Past Climate and Borehole Temperatures

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Introduction

For a decade geophysicists have studied global warming using borehole temperature logs. They have used them to estimate the timing of recent warming and its magnitude (1,2,3); to explain the discrepancy between observed air temperature rise and estimates from global climate models (4)(GCMs); to examine temperature trends century by century during the last 500 years (5,6); and, to establish a baseline temperature to compare to the observed 20th century warming (7). These studies generally confirm the predictions of GCMs, including their expected latitudinal variation (8), and present more precise long term estimates of temperature trends than do air temperature records. A significant finding is of some past period of stable climate(6).

Do analyses of borehole temperatures allow one to make definitive statements about past climate?

Despite a few exceptions (9) geophysicists calculate temperature with a 1-d model of heat conduction. Details are well documented elsewhere, but, briefly stated, temperature at any depth and time in homogeneous material is

$$1)\ T(z,t) = \int_{-\infty}^{t} \frac{z\,\mathrm{Exp}[-z^2/4\alpha(t-\tau)]\, f(\tau)}{\sqrt{4\pi\alpha\,(t-\tau)^3}}\, d\tau \quad (10)$$

where t is the time at which the borehole temperature is measured, f(t) represents the time variation of surface temperature, and α is thermal diffusivity. Adding a term like $T_o + Bz$ to Equation 1, lets it represent background temperature also.

Through test and expansion functions, one may transform Equation 1 into a linear form for calculation on computers (11).

$$2)\ T = L \cdot f$$

where T and f are now vectors rather than continuous functions. The linear operator (L) is a product of matrices.

3) $L = P \cdot \Lambda \cdot Q^t$;

where Λ is a diagonal matrix of shifted eigenvalues (12). Equation 1 transforms into operators with many very small eigenvalues--a parasitic spectrum. This spectrum plays no role in Equation 2 other than to prevent information regarding long past surface temperature from influencing borehole temperature. However, in the inverse problem each estimated surface temperature is

4) $f_i = \Sigma_k \Sigma_j \, q_{kj} \cdot p_{ji} \cdot T_k / \lambda_j$;

where p_{ji} and q_{kj} are elements of the operators P^t and Q, respectively, and λ are eigenvalues. Very small eigenvalues now become a serious problem. If temperature T_k contains error, the small eigenvalues amplify and spread this error through the estimated temperatures f_i.

Equations 2 and 4 provide forward and inverse solutions, and also measures of merit. For example, we obtain the uncertainty in recovered surface temperature by applying propagation of error to Equation 4).

5) $s^2_i = \Sigma_k \Sigma_j \, (q_{kj} \cdot p_{ji} / \lambda_j)^2 \, \sigma^2_k$.

where σ^2_k is the squared uncertainty of the k^{th} borehole temperature, which we assume is uncorrelated with other measurements. The dot product between column vectors that comprise the operator L measure the independence between estimated temperatures. Letting L_i and L_j represent different columns of L, the normalized dot product

6) $L_i . L_j / |L_i||L_j|$

is zero for complete independence, and one for complete dependence between temperatures (or parameters) f_i and f_j.

Recovering past temperature from boreholes is well understood as an *ill-conditioned* problem

(6). Its ill-conditioning results from physical processes which are irreversible, such as thermal diffusion and the mixing of materials at different temperature through groundwater flow and latent heat transfer. If irreversible processes operate for any time at all, they prevent recovering past temperatures with arbitrary precision. The longer they operate, the lower the precision.

