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# Land Development and Role of Evapotranspiration in Climate Change

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**Abstract**

Analyses of underground temperatures have been used to obtain ground surface temperature (GST) histories. At individual sites, changes in the GST over time are synchronous with development which altered the evapotranspiration. At different, closely spaced sites, measured differences in GST between sites depend on the relative amounts of evaporation and transpiration at each site. These observations prove that a significant portion of the climate change observed on land is caused by changes in the amounts of evapotranspiration at each location. The magnitudes of GST changes vary from 0.6 to 2.6 C, for developments occurring from 8 to 52 years ago. In the temperate zone of Canada, these differences occur primarily in the summer. Our development, including urbanization and development of agricultural land, has produced a significant warming. It is best defined from underground temperature data.

**1. Introduction**

A main cause of climatic change on continents is attributed here to changes in evapotranspiration, caused by land development. In many locations its effects exceed the effects of increases in concentrations of so-called greenhouse gases in the atmosphere. Huge amounts of heat are required at Earth's surface to evaporate water from the ground and transpire it from vegetation, and this requirement is largest in the summer period in the temperate climatic zone.

Many researchers have used detailed analyses of underground temperatures and measured rock properties to obtain past ground surface temperature histories (GSTHs) at particular locations. Conduction of heat is a diffusive process, so data from greater depths are needed to obtain histories over longer periods of time, and the GST is determined with less accuracy the further back in time we look. The average GST is here defined as the observed GST averaged over two or more years, at the upper boundary of the bedrock in which heat is only moved by conduction – the bottom of the critical zone. This type of analysis is well tested and accepted (e.g., Lewis, 1992). Changes in air temperature are reliably recorded in the bedrock in many locations (e.g., Bartlett et al., 2006).

Variations in the terrain surrounding a borehole collar (e.g. surface bodies of water, topography, vegetation) and/or changes with time in the surrounding terrain will influence the GST surrounding the site, and therefor temperatures measured in any nearby borehole (Blackwell et al., 1980; Lewis and

Wang, 1992; Lewis and Skinner, 2003). To obtain estimates of temperatures deep in Earth's crust we need the average equilibrium heat flow, so we remove the effects of terrain, treating them as errors. But one of these effects, land development, is changing the climate.

Geothermal researchers (e.g. Pollack and Huang, 2000) have claimed that by averaging underground temperature data or averaging results from data taken from various borehole locations within a large region, we can obtain the GSTH that represents the region. Supposedly such averaged results are not affected by the different surficial perturbations to the terrain at individual borehole sites nor their changes with time. For North American data, the resulting GSTHs differ significantly from east to west (Pollack and Huang, 2000), in agreement with the averaged results from analyses on many individual boreholes in Canada (Wang et al., 1994; Skinner and Majorowicz, 1999). These do indicate the general pattern of warming over this large region, but they may not represent a true average.

At some individual sites with temperature data from several boreholes, there are large differences in GSTHs, attributed to known or unknown localized terrain effects. When individual temperature profiles are analyzed, we obtain the actual GSTH for that very localized site. Since evapotranspiration is a large effect which can vary locally between borehole collars, to examine it we must use temperature data from individual boreholes.

## 2. Geothermal data from areas with exact times of deforestation

Listed in Table 1 are borehole sites where trees were removed at a known time, and did not regrow, herein called deforestation. At some sites, drainage was also improved, at the same time. At each site, the GST increased at the time of deforestation, from one constant value to another constant value. Any increases in GST due to greenhouse gases should be observed regionally, be somewhat synchronous, and be gradual over many years, as are the increases in the concentrations of greenhouse gases.

Table 1 – Location and Coordinate data of boreholes (NB – Number of Boreholes; NS – Number of Sites).

ID	Location	Coordinates		NB	NS
		North	West		
1	Vancouver Island	50-51	125-128	15	15
2	South Yukon	63	136	6	1
3	Central B. Columbia	51	121-122	11	3
4	Cassiar, B. Columbia	59	130	1	1

Each observation referred to here had a single step increase in GST, synchronous with the local deforestation, and these deforestation events occurred at various times during the last century. None of these sites have unusual heat sources. The values of the change in GST and time between causing action and temperature measurement are given in Table 2.

