Perturbation of ground surface temperature reconstructions by groundwater flow?

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[1] Subsurface temperatures have been shown to be a robust source of information on past climates. Most analyses neglect groundwater flow (GWF) and assume purely conductive heat flow. However, in many situations GWF has not been fully considered and to date there are no general GWF criteria for either accepting or rejecting a temperature profile for paleoclimate analysis. Here we examine the transition from conduction dominated environments to environments where advection has a significant effect on the subsurface temperature regime and thus ground surface temperature (GST) histories. We provide guidelines indicating when advection is important and conclude that it is unlikely that groundwater flow is a significant source of error in the global data set maintained by the International Heat Flow Commission. **Citation:** Ferguson, G., H. Beltrami, and A. D. Woodbury (2006), Perturbation of ground surface temperature reconstructions by groundwater flow?, *Geophys. Res. Lett.*, *33*, L13708, doi:10.1029/2006GL026634.

1. Introduction

[2] General circulation models are used to study the variability of the climate system under natural and human induced perturbations. However, for model simulations of future climate to be interpreted with confidence, we require a robust record of past climatic changes to use as model validation. Without such a record, anthropogenic forcing of the climate system cannot be separated from its natural variability and identification of individual contributions of forcing mechanisms cannot be ascertained [*Levitus et al.*, 2001, 2005; *Beltrami et al.*, 2002, 2005, 2006; *Hansen et al.*, 2005]. However, there is far from a clear consensus on the reconstructed climate of the past millennium. Borehole temperature reconstructions appear cooler by about 0.5 K between years 1500 and 1800, than some reconstructions based on multiproxy data [*Huang et al.*, 2000; *Harris and Chapman*, 2001, 2005; *Jones and Mann*, 2004; *Mann and Schmidt*, 2003; *Esper et al.*, 2004; *Pollack and Smerdon*, 2004; *Beltrami and Bourlon*, 2004; *Moberg et al.*, 2005]. Some issues considered in this debate have been those pointing to potential biases of the borehole temperature reconstructions. Examples of such issues include: changes in land-use; vegetation cover; snow cover; soil moisture; topography; and groundwater flow. These factors could create apparent long-term, low-frequency, transient changes in the energy balance at the ground surface which could affect the surface air temperature (SAT) and GST coupling, complicating the ground thermal response to SAT changes [*Lin et al.*, 2003; *Kohl*, 1999; *Mann and Schmidt*, 2003; *Mann et al.*, 2003; *González-Rouco et al.*, 2003, 2006; *Pollack and Smerdon*, 2004; *Chapman et al.*, 2004; *Schmidt and Mann*, 2004; *Rutherford and Mann*, 2004; *Nitoiu and Beltrami*, 2005; *Ferguson and Beltrami*, 2006]. For these reasons a large percentage of the total number of temperature profiles available were rejected from the International Heat Flow Commission (IHFC) database and in many other cases there is insufficient information to determine the existence or nature of noise in the data [*Pollack and Huang*, 2000].

[3] In this study, we examine the potential effects of groundwater flow (GWF) in porous media on the thermal regime of the subsurface and thus on the ability of retrieving paleoclimatic information from borehole temperature data. We analyze the transition from environments that can be considered purely conductive to those where advection may be important using analytical solutions to the steady-state temperature field with constant GST, and focusing on areas of groundwater recharge. Temperature profiles in these areas exhibit temperature gradients that increase with depth, which is similar to the profiles that result from increases in GST. We suspect such profiles are less likely to be rejected than the distinctive temperature profiles found in discharge zones, which are characterized by decreasing temperature gradients.

[4] Hydrogeologists have been examining the effect of fluid flow on subsurface temperatures since the 1960s to estimate Darcy velocities [*Anderson*, 2005, and references therein] but only recently has this been considered in the context of climate change. Some researchers have already examined the relative importance of changes in GST and GWF on the subsurface temperature field. *Chisholm and Chapman* [1992] and *Harris and Chapman* [1995] analyzed the possible effect of advective heat transport in their studies of climate change in Utah. *Taniguchi et al.* [1999], *Ferguson and Woodbury* [2005] and *Reiter* [2005] examined the ability to estimate groundwater recharge rates from areas subjected to GST changes. *Reiter* [2005] concluded that in a number of situations, subsurface temperature anomalies could be explained by either groundwater flow or GST changes. *Kohl* [1998] examined whether climatic signals were recorded in areas where GWF was significant, and showed that the signals were preserved but extracting them would require good knowledge of GWF. Preliminary research has been conducted on the possibility of correcting

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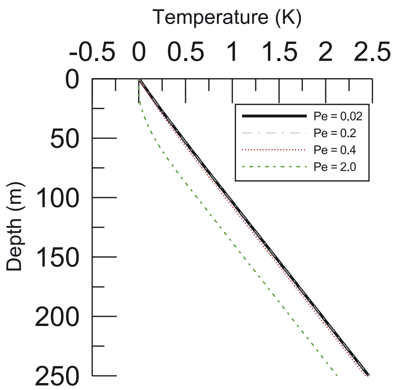

Figure 1. Temperature profiles for 100 m thick aquifer and underlying rock for various N_{pe}. Profiles shown are relative to the surface temperature.

for GWF in such environments [*Bodri and Cermak*, 2005; *Ferguson*, 2005] but this work is largely theoretical to date.

[5] In the current study, we examine the conditions necessary for GWF to significantly affect ground surface temperature reconstructions, through analysis of synthetic temperature profiles. These temperature profiles are then inverted to calculate an apparent GST history. The results provide data quality criteria to accept (or reject) a temperature profile for use in a climate reconstruction under the assumption of purely conductive conditions. Currently, no such data quality control criteria exist and data are usually only inspected visually, primarily to identify GWF in high permeability zones such as fractures. Our criteria can be interpreted in terms of basic and easily obtainable meteorological and hydrogeological information.

