence of slope aspect on soil cover thermal response

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## Introduction

The surface energy balance (SEB) boundary condition in TEMP/W was used to simulate the thermal response of two capillary barrier soil covers overlying municipal waste. Both covers are comprised of the same materials; however, one cover faces north while the other south. The simulated responses are compared to field measurements to explore the effect of slope direction on the thermal response within the cover systems.

## Background

Four test plots were designed and constructed by Golder Associates Ltd. (GAL) and O'Kane Consultants Ltd. (OKC; 2005) at a landfill site near Regina, Saskatchewan. A store and release cover and a layered capillary break cover were constructed on north and south slope faces (Strunk, 2008). The thermal response of the layered capillary break covers on the north (TP2N) and south (TP2S) facing slopes were simulated as part of this example. The capillary break soil covers comprise approximately 0.3 m of sand at the base of the covers (Figure 1). The sand is overlain by 1.2 m of glacial till at TP2S and 1.5 m of glacial till at TP2N. Both covers are capped by about 0.2 m of top soil.

Soil monitoring at each of the sites included measurements of matric suction, volumetric water content, gas pressure and composition, and soil temperature. A meteorological monitoring station on the north facing slope measured wind speed and direction, air temperature, relative humidity, net radiation, and precipitation. Net radiation was also monitored on the south facing slope. Monitoring data was obtained from 2004 to 2006 and reported by Strunk (2008).

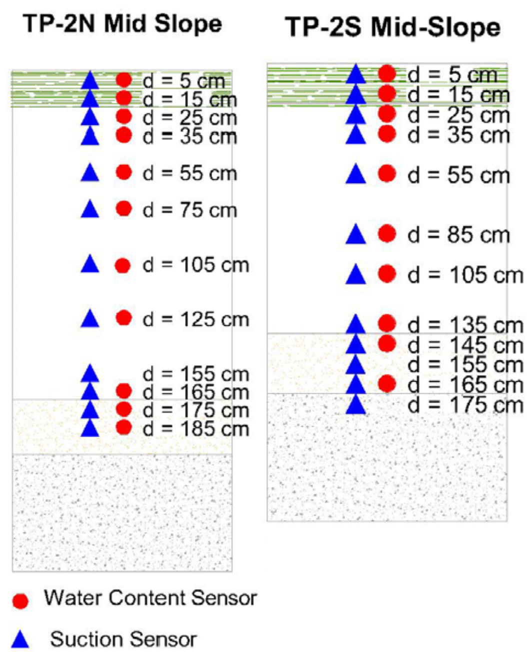


**Figure 1. Soil sensor depths and cover material configuration for TP2N and TP2S (GAL and OKC, 2005).**

## Numerical Simulation

The one-dimensional soil cover analyses for the north and south facing slopes are shown in Figure 2 (refer to the associated GSZ project files). A spin up analysis was used to obtain the initial temperature profiles for both analyses (Figure 3). Incidentally, the measured values could have been used directly; however, a spin-up was completed to illustrate how an initial condition can be obtained without measured temperatures. The objective of a spin-up analysis is to minimize the effect of the assumed, and arbitrary, initial temperature profile. The initial conditions for the spin up analyses were assumed to be characterized by linear temperature profiles. The climate functions are set to cycle and are defined over a period of 730 days with an elapsed time of 0 day corresponding to June 30, 2004. The spin-up analysis had a Starting Time of 0 day and Duration of 914 days, which means the results on the last time step correspond to the climate conditions measured at 184 days (914 – 730) past June 30, 2004; that is, December 31, 2004. These results were then used to define the initial condition for the final analysis commencing at a Start Time of 914 days (December 31, 2004) and having a total duration of 365 days.

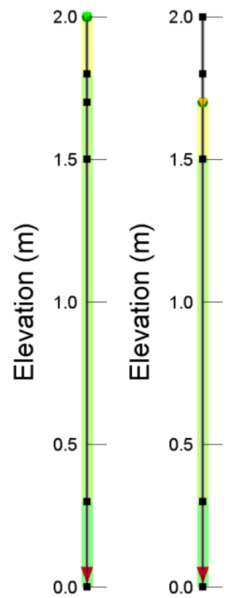


Figure 2. Problem configuration for TP2N (left) and TP2S (right).

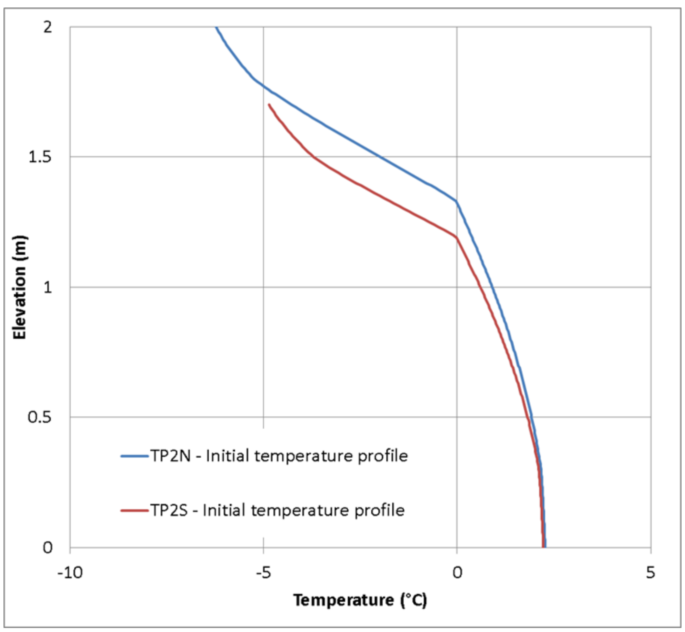


Figure 3. Initial temperature profiles for each analysis.