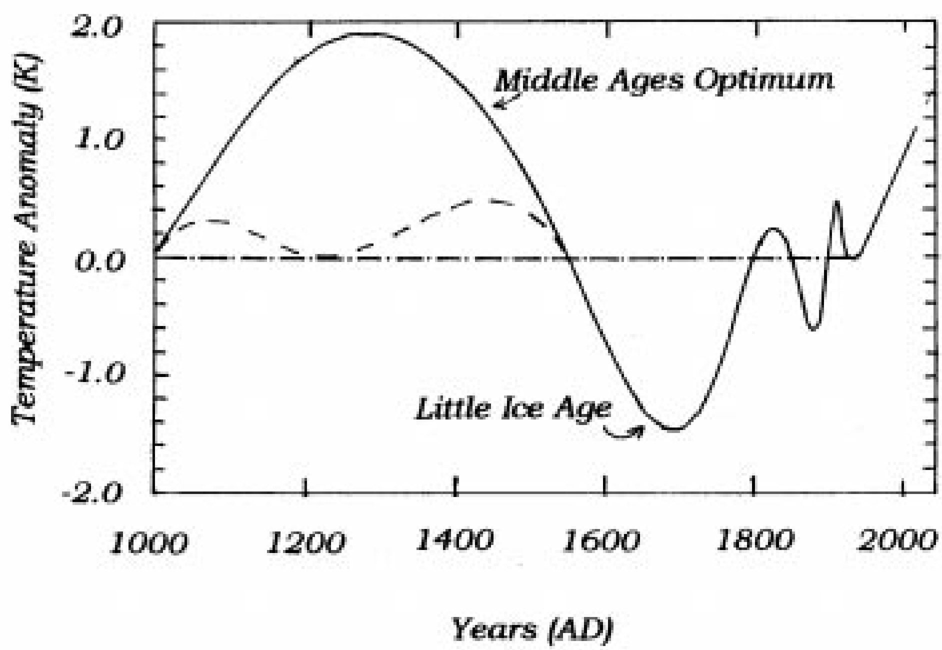
Thus, it is no surprise that Clow (13) found the resolving power of borehole temperature data to be a function of elapsed time, τ. The spread function, $S(\tau)$, which represents temporal resolution, depends also on borehole depth, measurement noise, and what precision is demanded of estimated temperature. Borehole data will not resolve events more brief than $S(\tau)$. If surface temperature resolution is expected to be $\pm$0.5K, and typical measurement error is $\pm$5mK, then optimum resolution of events occurs when $\tau<0.03z^2/\alpha$. Unfortunately, optimum means resolution no better than 50% of time elapsed since the event. Resolution, which is never very good in these problems, is nil when $\tau>0.10z^2/\alpha$.

Borehole Temperature and Recent Warming

Despite irreversibility and limited resolution, people expect that borehole temperatures can supply accurate air temperature estimates for the period beginning at 1700AD and ending at

Figure 1

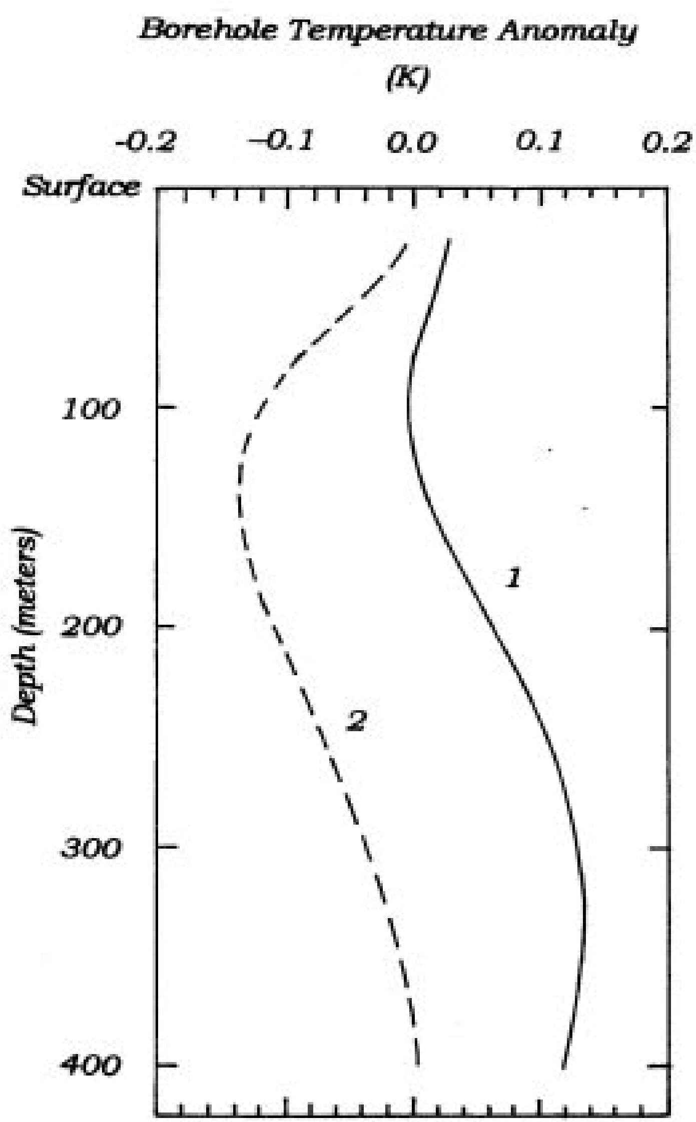
Ground Surface Temperature History



1850AD. This spans the time between the beginning of the industrial revolution and the advent of general air temperature recording.

