Climatic Warming in North America: Analysis of Borehole Temperatures

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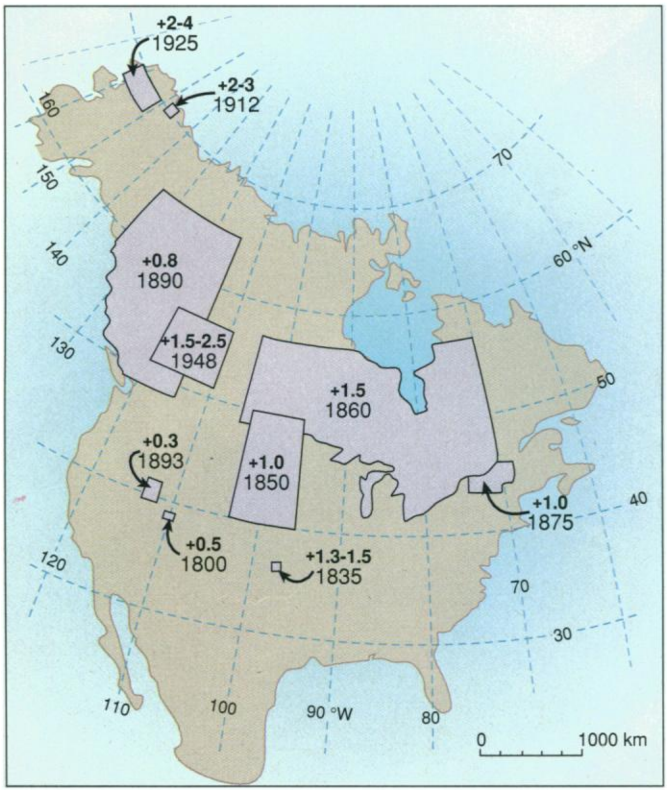
The primary database that has been used to assess climatic warming over the last 100 to 150 years is the history of surface air temperatures (SATs) as recorded on a daily basis for the purpose of weather forecasting (*1*). Hansen and Lebedeff (*2*) found a mean global increase of ~0.5° to 0.7°C in SAT over the period 1880 to 1985. Similar results were obtained by Ellsaesser *et al.* (*3*) and Jones *et al.* (*4*). However, the observed rise in SAT (~0.5°C) is significantly lower than most predictions of warming resulting from increased concentrations of greenhouse gases in Earth's atmosphere. Theoretical estimates of the mean global rise in SAT above a pre-1765 mean that should have taken place by 1985 range from ~0.6° to 1.2°C with a nominal "best" estimate of ~0.8° to 0.9°C (*5, 6*).

An obvious explanation for the apparent discrepancy between theoretical predictions and observations is the possibility that a significant portion of the warming may have taken place before the inception of the reliable instrumental record. The global SAT record before about 1870 is sparse to nonexistent; the SAT history of North America can be reliably reconstructed back only to 1880 (*2*). The limitation of the SAT record to reveal climatic trends before the late 1800s is particularly grievous because it is unclear if the modest global warming trend of the last 100 years is a rise above a long-term mean that may be related to increasing concentrations of greenhouse gases, or simply a return to normal temperatures after a cold spell over the last part of the 19th century. Interpretation of SAT trends is ambiguous because the instrumental record is not long enough to determine the long-term mean and thus assess if recent data represent significant departures from it.

Climatic information that is missing from the truncated SAT record may be found in borehole temperature profiles. Changes in ground surface temperature (GST) propagate into the subsurface, exponentially decreasing in amplitude with increasing time and depth . The solid Earth is a low-pass filter that efficiently and continuously filters out daily and seasonal changes in GST while maintaining a running record of the long-term mean and departures from it. If the average GST increases over a period of several years, the normal upward flux of heat in the solid Earth is lessened or even reversed, leading to anomalously high temperatures and an energy imbalance in the upper 100 m or so of the Earth's crust (*7–12*).



Average GST changes (in degrees celsius) with respect to the long-term mean in North America and approximate starting dates (see table). Starting dates are uncertain by approximately +25, –50 years, depending on constraints available in individual studies.

Unlike proxy methods for estimating temperature change (such as tree ring thickness, oxygen isotopes, glacier termini, and so forth), changes in subsurface temperature are a direct thermophysical consequence of changes in GST (*7*). Studies to date have shown that changes in SAT tend to be tracked in GST changes (*10, 13, 14*), and GST is a valid indicator of climate change (just as sea-surface temperature is), regardless of any inferred relation with SAT.

Although the methodology is conceptually simple, interpretation of borehole temperature profiles may be problematical. Subsurface temperatures that appear to be anomalously warm (or cold) may be the result of a number of causes other than climate. Changes in thermal conductivity and lateral gradients in solar insolation related to factors such as vegetation and topography may produce apparent warmings in the upper sections of boreholes that mimic increases in GST. Even if GST has changed, the change may not be from a change in climate but could simply reflect a change in land use (for example, deforestation). Groundwater flow may also introduce interpretation errors in thermal profiles thought to be purely conductive (*15*).

