Monitoring and Modelling: Permafrost Temperature

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Introduction: Ground Temperatures In Canada

- Permafrost is a significant feature of Canada's natural environment, affecting some 50% of the nation's land area.

- Tens of thousands of square kilometres of permafrost are within one or two degrees of its melting point, according to Figure 1.

- Where permafrost contains significant amounts of moisture, its properties and structural stability are strongly temperature dependent within one or two degrees of 0^{o}C.

- The climate warming widely expected over the next century, due to the enhanced greenhouse effect, poses significant implications for the permafrost environment. For this reason, systematic monitoring of climatic and ground thermal conditions in the permafrost regions is being discussed.

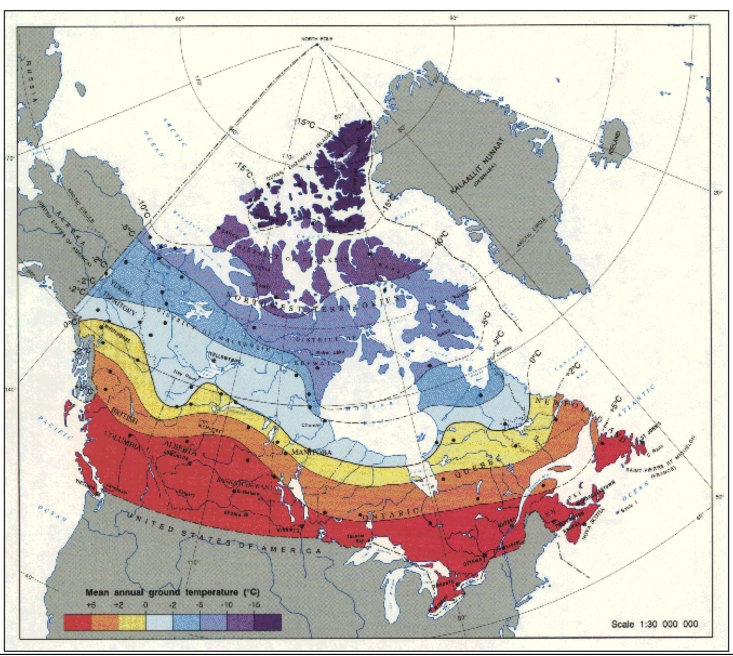


Figure 1. Ground Temperature Map of Canada (Heginbottom et al. 1995)

Permafrost Monitoring And Detection Of Change

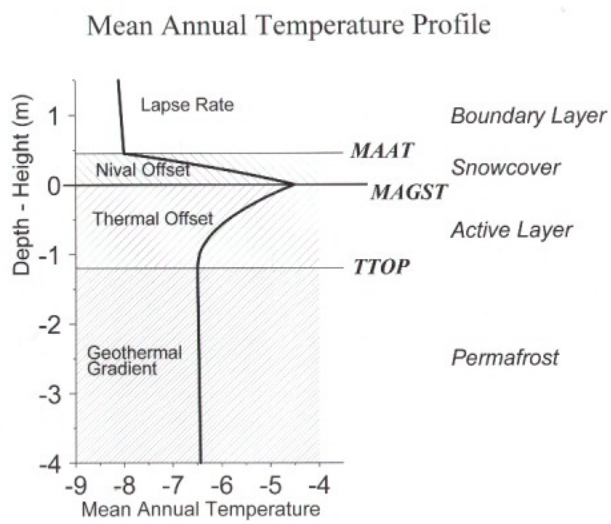
- While monitoring can reveal if change is occurring, we need to distinguish between identifying a change and detecting an effect, since there are factors other than air temperature that influence ground temperatures.

Identifying change = knowing what's happening
Detecting an effect = knowing why it is happening

- In order to understand how permafrost change is related to climate change we need to understand how permafrost is related to climate.
- The IPCC (1990) recommended that research be directed toward understanding the physical relationship between permafrost temperatures and air temperatures.
- Analysing the responses of permafrost to climate forcing requires an adequate functional description of the permafrost-climate system, including the effects of:
  - temperature forcing from climatic variation,
  - local terrain and environmental factors,
  - lithologic conditions.
- Air, surface and permafrost temperatures will change differentially, depending on theinterplay of these climatic, local and lithologic effects.
- Detection requires we keep track of these separate influences on permafrost temperature in monitoring programs.