The Full Thermal material model was used to characterize all materials in the cover. The Full Thermal model requires that the thermal conductivity (Figure 4) and unfrozen volumetric water content (Figure 5) be defined as functions of temperature. The volumetric heat capacity is defined for both the unfrozen and frozen states and the *in situ* volumetric water content is assumed constant (Table 1). These values were estimated based on typical parameters described in the literature for these types of materials. These material properties were used to establish the base case. A sensitivity analysis was subsequently completed to explore the role of certain parameters on the thermal response of the cover systems.

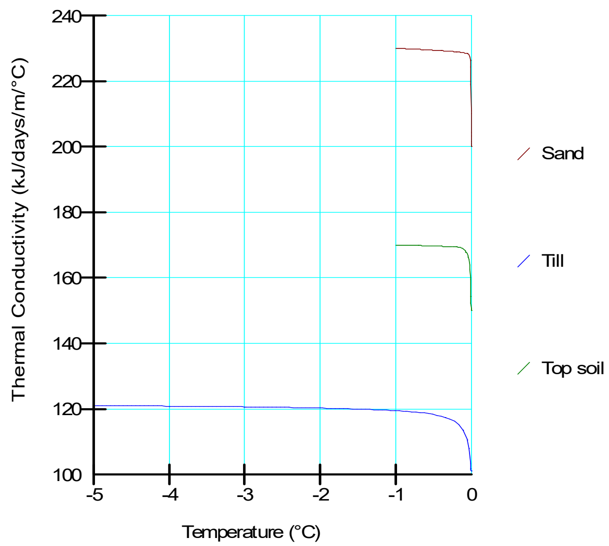


**Figure 4. Thermal conductivity functions for each material.**

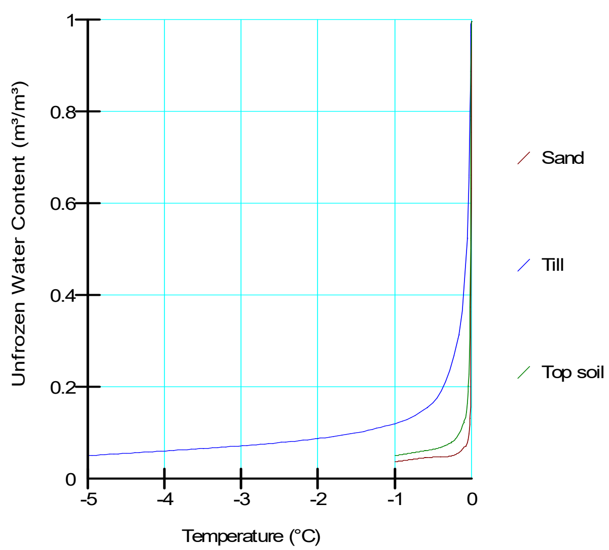


**Figure 5. Unfrozen water content functions for each material.**

**Table 1. Thermal properties for the soil cover materials.**

| Material | Unfrozen VHC (kJ/m³/°C) | Frozen VHC (kJ/m³/°C) | Insitu VWC |
|---|---|---|---|
| **Topsoil** | 2377.6 | 2178.7 | 0.2 |
| **Till** | 2865.5 | 2132.9 | 0.3 |
| **Sand** | 2005.7 | 1717.9 | 0.1 |

The climate functions required for the surface energy balance (SEB) boundary condition include the air temperature (Figure 6), wind speed (Figure 7), relative humidity (Figure 8), snow depth (Figure 10) and net radiation (Figure 11). Data deficiencies were overcome using information from the nearest Environment Canada weather station. Net radiation was uniquely measured on both slope faces, while all other climate data was measured on the North Slope. In the Northern Hemisphere, air temperatures at conventional monitoring heights (e.g. 1.5 m) are generally warmer on south facing slopes; consequently, the air temperature function for TP2S was estimated by adding 3.5°C to the measured temperature values.