Consider two of the hypothetical air temperature records in Figure 1. One, which is dashed and dotted, exhibits a constant temperature until 1910AD, and a gradual warming thereafter until the present time. The other, shown as a solid curve, exhibits the same recent warming combined with a complex series of warm and cold episodes, including a cold period from about 1500AD until 1800AD (Little Ice Age), and a warm period that began about 1000AD (Late Middle Ages Optimum) (14). Figure 2 displays the difference in borehole temperature between them as a solid curve. The maximum difference is only 0.05K in the upper 200m depth, rising to two and one-half times this near 350m. With measurement error of 0.03K, which is typical, χ^2 arising from the 20 measurements typically taken in the upper half of the borehole(5) is an insignificant value

Figure 2



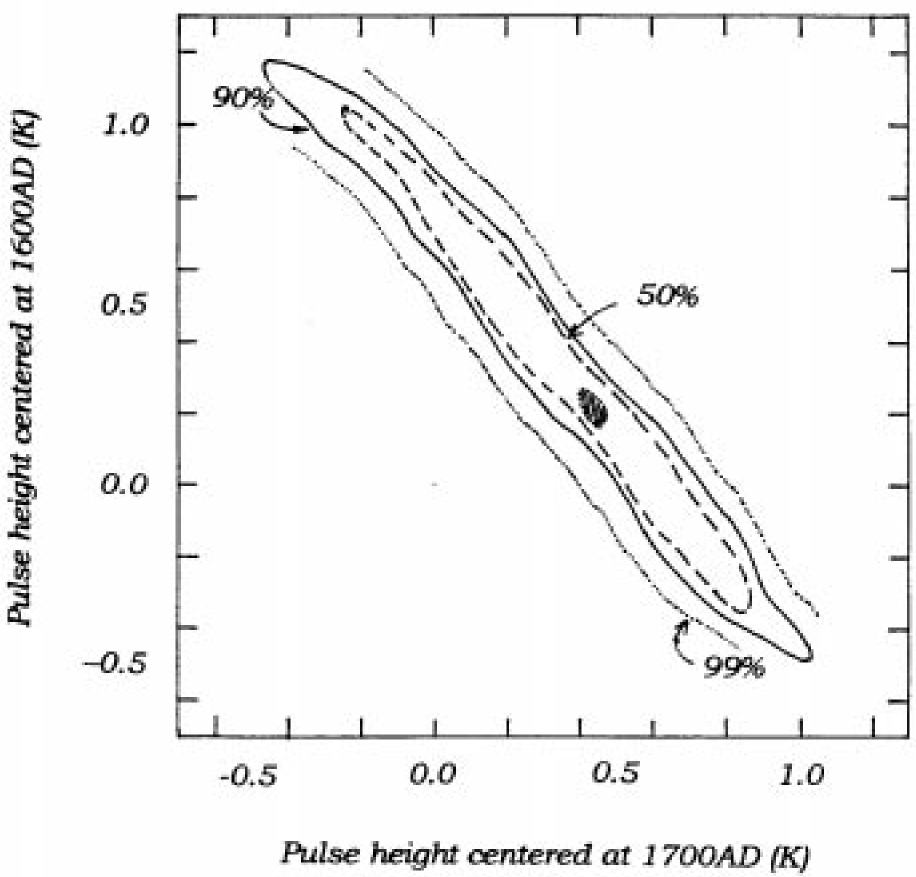
of 14. Viewed through a noisy earth filter, these very different temperature histories are equivalent.

Recent appraisals of Utah borehole data provided a precise 19th Century baseline temperature (7,15), but could not resolve an event as significant as the Little Ice Age ending at mid century (16). A spread function which lies between 1.5τ and 2.0τ partially explains this poor resolution. Events are smeared across a window 150-225 years long centered at 1775AD.

Figure 1 suggests something more, however. Through Equation 6 we see that estimated average temperature between 1700AD and 1850AD depends substantially on average temperature in earlier periods. The end of the Little Ice Age in Figure 1 might be resolved in the borehole data if it were not for interference from the earlier warm period. Eliminating the warm period in the hypothetical temperature history, as in the dashed curve, leads to a different temperature depth

Figure 3

Cross Section of Model Space



curve, dashed in Figure 2. The value of χ^2 in the upper 200m is now a significant 240.

Pollack et al (6) recently used borehole temperatures to estimate rates of global warming century by century from 1500AD to date. They arrived at an estimated warming since 1500AD of 1.0±0.1K. This is much more precise than the global air temperature record over a period of only 120 years. Moreover, the period from 1500AD to 1800AD seems to exhibit no temperature trend at all. Yet, if we analyze resolution in this situation, we conclude that the boreholes are too shallow, and the century-long periods too short for good resolution. Consider an operator, L, that consists of triangular pulses centered on century marks, plus a gradient and constant to represent background temperature. Assume measurement noise of 0.01K in 400m deep boreholes, typical of the data in this study, and assume a steady temperature rise of 1K in 500 years.