Monitoring ↔ Modelling

- A complementary relationship between monitoring and modelling:
- Monitoring results are used to develop, test and improve predictive capability (models)
- Models are necessary to interpret monitoring results and to extrapolate results to locations where monitoring data are absent (i.e. most places)
- This suggests that models are both useful and necessary in designing monitoring programs and protocols (what and where to monitor).
- Consider the following schematic of the climate-permafrost system:



TTOP Model

- Smith and Riseborough (1996) have presented a formulation of the permafrost-climate relation that provides a functional means of analyzing the influence of climate, terrain and lithologic factors on the temperature condition and distribution of permafrost.

- The TTOP model links permafrost temperature conditions with the surface climatology through seasonal surface transfer functions and subsurface thermal properties.

- The model is exact for equilibrium conditions, and provides a reasonably accurate estimate of subsurface temperatures under transient conditions.

- Since the model contains relatively few parameters, it is suitable for use with monitoring programs at a variety of scales.

- *The TTOP model offers one rational method for regional and national scale assessment of permafrost temperatures under current and future climatic conditions.*

The TTOP model can be summarized in the following equation:

$$TTOP = \frac{\frac{k_T}{k_F} nt.It - nf.If}{P} \tag{1}$$

or:

$$TTOP = \frac{rk.nt.It - nf.If}{P} \tag{2}$$

Where:

TTOP = Temperature at Top Of Permafrost
It = thawing index for air temperature
If = freezing index for air temperature
kt = Thermal conductivity of ground (thawed)
kf = Thermal conductivity of ground (frozen)
rk = Thermal conductivity ratio (kt/kf)
nt = scaling factor between summer air and surface temperatures vegetation effect)
nf = scaling factor between winter air and surface temperatures (snow cover effect)
P = Period (365 days)

- With values for each of the parameters inserted into the equation, the corresponding value for TTOP can be determined.

- With results from a ground temperature monitoring program, the influence of climate, surface and subsurface changes can be evaluated and the changes interpreted.

- With parameter values available over geographic areas, maps of TTOP can be compiled.

Climate Controls On Permafrost Temperature

- From equation (2) we can deduce the following air temperature (climatic) controls on TTOP:
  - TTOP decreases with an increase in If and a corresponding decrease in It.
  - TTOP is negative (permafrost condition) wherever (nf.If) > (rk.nt.It)
  - Where If >> It, TTOP is likely to be negative everywhere in an area (regardless of nt, nf and rk)
  - When It = If (i.e. MAAT = 0oC), TTOP will be negative wherever nf > (rk.nt)
  - Wherever nf (rk.nt), TTOP is sensitive to variations and changes in the seasonal nature of air temperature (without any necessary change in the MAAT).

Local Controls On Permafrost Temperature

- From equation (2) it is evident that permafrost temperatures can vary/change, even in the absence of changes in climate, as a result of local and lithologic factors. Because nf, nt and rk are multipliers, their effect on TTOP changes with the magnitude of It and If. That is, they will modulate climate forcing of TTOP. *Implications for monitoring?*

- We consider the possible range of variation in:
  - nf is on the order of 5-times (Riseborough and Smith 1998)
  - rk is on the order of 3-4 times (Riseborough and Smith 1998)
  - nt is on the order of 1.5-times (Jorgensen and Krieg 1988)