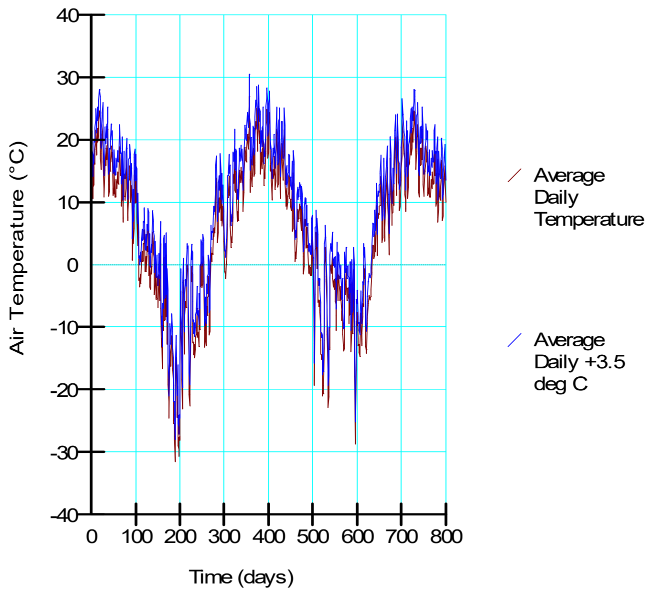


**Figure 6. Air temperature functions.**

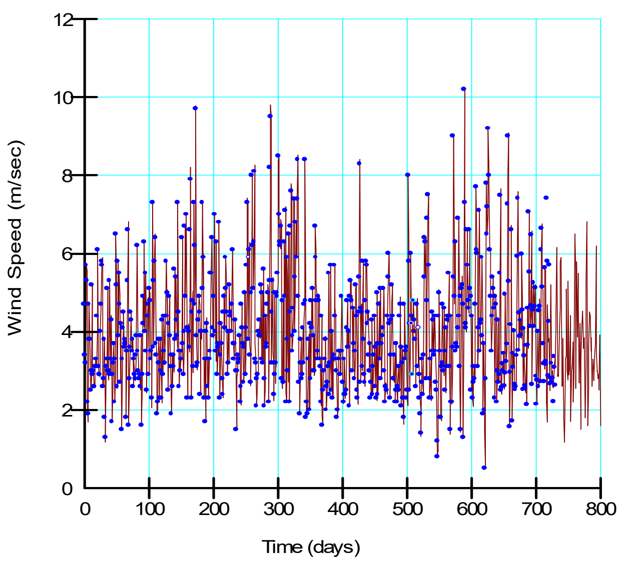


**Figure 7. Average daily wind speed function.**

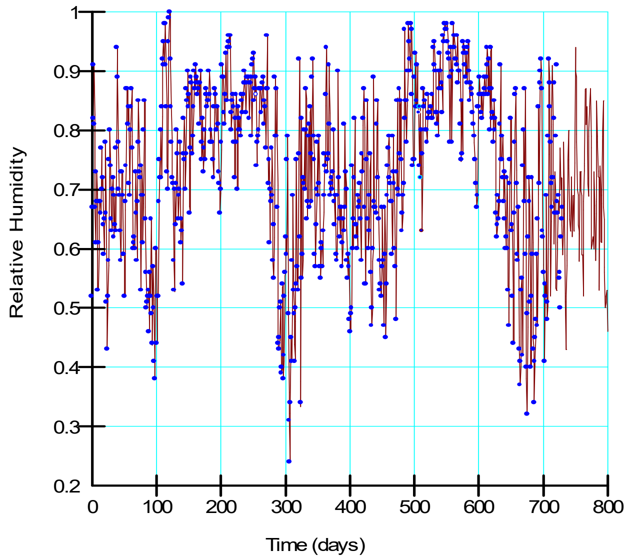


Figure 8. Relative humidity function.

The total precipitation and snow depth functions are based on data collected at nearby weather stations maintained by Environment Canada (Figure 9 and Figure 10). It was noted by Strunk (2008) that the monitoring conducted on site for these parameters are not considered completely accurate. Strunk (2008) also noted that the south facing slope typically had shallower snow depth when compared to the north facing slope. To account for this in the SEB boundary condition, only 60% of the Environment Canada snowfall was applied to TP2S. The snow density was estimated as 0.02 and 0.025 Mg/m$^3$ for the north and south locations, respectively, based on snow surveys completed by Strunk (2008). The snow conductivity was defined as 1.2 x 10$^{-4}$ kJ/sec/m/°C for both locations.

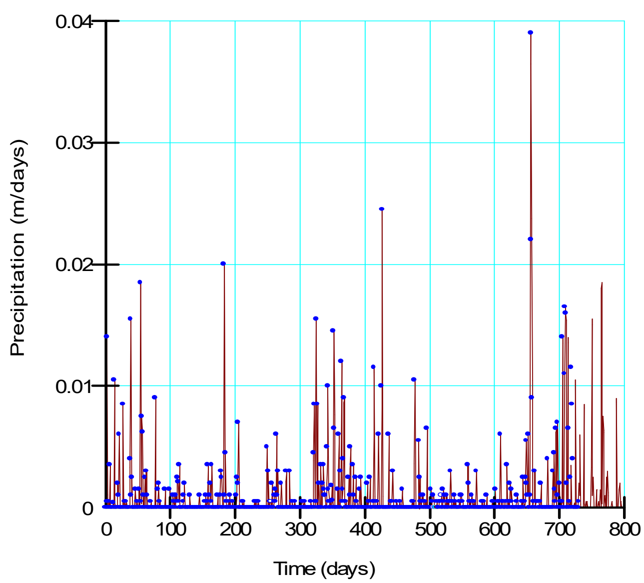


Figure 9. Precipitation function from Environment Canada for the Regina Airport weather station.