Table 2 – Surface process, associated local changes in GST and time elapsed (t).

ID	Cause	$\Delta$ GST (C)	t (y)	Ref.
1	Logging	0.8-2.6	8 - 52	Lewis and Wang, 1998
2	Wildfire	0.6-1.5	23	Lewis and Wang, 1998
3	Logging	1.4-2.6	8 - 10	Lewis and Wang, 1992
4	Road Construction	2.4	14	Lewis and Skinner, 2003

These data, from 20 individual sites, some with more than one drill hole (e.g., Clear Lake, Yukon has six), show no change in the GST except at the time of deforestation. Climatic change due to greenhouse gases would have less of an effect on the average GST for the two sites at more northern latitudes, due to air temperatures going below the freezing point of the groundwater for long periods each winter (Lewis and Skinner, 2003). However, the GSTH from all sites in Table 1 are in accord with, a single step increases in the GST. This indicates an evapotranspiration cause: deforestation/improved drainage. And there is no indication of any other climate change. Ziemer (1964) reported soil moisture was lost more rapidly during the summer from forested areas, compared to enclosed clearings. Data from the 18 southern sites show that the increases in GST cannot be caused by the proposed increase in the concentrations of greenhouse gases in the atmosphere over long periods of time. All these sites have

the advantage of being remote and uninhabited with no other land development occurring in the last decades.

Figure 1, given as an example of this, shows the measured and modelled temperatures from two of the deforested sites on northern Vancouver Island, BC.

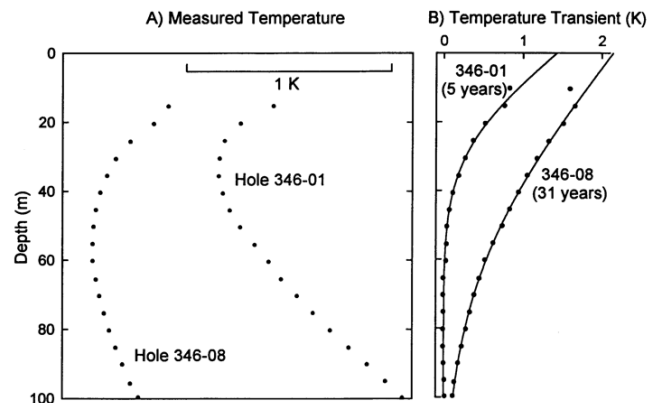


Figure 1 – Examples of borehole temperatures from boreholes 346-01 and 346-08 on Vancouver Island. A) measured temperatures, and B) the transient component after subtracting the steady state temperature: fitted (line) and measured (symbols). Large annual variations penetrating to depths of approximately 15 m are not modelled. The time (in years) prior to the measurements is shown for each borehole in B), (Lewis and Wang, 1998).

## 3. Data from deforested areas with less exact deforestation times

The underground temperatures logged in many other drill holes exhibit a similar warming at ground level (e.g., Beltrami and Mareschal, 1991; Wang et al., 1992; Majorowicz, 1993). Deforestation was suspected to be the cause of warming events previously in Australia (Hyndman and Everett, 1968) and in Cuba (Cermak et al., 1992), but the exact times of deforestation at the sites were unknown. We have referred in Table 1 only to sites in western Canada where thermal data were acquired in crystalline rock after deforestation and where the times of deforestation are well known.

Originally forests covered many of the areas in Canada, and early settlers cleared the lands in order to farm them. This produced a warming of the countryside north of the Great Lakes over the period of time when agricultural land was being created (Lewis and Wang, 1998). Skinner and Majorowicz (1999) associated step changes in the GST with anthropogenic changes to the landscape on the Canadian Prairies.

Urban heat islands (UHIs) are well known and are supposedly caused by excess heat from sources such as people, cars, buses, trains, factories and structures in large urban centers (National Geographic, 2020). The warming, relative to the undeveloped surrounding countryside, has increased as these centers gradually grew, just as the concentrations of greenhouse gas concentrations have gradually increased. Recently Kumar et al. (2017) have shown that the observed warming, relative to the surrounding area, is related to increased agriculture and irrigation in regions surrounding urban areas in India. Agriculture and irrigation increase the amounts of heat required at the ground surface for evapotranspiration. They found that the urban cold islands that exist in India, are caused by lack of vegetation and moisture in the non-urban areas surrounding these cities.