The possibility of alternative hypotheses implies that it is often difficult to draw unique conclusions concerning GST histories from analysis of borehole temperatures. However, such is usually the case for other types of scientific data: To arrive at unique interpretations, one must carefully consider alternative hypotheses and then reject them as circumstances permit.

Since Lachenbruch and Marshall (*7*) first pointed out the dramatic warming that has taken place on the North Slope of Alaska, there has been a concerted effort to estimate the magnitude and timing of GST changes throughout North America (see table) (*16*). Although individual boreholes have been found that are consistent with a decrease or no significant change in GST, averages inferred from groups of boreholes have all revealed warming trends. A collation of studies to date shows that the average GST increase in the eastern part of the North American continent is ~1.0° to 1.5°C; the average increase in the western half is generally lower (except at high latitudes in Alaska). The inception of warming in the eastern half of North America appears to date from the middle 19th century, whereas the warming in the west appears to start near the beginning of the 20th century or later (see figure).

Because of the inherent ambiguity in interpretation, it has been heretofore problematical to individually attribute GST increases to climatic causes. However, the assembly of the data now shows that it is difficult to argue that the inferred warming is a

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Estimated GST changes in North America							
Site	Latitude (°N)	Longitude (°W)	GST change (°C)*	Approximate inception date†	Number of boreholes	Depth (m)	Reference
Eastern and central Canada	45–57	70–105	+1.5	1860	126	~150–3000	(*22*)
Western Canada	50–65	115–135	+0.8	1890	94	150–1000	(*22*)
Western Utah	39.5–41.5	112–114	+0.3	1893	6	160	(*10*)
North Slope, Alaska	68–70	152–162	+2.0–4.0	1925	21	~500–900	(*7, 23*)
Prudhoe Bay, Alaska	70.3	148.6	+2.0–3.0	1912	9	~750	(*23, 24*)
Southeast Utah	38.5–39.0	110–111	+0.5	1800	9	300–500	(*13*)
Northern Great Plains, United States	40–50	96–104	+1.0	1850	45	?	(*28*)
Northeast United States	43.2–45.4	68.6–74.3	+1.0	1875	10	213–710	(*25*)
Alberta, Canada	51–56	110–120	+1.5–2.5	1948	42	30–220	(*26*)
North central Oklahoma	36.36	96.70	+1.3–1.5	1700–1835	6	380	(*27*)

*Above a long-term mean. †Estimated dates should be considered uncertain by at least +25, –50 years.

coincidental collection of spurious effects. The estimated GST changes for North America exhibit latitudinal amplification similar to that predicted by general circulation models and found in Pleistocene and Holocene climate changes (*18*). General circulation models also tend to forecast warmings in North America that generally are higher on the eastern section of the continent, although this pattern is not so certain as latitudinal amplification (*19*). The most parsimonious interpretation of the GST studies as a whole is that they represent a continental-scale climatic warming. Alternative interpretations invoking unwieldy and coincidental collections of phenomena, such as deforestation or changes in precipitation, fail the test of simplicity.

Warming estimated from borehole temperature profiles in North America is consistent with estimates of increases in SATs from 1880 to 1987 made by Hansen and Lebedeff (*2*). The trend of SAT increases for 1880 to 1987 estimated from Hansen and Lebedeff's (*2*) data is 0.9°C for western Canada, 1.0°C for eastern Canada, 0.8°C for the western United States, and 0.5°C for the eastern United States (boxes 6, 7, 15, and 16, respectively, of their model). However, in eastern North America (see figure), where the apparent onset of warming predates the meteorological record, changes in GST (+1.0° to 1.5°C) are significantly higher than increases in SAT (+0.5° to 1.0°C). It is therefore possible that the meteorological record in North America may underestimate the magnitude of warming that has taken place, simply because a significant portion of the warming may have occurred before the reliable SAT record began in the late 19th century.

An objection could be raised that significant 19th-century warming is inconsistent with theoretical predictions of greenhouse scenarios wherein the warming accelerates with time. However, the compounding effect of natural variability must be taken into account (*20*). For example, it may be possible that the latter half of the 19th century was a period of natural warming, whereas the 20th century is a period of natural cooling that has masked the greenhouse signal.

Studies of borehole temperatures provide a relatively good constraint on the total magnitude of warming; inferences concerning the date at which the warming trend began and the rate at which it proceeded are much less certain. The available evidence from both GST and SAT studies is consistent with a major climatic warming over the North American continent that likely began near the middle of the 19th century in the east, later in the west. The magnitude of warming in eastern North America estimated from changes in GST significantly exceeds that estimated from changes in SAT. The sum of the evidence is consistent with theoretical predictions of warming related to the accumulation of greenhouse gases in the Earth's atmosphere from anthropogenic activities. However, the magnitude of the observed warming (~1°C) in North America is still within the range of estimated natural variability (~±1°C) for the Holocene (*21*). A cause and effect relationship between anthropogenic activities and climatic warming cannot be demonstrated unambiguously at the present time.

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