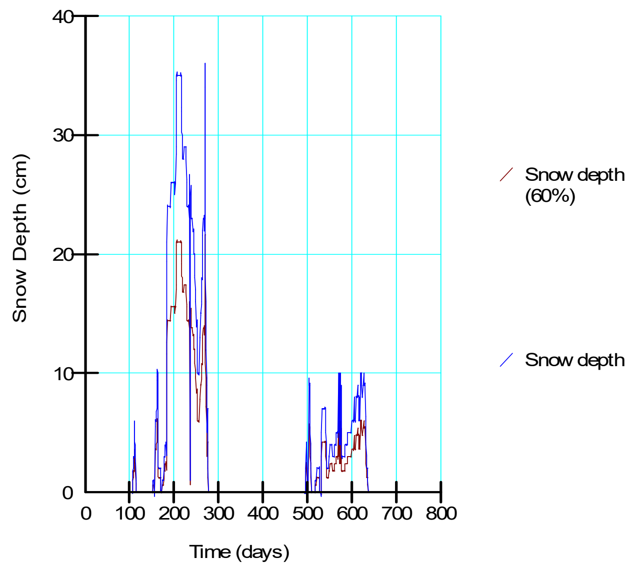


**Figure 10. Snow depth functions for the North and South locations.**

The net radiation was monitored on both the North and South Slopes (Figure 11). Strunk (2008) also estimated the potential evapotranspiration (PET) for the North and South Slopes based on the net radiation monitoring (Figure 12). Actual evaporation flux is required by the SEB boundary condition; however, such information is generally only available if the water transfer dynamics are also being simulated using a land-climate-interaction (LCI) boundary condition. A thermal heat flux of $5 \times 10^{-4}$ $kJ/sec/m^2$ was applied to the bottom of the models to represent the geothermal heat flux for the area.

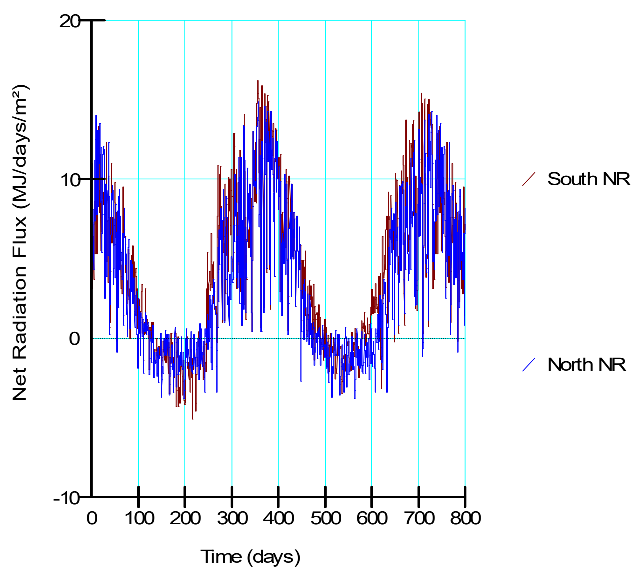


**Figure 11. Net radiation functions for the North and South locations.**

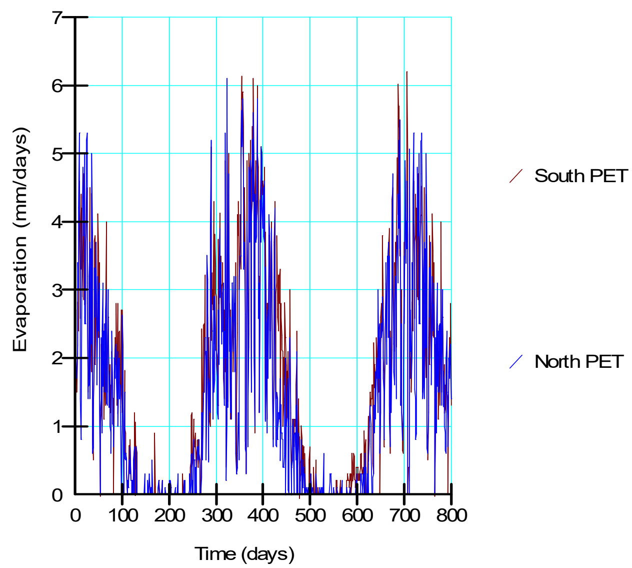


**Figure 12. North and South potential evapotranspiration functions.**

The vegetation height is set to 1 m for the summer months based on the air temperature. Only one year (2005) was developed for both analyses and cycled throughout the entire duration of the simulation. Each analysis has a total duration of 365 days with a start date of January 1, 2005. Both analyses have 1 hour time steps, saving data every 24 time steps or 1 day. The global element size is 1 cm for the entire one-dimensional mesh.

## Results and Discussion

Figure 13, Figure 14, and Figure 15 compare the simulated and measured temperature responses of the sensors installed within the north facing cover at 10, 70 and 190 cm. The overall trends and diurnal variability is captured reasonably well throughout 2005. The shallowest sensor is most susceptible to diurnal climate variability, but the climate inputs do not necessarily reflect the diurnal variability. For example, the air temperature functions are based on average daily values. As a result, the simulated response at 10 cm does not always track precisely (in a relative sense) with the measured diurnal variations. The overall response, however, suggests that the estimation of the surface energy balance (SEB) boundary condition functions and material properties are appropriate for exploring the influence of climate conditions on the thermal response of the soil cover.