#### 4. Attributions

Majorowicz and Skinner (1997) attributed the increase in GSTs to changes in the surface's albedo. Here we attribute a large part of the warming in Canada in both UHIs and other developed areas to "land development" which has decreased the amount of heat previously required to evaporate and transpire water. In urban areas we drain much of the surface water into nearby waterways. We have increased the amounts of runoff and we generally have lowered the water table. Bruijnzeel (1996) predicted the large increase in runoff from changes in land cover in the humid tropics. Using the appropriate parameters to calculate the heat required to transpire the water from a coastal forest in BC annually, we find it is 10% of the net annual radiation contribution to the total heat budget at the ground surface (Lewis and Wang, 1998; Lewis, 1998). It is equivalent to the calculated increase in forcing by the long-lived greenhouse gases since the beginning of the Industrial Revolution (Houghton et al., 1996). This amount of heat does not include the heat needed to evaporate 10-40 % of the rainfall that is intercepted by the forest canopy (e.g., Murakami, 2005).

According to this attribution, developed areas located next to undisturbed areas, at the same altitude, should have different GSTs. Lewis (1998) observed such differences in local studies on southern Vancouver Island, where the average daily air temperature was slightly less than 0 C for only 14 days during the year. Accurate temperature recorders buried 30 – 60 cm below the ground surface in a small area, measured the temperature every hour, for a year. The largest temperature differences between the various sites occurred in the summer months, when radiation inputs and the heat required for evapotranspiration were largest. The highest GST was for a deforested area, and the forested sites were up to 3 C lower.

However, one of the lowest GSTs occurred at one of the two deforested sites, where the water table was high. When one walked in the tufted grass at this site on a sunny summer day, the soles of your boots became wet. A similar situation existed near a road constructed in a boreal forest (Cassiar site, in Lewis and Skinner, 2003). The trees in this forest were generally spread apart more than usual, with a carpet of low undergrowth which one could walk on or through (Figure 2).



Figure 2 – A picture of the road leading to Cassiar, BC, with the collar of borehole a marked. (Lewis and Skinner, 2003).

On a hot, sunny July afternoon, the road right-of-way was dusty, but there was water at the surface of the undisturbed

forested area. Figure 3 shows the temperatures logged in two boreholes: borehole a sited on the road right-of-way, and borehole b sited in the forest, only 225 m away. Seasonal temperature variations become very small below 15 m depth.

Borehole data define a temperature disturbance propagating downward from the road right-of-way, where the GST has been increased by the construction of drainage ditches and the removal of all vegetation, decreasing the amount of heat needed for evapotranspiration. Borehole b has a constant, heat flow up to the undisturbed surface, in the boreal forest. Note that at this northern latitude where winter temperatures are much below freezing for significant times, the change in the average GST caused by change in the amount of radiation reaching the ground surface ("climate change" due to greenhouse gases) would be reduced (Lewis and Skinner, 2003). The large increase in GST recorded in the ground, is caused by decreased evapotranspiration during the summer period.