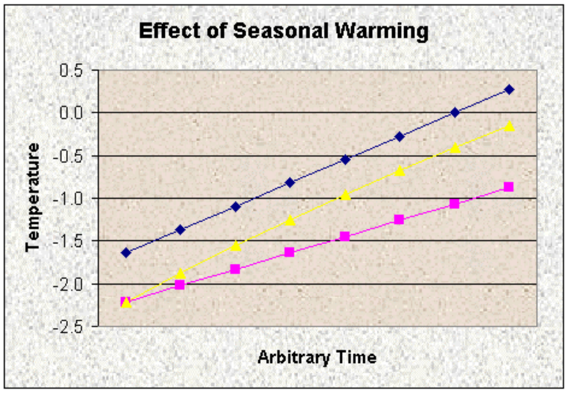
- From this, it is apparent that lithologic conditions and snow cover comprise the primary localised influences on permafrost temperatures, while variations in nt (vegetation effect) appear to be a second order effect.

- Wherever It and If are similar in value, small differences in the surface and subsurface parameters become critical in determining the conditions under which permafrost can exist or persist (that is TTOP negative). *Implications for monitoring?*

Climate Change Effects On Permafrost Temperature

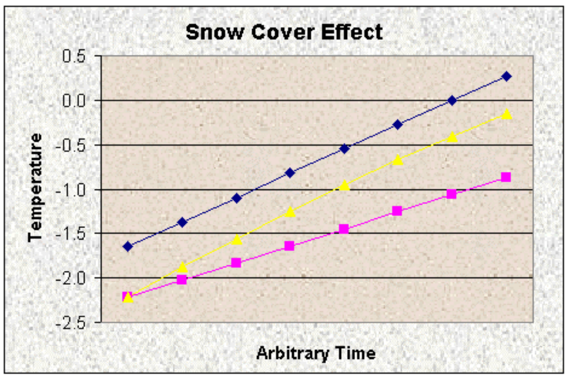
- From equation (2) we can investigate how changes in air temperature and snow cover will affect permafrost temperature (TTOP).
  - Wherever nt.rk ≠ nf, changes of equal magnitude in It and If have a differential effect on TTOP.
  - Where nf > nt.rk (commonly?), changes in winter air temperatures will have a greater influence on permafrost temperature than equivalent summer changes.

- The Figure shows the effect of an increase in MAAT, concentrated in winter (yellow) or in summer (pink). The air temperature change is shown in blue.



  - For an equal increase in MAAT, winter warming produces an increase in TTOP of 0.5°C more. Therefore, knowledge of the seasonal nature of climate change will be important in understanding the permafrost response.
  - Recall that this seasonal response is conditioned by the values of nf, nt and rk, so these should be monitored also.

Snow Cover



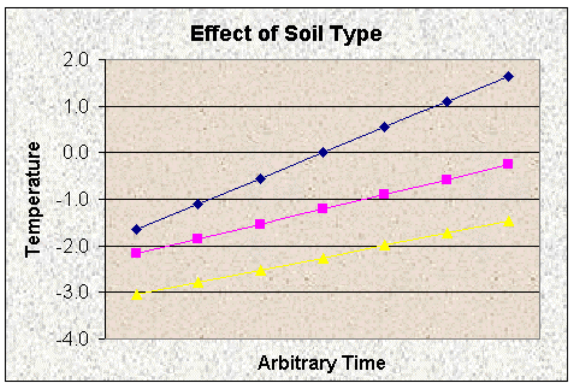
  - Any change in the snow cover regime (nf) which accompanies climate warming will control the net effect on the temperature of permafrost. When climate warming is accompanied by a 20% increase in snow (yellow), TTOP is warmer by 0.7oC compared to the simple warming case (pink):

- The difference is significant and equivalent to that resulting from an additional 1.5oC warming in mean annual air temperature.
- Of course, a decrease in snow cover would lead to a decrease in permafrost temperatures, offsetting the effect of climate warming.
- *Monitoring programs will need to keep track of changes in snow cover conditions*.

Soil Conditions

- Permafrost temperature will also change with the value of rk, which varies spatially and temporally. Permafrost temperatures will change as the values of soil conductivity change, even as the MAAT and/or MAGST remain the same.

- The following Figure shows the permafrost temperature response to an increase in air temperature (equal warming in summer and winter) for constant soil conditions (pink) and drying soil conditions (yellow).