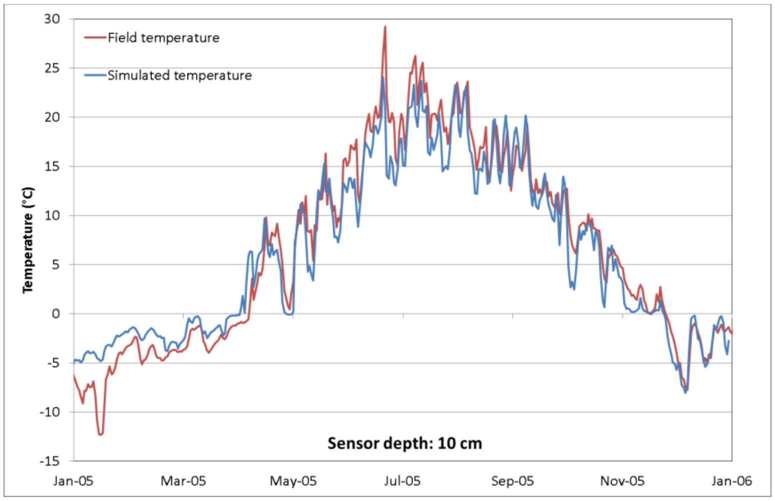


Figure 13. Simulated vs. measured temperatures for year 2005 at TP2N at a depth of 10 cm.

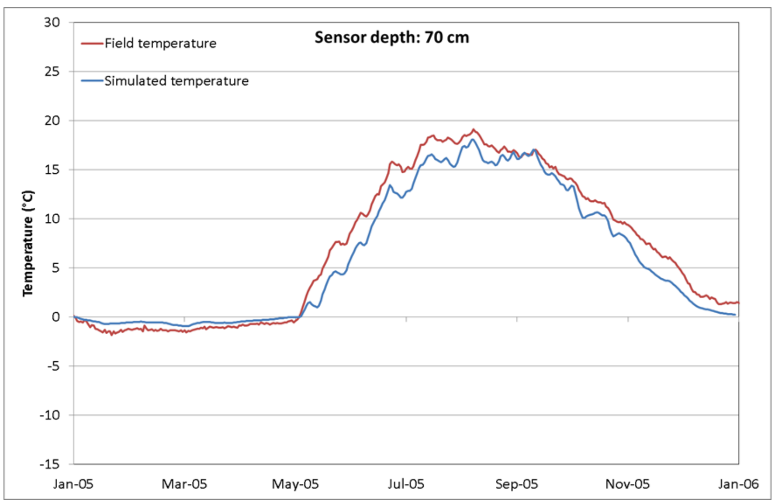


Figure 14. Simulated vs. measured temperatures for year 2005 at TP2N at a depth of 70 cm.

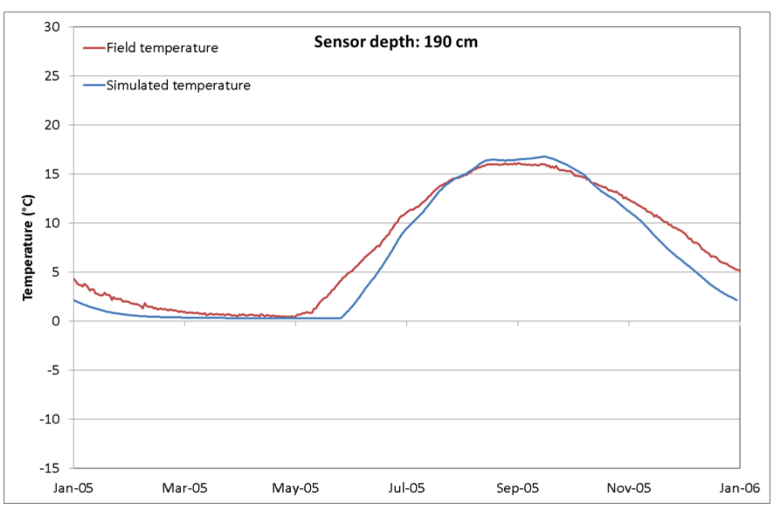


Figure 15. Simulated vs. measured temperatures for year 2005 at TP2N at a depth of 190 cm.

Figure 16 compares the simulated (left) and measured (right) temperature profiles at TP2N during 2005. The simulated thermal response shows freezing temperatures propagating further than measured. Vegetation monitoring on-site indicate that vegetation was well established on both soil covers by 2005, which may act as further insulation to freezing temperatures. As the vegetation layer was not simulated in the analyses, this insulation effect was ignored. Variations in the snow density and conductivity over the winter months (fresh vs. old snow) were also not included in the simulation.

