EARTH Interactions

Inferring Climate Change from Underground Temperatures: Apparent Climatic Stability and Apparent Climatic Warming

Trevor Lewis*

Pacific Geoscience Centre, Geological Survey of Canada, and Sidney Geophysical Consultants, Ltd., Sidney, British Columbia, Canada

Walter Skinner

Atmospheric Environment Service, Climate Research Branch, Environment Canada, Downsview, Ontario, Canada

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ABSTRACT: Data are used to demonstrate two effects apparent in ground surface temperature histories coming from inversions of borehole temperatures: apparent climatic warming and apparent climatic stability. Unrecognized local terrain effects, such as spatial or temporal change in land cover, cause warming locally. Where there is seasonally frozen ground, the ground temperature is not coupled to freezing air temperatures due to both latent heat of moisture in the ground and snow cover. Consequently, average ground temperatures can be much warmer than average air temperatures, and changes in average air temperatures result in much smaller changes in average ground temperatures. This produces apparent climatic stability when past air temperatures are inferred from borehole temperatures. However, increases in summer air temperatures,

* Corresponding author address: Trevor Lewis, Sidney Geophysical Consultants Ltd., 1107 Maple Rd., Sidney BC V8L 5P5, Canada.
E-mail address: sgc_ltd@telus.net

such as those due to deforestation, are well coupled to the ground temperature, causing the average ground surface temperature to increase, even in colder climates.

KEYWORDS: Solid earth, Anthropogenic effects, Evapotranspiration, Land–atmosphere interactions, Heat generation and transport

1. Introduction

Underground temperatures have been inverted by many researchers (e.g., Cermak, 1971; Lachenbruch and Marshall, 1986; Lewis, 1992) to obtain past ground surface temperatures (GSTs). Several methods developed for a one-dimensional, conductive regime have been shown to give somewhat equivalent results (Beck et al., 1992; Shen et al., 1992; Shen et al., 1996). The GST is assumed to have no spatial variation, and these analyses have not generally accounted for the latent heat of freezing and thawing of moisture in the ground. Inversion of borehole temperatures to obtain estimates of past ground surface temperatures is an extremely good technique to obtain both the long-term-average GST and variations in the past GST at a particular site. However, to infer regional GSTs and regional surface air temperatures (SATs), local effects must be evaluated. Changes in the GST at a site may be caused by spatial variations in slope and elevation, as well as spatial and temporal variations in land cover, such as vegetation and surface water (Roy et al., 1972; Blackwell et al., 1980; Cermak et al., 1992; Lewis and Wang, 1992; Lewis and Wang, 1998). These effects must be modeled and accounted for. The underground temperature anomalies from surface cover changes, both temporal and spatial, have been shown to be both consistently and accurately predicted by simple models.

GST histories inverted from borehole temperatures are site specific. To reach conclusions on climatic change based on GSTs, each site must be shown to be representative of the surrounding region. This criteria should be applied to climatological stations as well as borehole sites. We present borehole temperatures measured near Cassiar, British Columbia, as examples of both the effect of latent heat of ground water producing apparent stability and the effects of land cover changes causing warming. The GST we refer to is the boundary condition at the top of the conductive underground regime, which may be several centimeters below the ground surface. The average values of the GST and SAT we refer to are averaged over at least a year.

2. Underground temperatures at Cassiar, British Columbia

Temperatures and thermal conductivities on samples from two boreholes near Cassiar (Figure 1) were measured in 1996: borehole A is located on a right-of-way created by cutting down trees and draining surface water to build a road; borehole B is located in wet, undisturbed forestland, 225 m to the south. Temperatures from borehole B indicate an insignificant change in the GST over the last century, whereas temperatures from borehole A indicate a warming during the time period in which the road was built and widened (Figure 1). We relogged these two holes a