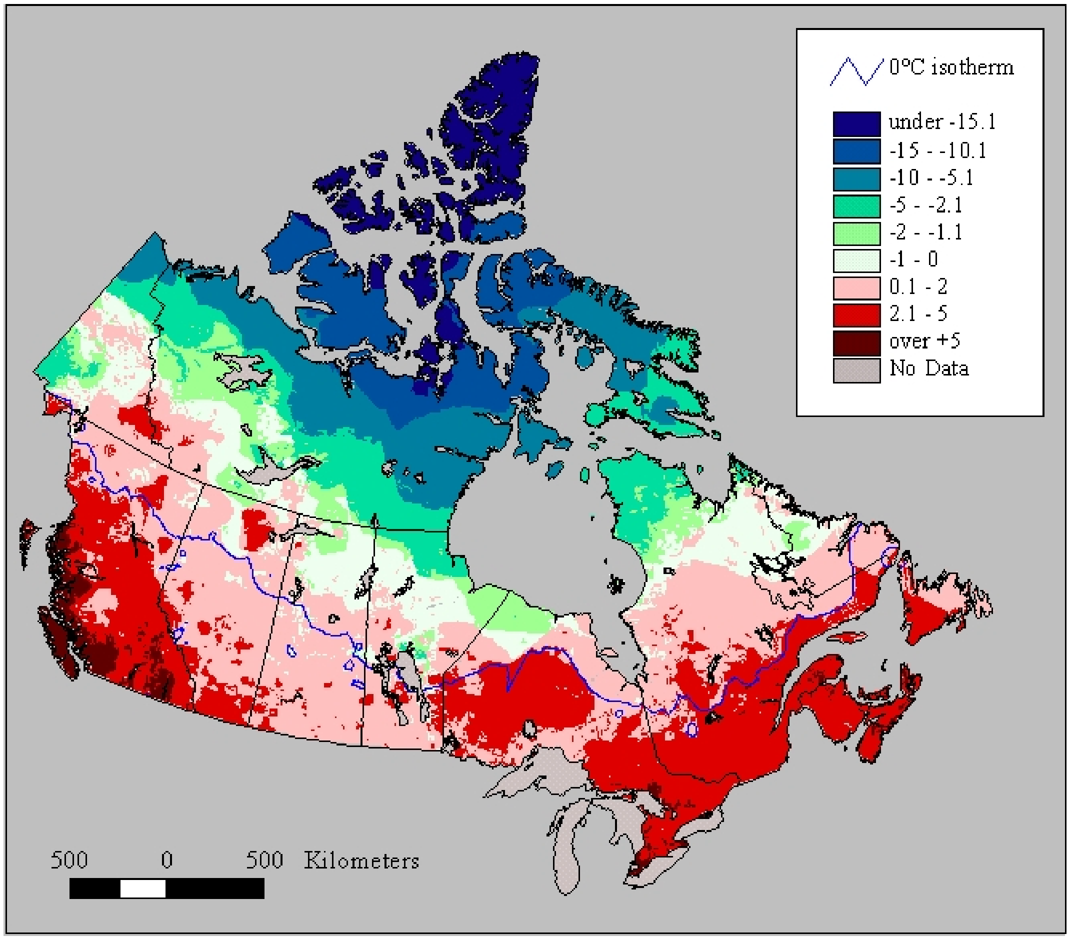
- While the air temperature change is 3.3^{o}C:
  - in the constant soil TTOP increases by 2^o to a temperature of -0.2^{o}C, whereas
  - in the drying soil it rises by only 1o to a temperature of -1.2^{o}C.

- In the case of the constant soil, permafrost stability is significantly threatened.

- In both soils, permafrost warms less than the air: the ratio of increase is determined by the surface and lithologic conditions.

- *Monitoring programs will need to keep track of changes in soil conditions.*

TTOP Map For Canada



Map based on current climate data. A similar exercise using 1xCO2 output from the Canadian GCM produces strikingly inferior results

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