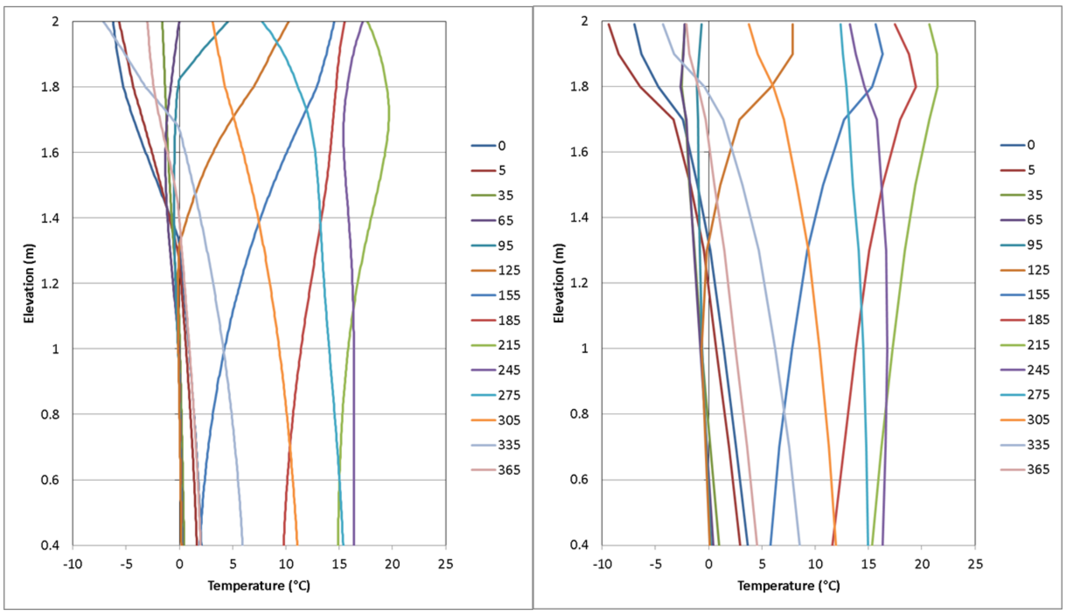


Figure 16. Tornado plot of TP2N temperature profiles over 2005 simulation (left) and in the measured (right).

Figure 17, Figure 18, and Figure 19 compare the simulated and measured temperature responses of the sensors installed within the south facing cover at depths of 13 cm, 83 cm and 153 cm. In this case, the simulated response tracked well near the surface but deviated significantly at the deeper sensors during the early spring warm up period. Once again, the discrepancies could be the result of deficiencies in the climate and snow depth functions or the insulating effect of vegetation. The difference between the north and south facing slopes, however, suggests a different mechanism is responsible for the rapid thaw at depth. Kelln et al. (2007) demonstrated that snowmelt water was infiltrating through macropores of a clay rich layer within a reclamation cover in Northern Alberta. The development of macropores and fractures within the glacial till may be similarly controlling the thermal response of the covers during the spring freshet. Water flow through the macropores transfers heat by advection (i.e. forced convection); which would promote rapid thaw deeper into the cover because conduction alone would not be the only process operating to thaw the cover. A difference in responses would therefore be expected given that the south facing slope is subject to more rapid melt rates during the freshet. The same mechanism might be operating on the North Cover but to a lesser degree.

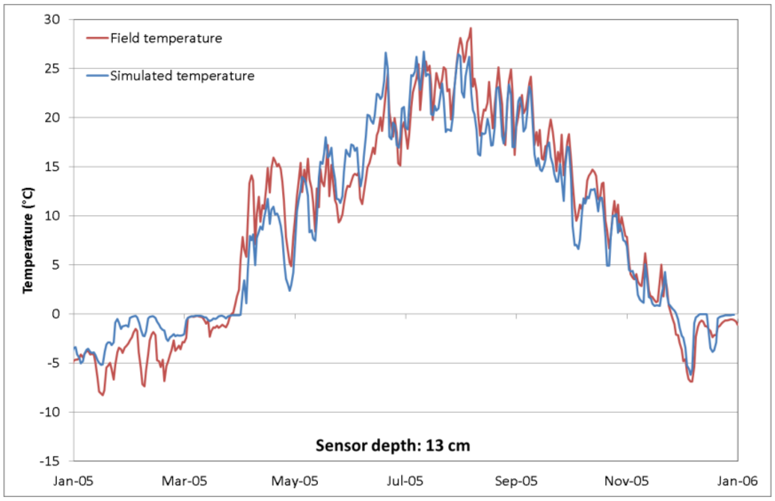


Figure 17. Simulated vs. measured temperatures for year 2005 at TP2S at a depth of 13 cm.

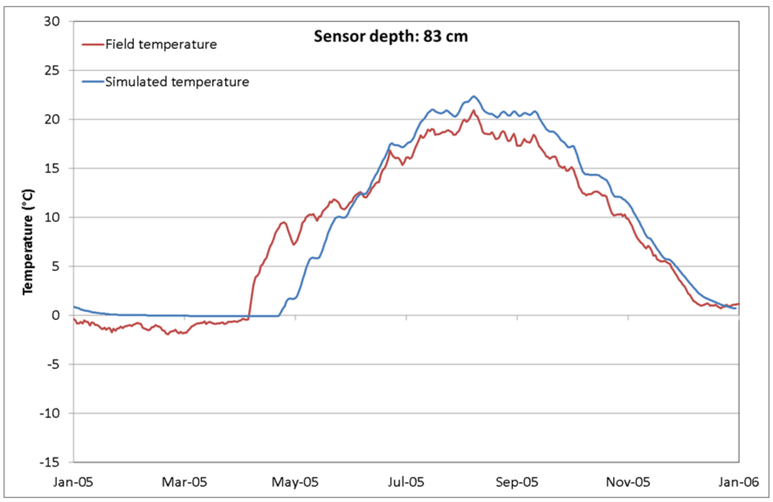


Figure 18. Simulated vs. measured temperatures for year 2005 at TP2S at a depth of 83 cm.