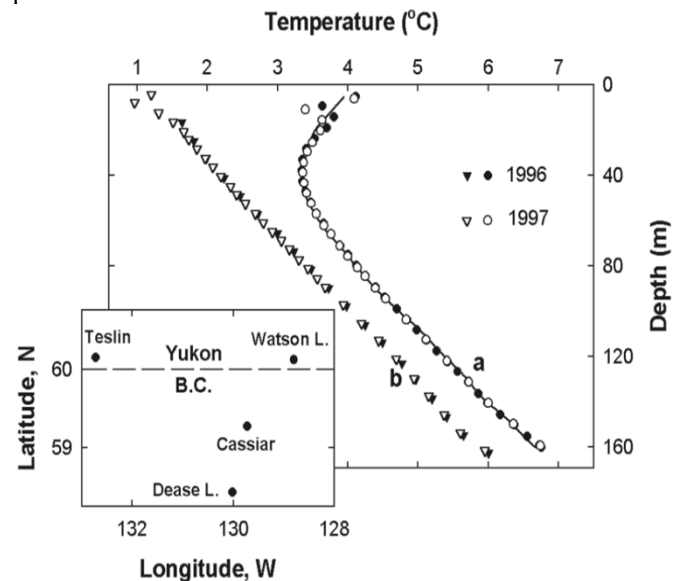


Figure 3 – Borehole temperatures measured in 1996 and 1997 in two boreholes near Cassiar, BC (Lewis and Skinner, 2003). One degree has been subtracted from all data from borehole b (triangular symbols), for the sake of clarity. Inset: location of Cassiar and the three nearest meteorological stations.

If the two sets of temperature data seen in Figure 3 were averaged, the resulting GST history would be very different from both of the histories at the two sites, 225 m apart. Averaging results over large areas may give an average result (biased by the collar locations), but by studying results from individual sites, we can see that one of the main causes of climatic warming is a change in the amount of evapotranspiration, caused by development.

#### 5. Possible Consequences

The temperature of masses of air near the ground will generally be the same as GSTs. Where the GST varies over short distances, the moving air masses will be moving heat between locations with differing temperatures, creating more of an average air temperature. Some researchers have included evapotranspiration in their models, as a part of the albedo term. However, water vapor produced at the ground surface either is absorbed (condensed) over head, or it is moved in the atmosphere before being absorbed at a different location: none of it is lost or reflected or absorbed by carbon dioxide.

Also, more water now goes into the runoff. In the summer this increases the amount of runoff from all land areas into the oceans, and the average temperature of the total runoff is increased, particularly for water flowing north into the Arctic Ocean.

## 6. Conclusions

There are undeveloped areas in Canada where there is no evidence of climatic warming over the last two centuries; there are other areas where the observed climatic warming is synchronous with deforestation, and any longer term warming due to the increase of greenhouse gas concentrations over the last two centuries is much smaller. We attribute these changes to the change in evapotranspiration caused by development. This is similar to some areas of India where agriculture and irrigation are responsible for enhancing evapotranspiration and causing lower GSTs relative to neighboring areas. Our development of agricultural areas in Canada caused climatic warming.

Using underground temperatures and measured rock properties to obtain GSTHs is an excellent way to study past climate change. The GSTHs give the actual temperatures in the past. In studying areas of intense development, both hot and cold “islands”, it would be better to use past values at the same location as reference points, rather than comparing results between nearby areas where both GSTHs have changed over time.

We have observed locations where the evapotranspiration from a deforested area is much less than the amount from the surrounding forested area (see also Zeimer, 1964). Differences between the measured SAT and GST are known for large regions (Skinner and Majorowicz, 1999). To establish a permanent weather station in Canada, any vegetation in the area is cleared and grass is planted. There are no records for watering of the grass around meteorological stations for Canada. Therefore, GSTHs obtained from analysis of underground temperatures measured accurately in boreholes in undisturbed terrains yield more reliable past temperatures for regions than the measured data from meteorological stations.

The land area of Earth is only 29% of the total surface area, and only a fraction of this has been developed. Consequently, the GST changes produced by changes in evapotranspiration documented here cannot account directly for all of the supposed warming in worldwide air temperatures constituting “climate change”. Although they might account for a lot of the climate change in developed lands in the last two centuries. Decreased cloud cover and increased, warmer waters discharging into the oceans also contribute to warming caused by evapotranspiration.

However, the most significant greenhouse gas is water vapor. The current IPCC report (Summary for Policymakers of IPCC Special Report on Global Warming of 1.5°C, 2020) states that Global net human-caused emissions of carbon dioxide (CO<sub>2</sub>) would need to fall by about 45 percent from 2010 levels by 2030, in order to limit the temperature rise of Earth to 1.5 °C. Water vapor from evapotranspiration at the ground surface carries large amounts of heat very efficiently up to where it condenses and heats the atmosphere, unaffected by any carbon dioxide along its path.

We should be examining more closely how much our development of the land has caused the climate to change.

## 7. Acknowledgments

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