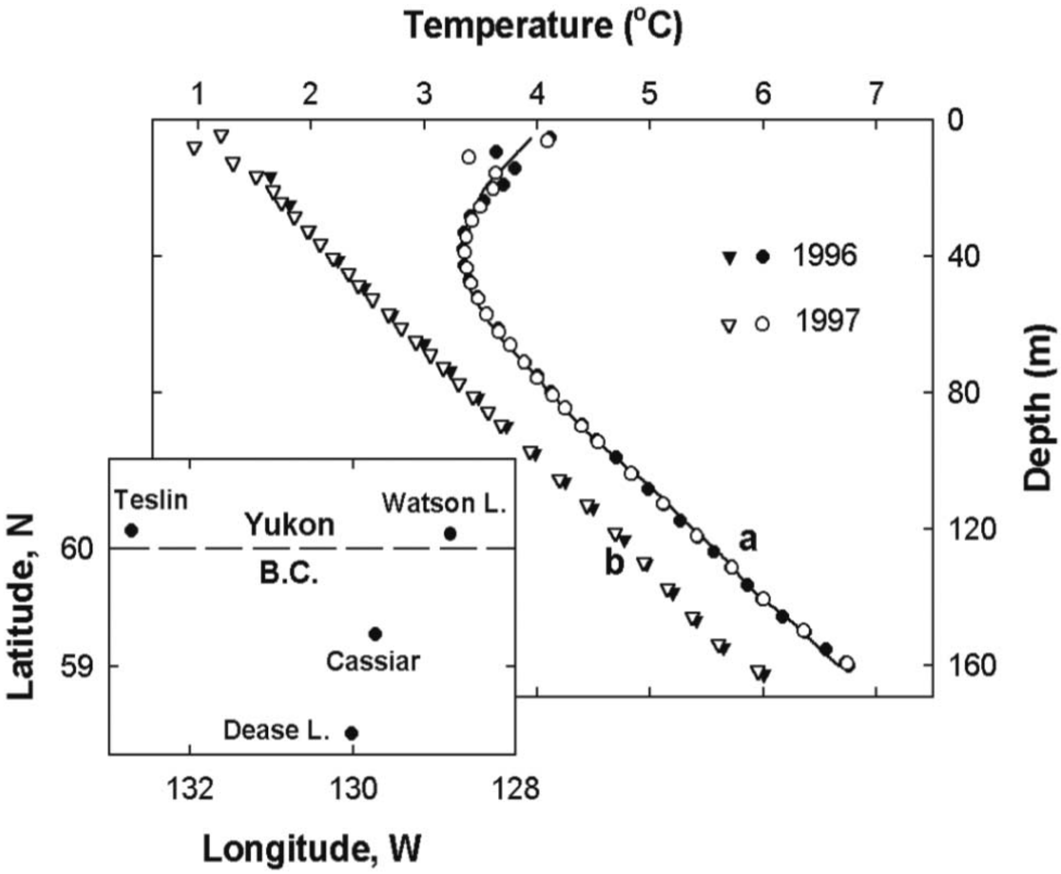

Figure 1. The large effects on the GST of deforestation and drainage of surface water are evident in temperatures logged in 1996 and 1997 in nearby boreholes A and B near Cassiar. For clarity in this diagram, a degree has been subtracted from the temperatures for borehole B. The curve (solid line) fitted to the disturbed site, borehole A assumes a 2.94-K step in the GST occurring 11.4 yr before measurement. The diffusivity of 1.6×10^{-6} m^2 s^{-1} corresponds to the average thermal conductivity of 3.73 W m^{-1} K from 10 samples in the upper 50 m of borehole A. (inset) Locations of Cassiar and the three nearest meteorological stations.

year later, in 1997. Temperatures in borehole B were within mKs of the earlier values, other than in the upper few meters where annual variations exist. The temperatures in borehole A had changed as expected in a conductive regime with a surface temperature increase propagating downward. It is important to recognize that averaging the data from these two boreholes or others like them would lead to an erroneous conclusion that the surface temperature warmed over the last several years for the entire region.

The past SAT at Cassiar is approximated from SATs from three nearby meteorological stations (Figure 1). These SATs (Figure 2), taken from the