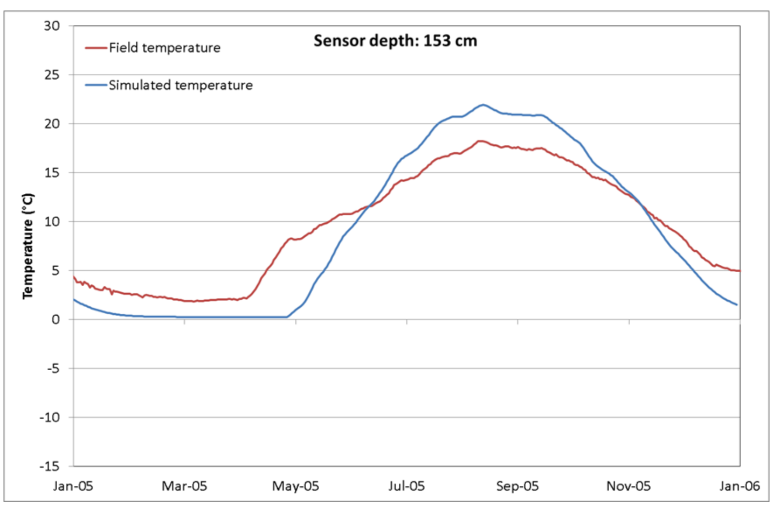


Figure 19. Simulated vs. measured temperatures for year 2005 at TP2S at a depth of 153 cm.

Figure 20 and Figure 21 compare the measured responses at similar depths within the north and south facing covers. The near surface temperatures within the South Cover are generally higher through the majority of the year. Temperatures equal to or greater than zero were measured earlier in the year within the South Cover at both depths. These periods would be associated with snowmelt and possible infiltration through the macropores within the glacial till. Temperatures were sustained above zero starting on March 26 at 3 cm and April 6 at 80 cm depths at TP2S. In contrast, temperatures were not sustained above zero until April 7 at 1 cm and May 4 at 70 cm depths at TP2N. In other words, there was an 11 day delay in thaw propagation of the thaw front in the South Cover and a 27 day delay in the North Cover. Again, this difference is likely the result of forced convection – that is, heat advection with flowing water – playing a more prominent role in the South Cover.

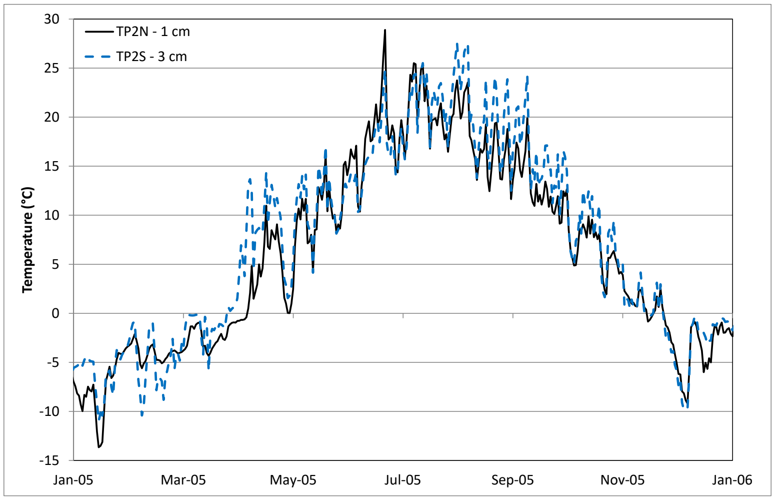


**Figure 20. Measured temperature at 1 cm and 3 cm depths in TP2S and TP2N, respectively.**

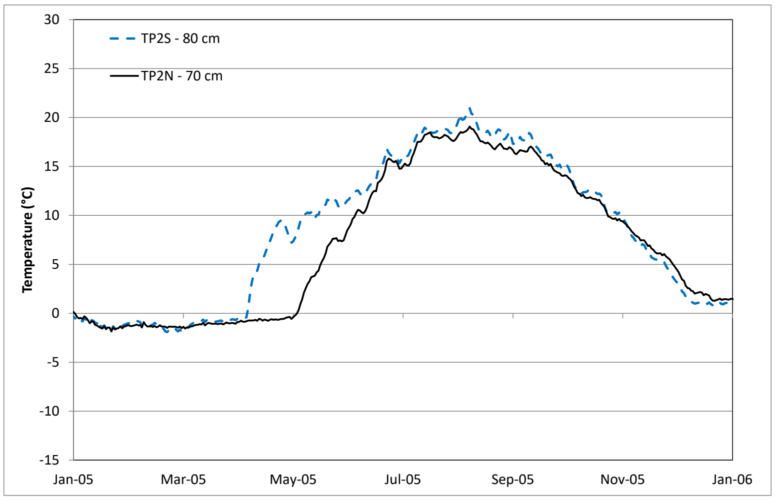


**Figure 21. Measured temperature at 80 cm and 70 cm depths in TP2S and TP2N, respectively.**

Figure 22 compares the simulated (left) and measured (right) temperature profiles at TP2S during 2005. The aforementioned discrepancies are manifest in greater depths of simulated frost propagation.