Figure 3 shows a cross section of parameter space (the space of f_i) for the pulses centered at 1600AD and 1700AD. The contours are of confidence in percentages of Fisher's F. The diagonal trough shows that there is wide freedom to trade amplitude of one pulse against another and maintain acceptable fit to data. Thus, fit to data alone cannot discriminate between the shaded parameter values, which provide a smooth temperature increase, and values near the ends of the trough, which provide oscillation. Inverse solutions via Equation 4 often result in oscillating temperature like that in Figure 1. The oscillation may derive from noise, but it is consistent with plausible climatic events.

Yet, while inversion has both the opportunity and motive to produce oscillating solutions, published inverse solutions are often rather smooth. There are many approaches to inversion that achieve smoothness. One may simply include only a few, well resolved parameters in the inversion (17). One may improve condition of the operator L^{-1} by adding a small positive amount to each eigenvalue (18). One may seek an acceptable misfit with data subject to a minimal model norm (19), or by using a smooth *a priori* model of past temperature. This last approach, functional space inversion (FSI), seeks to minimize the measure

$$S(f) = (T-T_0)^t.c_T^{-1}.(T-T_0)+(f-f_0)^t.c_f^{-1}.(f-f_0); \quad (20)$$

where $(T-T_0)^t$ is a row vector of differences between observed borehole temperatures and those calculated from the current model, f. The row vector $(f-f_0)^t$ is the difference between the current (f) and *a priori* (f_0) models. The matrices c_T^{-1} and c_f^{-1} summarize covariation among the observations, and model parameters, respectively. The matrix c_f^{-1} acts like a Lagrange multiplier except it allows great flexibility to customize a penalty for deviating from the smooth *a priori* model.

These four methods have a similar effect on solutions. Lack of information concerning some model parameters, particularly in deeper parts of a borehole, leads to discarding or discounting parameters with small eigenvalues, or discouraging deviation from f_0. In any case smoothness comes from the *a priori* assumptions, not from the borehole data.

What do Borehole Temperatures Represent?

It seems reasonable to view borehole temperatures as filtered versions of air temperature (6,15), but observations do not support this unconditionally. For example, annual surface temperatures are often well above annual air temperatures (8). After culling boreholes with problematic settings or geology(2,7), one finds boreholes suggesting recent surface temperature warming as expected; but, also boreholes suggesting recent cooling (15), rapid 19th century warming with recent cooling (15), accelerating recent warming(8), and long term cooling(6). Since borehole temperatures are advertised as direct indicators of past climate, it is insufficient to explain this unexpected behavior as a variability like that of air temperature (6), or as a decoupling of the borehole from air temperature(15). In some instances divergence between air and soil temperature results from changes in land use (1), but otherwise there are few published explanations.

Latent heat appears to cause some deviation because air temperature and soil temperature track one another well until the average daily air temperature falls below freezing(8). However, latent heat keeps soil temperature above air temperature while soil is freezing, and depresses it while the soil is thawing. Divergence between air and soil temperatures requires a secular change in soil moisture.

Snow cover insulates soil and prevents it from reaching extremely cold air temperature (8,21). Yet, this explanation presents an apparent paradox in that an increasing temperature difference, derived from increasing soil temperature rather than decreasing air temperature, supposedly results from increased duration and thickness of snow cover.

An uncertain component of global climate models is how to represent energy transfer at the land surface (22). This also applies to the relationship of air temperature to ground surface temperature. Energy flows to the ground surface from below by conduction, and from above by solar and longwave radiation. Energy flows away by longwave radiation and convection. Radiative and convective heat transfer cause an effective temperature discontinuity between the soil and air immediately above it. Soil temperature, and the surface temperature discontinuity, reflect the current balance among these processes. A 1% change in emissivity of soil or air, a 6% change in cloudiness, or a change of 1 cm in precipitation that runs-off rather than evaporates each have an effect equaling a 1K change in surface temperature. These are important, but sometimes unrecognized, factors of soil temperature (22,23). Perhaps air temperature is the only consistent factor affecting surface temperature in the long term, but long term changes in these other factors are entirely plausible; making the relating of air temperature to recovered surface temperature a complex task.

Conclusions

Estimates of surface warming and its timing are well resolved during the past century (1,2). Useful estimates of more ancient climatic events are possible when these have especially large magnitude or long duration (24). However, typical borehole temperatures contain enough measurement noise to to hide significant and plausible climatic variation during the period 1700AD to 1850AD.

Simply fixing the time period of surface temperature history at one-century does not eliminate the problem of poor temporal resolution, but rather shifts it entirely into poor temperature resolution. Smooth inverse solutions do not confirm or deny hypotheses of stable climate a few centuries past because borehole temperatures contain no information to decide this issue.

Measurements cannot confirm one another unless they measure the same thing. The long-term relationship between air and surface temperatures is unknown, but probably they are not strictly proportional to one another.

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