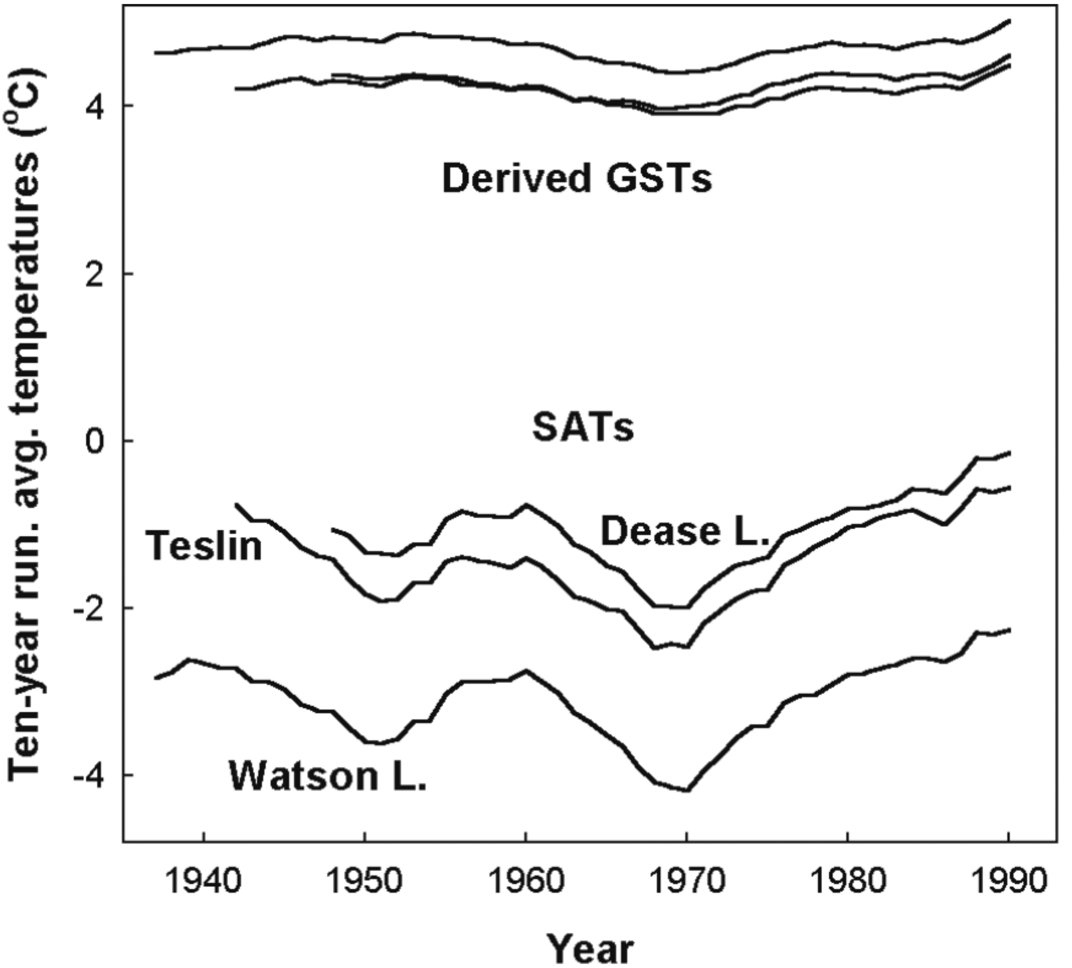

Figure 2. The 10-yr running averages of observed SATs and of the derived GSTs at three meteorological stations (Figure 1) illustrate the much smaller variations expected in the buffered, warmer GSTs.

Canadian historical climate database (Vincent and Gullett, 1998), have been rigorously quality controlled, assessed for homogeneity, and adjusted where necessary to ensure regional representativeness (Vincent and Gullett, 1999). The monthly average SATs range between record values of 16.75° and –38.00°C. However, before the GST can decrease to below the freezing point of water in the soil, all ground moisture must be frozen. Temperatures recorded in the ground closely follow the SAT, until the SAT goes below freezing; the GST remains at the freezing point for the rest of the winter (e.g., Lewis and Wang, 1992, their Figure 13; Gosnold et al., 1997, their Figure 8). In addition to the latent heat of ground moisture buffering the GST, snow often insulates the ground from the cold SATs. At the Cassiar site, and at most cold sites where there is no permafrost, the GST does not follow the SAT below the freezing point, and the average GST is a few degrees warmer than the average SAT (Judge, 1973).