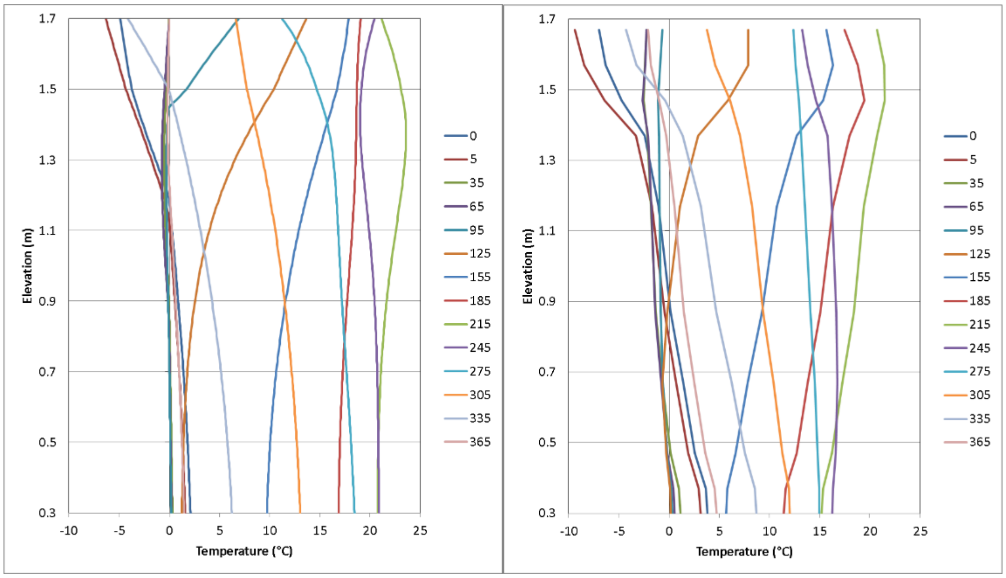


Figure 22. Tornado plot of TP2S temperature profiles over 2005 simulation (left) and in the measured (right).

In order to determine the influence of the chosen material properties on the overall thermal response of the soil cover, the thermal conductivity and water content values were increased and decreased. Figure 23 shows the resulting thermal response at the sensor depth of 70 cm at TP2N. The thermal conductivity function was simply multiplied or divided by 2 for the increase and decrease. The decrease in thermal conductivity caused the thermal response observed at a depth of 70 cm to be dampened from the base condition. Similarly, when increased, the thermal response experienced at the sensor location was amplified, leading to warmer temperatures during summer months and cooler temperatures in winter months.

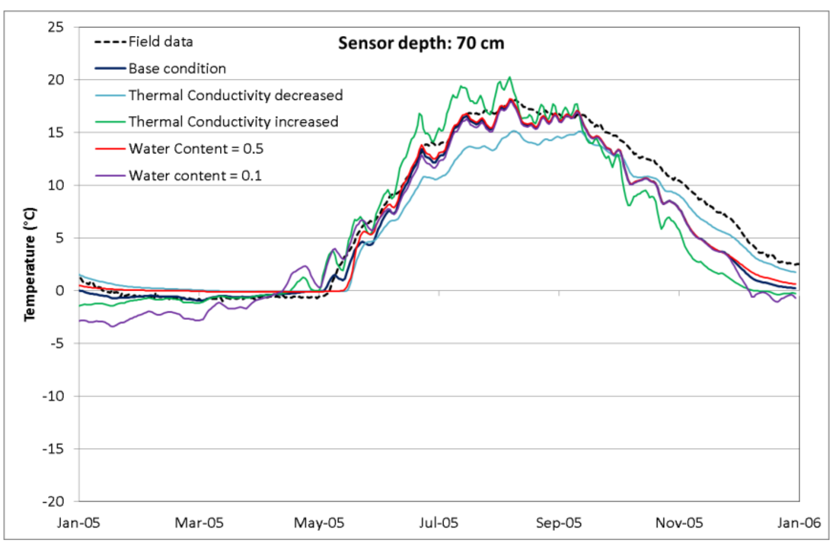


Figure 23. Sensitivity analysis of thermal conductivity and water content on thermal response at TP2N.

The influence of the water content specified in the Full Thermal material model was also included in the sensitivity analysis. The *in situ* water content values were increased to a constant 0.5 or decreased to a constant 0.1 throughout all materials. This change had little influence on the summer month thermal response, but the thermal response was more significantly altered during winter months. The decrease in water content resulted in a decrease in the soil's ability to "hover" around 0°C (the freezing point), causing the soil to cool faster in the winter months and warm up sooner in the spring. When the water content was increased, the temperature hovers around the freezing point for most of the winter and further into the spring. By increasing the water content, as the temperature drops to the phase change temperature, more latent heat must be released to drop the temperature below freezing. If the soil is dry, less latent heat must be released, causing the drop in temperature to occur more rapidly.

## Summary and Conclusions

Similar thermal response patterns were observed in the TP2N and TP2S analyses when compared to the field measurements. This example illustrated the use of the surface energy balance boundary condition to simulate the ground heat flux of the surface energy balance equation based on climate conditions. The influence of the material properties on the thermal response experienced within the soil cover was also demonstrated. Increasing the thermal conductivity or water content of the soil cover materials influences both the rate at which the ground surface cooling or warming has on the overall thermal response, as well as the length of time that the "zero curtain effect" is observed during phase change. The required increase in air temperature for the South Slope analysis was also observed throughout the soil cover, indicating that slope direction does influence the thermal response of a soil.

## References

Golder Associates Ltd. and O'Kane Consultants, Ltd. 2005. Fleet Street Landfill final cover evaluation study – design and construction report. Report submitted to City of Regina, January 2005.

Kelln C.J., Barbour S.L., Qualizza C.V. 2007. Comparison of tree growth statistics with moisture and salt dynamics for reclamation covers over saline-saodic overburden. Proc., Canadian Land Reclamation Association Symp., Halifax, North Scotia, Canada.

Strunk, Randi. 2008. An evaluation of the performance of prototype instrumented soil covers at the Regina Municipal Landfill. M.Sc. Thesis, Department of Civil Engineering, University of Saskatchewan. Saskatoon, Saskatchewan.