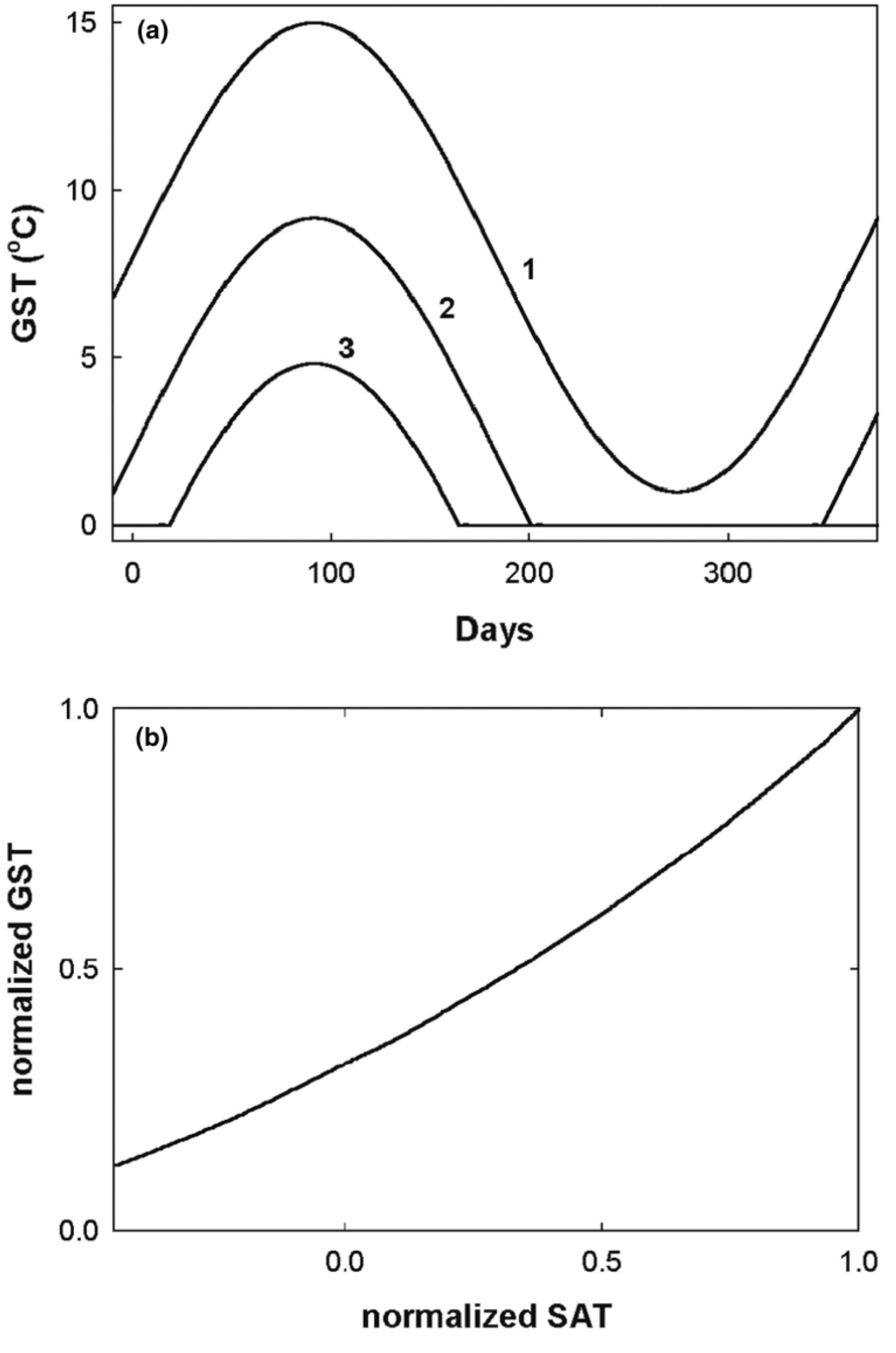

Figure 3. (a) Three hypothetical examples of the annual variation in the GST, assuming it follows a sinusoidal variation of the SAT, except that it is held at 0°C when the SAT goes below freezing. (b) The ratio of the long-term GST to an SAT having an assumed annual sinusoidal variation, assuming that the GST never goes below 0°C. Both are normalized by the amplitude of the annual SAT variation.

Figure 3 shows the expected variation in the GST, derived from a hypothetical sinusoidal SAT for different mean SATs. If the SAT warmed, causing the GST to go from values indicated by curve 3 to those indicated by curve 2 in Figure 3a, the increase in the annual GST would be less than 50% of the increase in the annual SAT. Figure 3b shows the proportion of the change in SAT that would be seen in the GST, assuming that the GST never goes below 0°C. At Cassiar, the long-term-averaged change in SAT varies by 3 or 4 times the derived GST (Figure 2), as predicted (Figure 3b.) The surface intercept temperatures from the boreholes are lower than the derived GST in Figure 2 because of the higher elevation at Cassiar and the difference in GST between the forested borehole site and the grassed climatological sites, plus whatever else was put into acquiring regional representativeness.

The small variation in GST from temperatures in borehole B is consistent with the expected, small regional change in derived GST (Figure 2). The large warming recorded in the underground temperatures of borehole A is attributed to deforestation and draining of the right-of-way. A warming of nearly 3 K occurring 11 years ago fits the observed data (Figure 1), as do combinations of multiple steps totaling 3 K during the last 50 years, which may better approximate the actual road development. Such increases do not agree with the observed change in the regional SAT (Figure 2).

3. Apparent warming due to local effects

A number of local spatial and temporal effects influencing borehole GST estimates can cause apparent warming (e.g., Blackwell et al., 1980). Deforestation, shallow streams, lakes, swamps, and wet ground all cause warming of the annual GST (e.g., Lewis and Wang, 1992; Lewis, 1998) at cooler latitudes. Drill sites are preferentially situated in clearings in forests and often beside, rather than in, bodies of water. Ignoring the three-dimensional effects results in inverted GSTs having apparent warming, and averaging such results does not remove this systematic effect. Of the many sets of borehole temperatures we have logged that exhibit local site effects, very few have shown apparent cooling of the GST, whereas many have shown apparent warming (see also Blackwell et al., 1980; Guillou-Frottier et al., 1998).

Unfortunately in the past, we and others have inferred regional climatic warming without adequate regard to these local site characteristics (e.g., Beltrami et al., 1992; Wang et al., 1994). The amount of warming obtained by analysis of data from many boreholes is dependent on the local site characteristics at each of the sites. Pollack et al. (Pollack et al., 1998) obtained global warming of 1 K over the last five centuries by assuming that the site effects cancel each other, rather than contributing to a systematic error. Only a few researchers have discarded data from disturbed sites (e.g., Guillou-Frottier et al., 1998; Wang et al., 1992).

4. Apparent stability during real change in SAT

We expect and observe the change in the average GST to be much smaller than the change in the average SAT where there is seasonal frozen ground (Figure 3b), which is in direct contrast to the findings of Gosnold et al. (Gosnold et al., 1997). In Finland where there is frozen ground during part of the year, Kukkonen (Kukkonen, 1987) found the change in average GST, going from site to site, was only 71% of the change in the average SAT, which is consistent with this apparent stability. Climatic warming over the last century was proposed for northern British Columbia, based on one inverted GST history (Majorowicz and Safanda, 1998). The data we have from a few undisturbed sites such as Cassiar (borehole B in Figure 1) indicate no increase in the GST. However, even if average air temperatures were increasing, the effect of ground moisture in this cold climate diminishes the resulting warming of the GST. These conditions exist over very large areas where borehole data have been inverted to obtain past GST histories. However, we note again that at the few apparently undisturbed sites in British Columbia we do not detect any significant change in the GST over the past one to two centuries.

One would expect to find this same apparent stability in eastern and central Canada where there is seasonal frozen ground, but a large warming (2–3 K) in the GST is detected over the past one to two centuries (e.g., Beltrami et al., 1992; Wang et al., 1992). This represents an even larger warming of the SAT if the changes to the SAT were throughout the entire year (Figure 3b). However, the warming produced by deforestation and increased drainage of surface water occurs mainly in the warm summer period (Lewis, 1998; Zeimer, 1964). Consequently, for sites where ground moisture buffers the GST, including the site at Cassiar and a large portion of Canada, deforestation can increase the average GST significantly. The large observed warming of the GST in eastern and central Canada over the nineteenth century is expected because of the deforestation and drainage of excess surface water in the creation of farmland (Lewis and Wang, 1998).

5. Conclusions

Temperatures from two boreholes near Cassiar, British Columbia, Canada, were used to demonstrate the effects of land development and of latent heat of groundwater. If these data had been averaged or if the results from these two sites had been combined to represent the region, then an incorrect climate history would have been obtained. The GST (and the SAT) were warmed by nearly 3 K by the creation of a road right-of-way at one site, while the GST 225 m away in the undisturbed boreal forest did not change significantly in the last one or two centuries. Small changes in SAT measured over the last 50 years at the three nearest meteorological stations are reduced, and therefore not apparent, in the GST history of the boreal forest. This is due to the effect of latent heat of groundwater, as the changes are not concentrated in the summer seasons. Since deforestation primarily increases summer temperatures, it is well recorded in the GST history. This result explains the large amount of warming in both the GST and the SAT observed over large regions of central Canada.

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