2. Theory and Analysis

[6] While GST analyses normally assume purely vertical heat flow, conservation of mass and permeability constraints normally dictate that groundwater flow will become increasingly horizontal with depth in the case of regional flow [*Toth*, 1963; *Domenico and Palciauskas*, 1973]. To assess when advection becomes an issue in GST history reconstruction, a series of models were created using the two-dimensional analytical solution developed by *Domenico and Palciauskas* [1973]. This solution requires a constant heat flux at the base of the model, fixed temperature at the upper surface and zero heat flux at the lateral boundaries of the model domain. Fluid flow boundary conditions are specified hydraulic head at the upper surface of the model, which declines from one side based on a topographical gradient, and impermeable boundaries at the base and sides of the modeled domain. For this solution, the Peclet number is defined as

$$N_{pe} = \frac{\Delta h K z}{2L\kappa} = \frac{qz}{2\kappa}, \quad (1)$$

where Δh is the change in head between the recharge and discharge areas, K is hydraulic conductivity, z is the depth of the aquifer, L is the characteristic length (length of the aquifer in this case), κ is thermal diffusivity and q is the Darcy flux based on the head difference across the model domain. We neglect changes in fluid density and viscosity.

[7] A two-dimensional aquifer model was constructed to simulate heat flow in the upper 100 m of the Earth's crust in a basin 1000 m long to assess the effects of different groundwater flow regimes on the subsurface temperature field. We chose typical hydraulic and thermal parameters [*Domenico and Schwartz*, 1998] to create Peclet numbers ranging from 0.02 to 2.0. These Peclet numbers correspond to downward Darcy fluxes of 0.02, 0.2, 0.4 and 2.0 $\times$ 10^{-8} m/s respectively, which are plausible in a range of subsurface environments. From these simulations, we sampled profiles at the point of maximum downward groundwater flow to provide an upper bound for the thermal disturbance (Figure 1). We used a singular value decomposition (SVD) routine to invert the temperature anomaly assuming conductive heat flow for a model consisting of fifteen 20-year steps to estimate GST changes induced by GWF [*Mareshcal and Beltrami*, 1992]. Where N_{pe} = 0.4, a GST perturbation signal of nearly 0.1 K was present in the reconstructed record and this increased to 0.35 K at N_{pe} = 2.0 (Figure 2). Overall, the size of the perturbation is directly proportional to the Peclet number for a given depth to length ratio. Temperature profiles were also examined at various positions between the recharge end of the model and the hinge line. In cases where $N_{pe} < 2.0$, the perturbations were insignificant in all areas except for the 10 percent of the domain closest to the recharge area. However, for where $N_{pe} > 2.0$, effects were noticeable over almost the entire recharge side of the model. In these areas, discerning the effects of groundwater flow will be more difficult as greater variety of models could fit the data [*Reiter*, 2005]. This issue could become more significant in dipping formations where GWF is subhorizontal over large areas.

[8] Temperature perturbations become more problematic where there is deeper circulation of groundwater. For a constant length, the size of the perturbation increases in a non-linear manner with the depth of the model domain for a given N_{pe} (Figure 3). Profiles measured in deep and short basins are the greatest potential source of error in climate change studies. For N_{pe} = 1.0, a perturbation of 1.78 K was found a basin 500 m deep and 1000 m long whereas a basin of the same depth with a length of 100 km had a maximum perturbation of only 0.08 K. While deeper GWF creates the largest apparent GST anomalies these temperature profiles

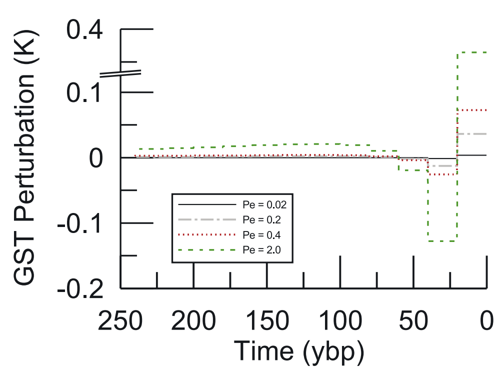

Figure 2. Apparent GST history reconstructions for temperature profiles shown in Figure 1. The maximum standard error observed in any of the reconstructions is 0.044 K.

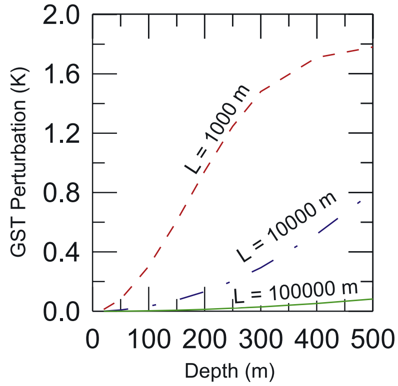

Figure 3. Relationship between maximum GST perturbation and basin depth for various basin lengths and $N_{pe} = 2.0$.

with GWF effects deeper than 100 to 200 m will likely be excluded from paleoclimate analysis. The curvature in the temperature profile at these greater depths should be easily recognized as a deviation from steady-state conductive heat transport.

3. Discussion and Conclusions

[9] For typical hydrogeological parameters, advection can produce a significant perturbation to the GST signal (0.3 K) when $q > 2 \times 10^{-8}$ m/s (630 mm/yr) for fluid flow in two dimensions for a basin 100 m deep and 1000 m long. For a 200 m deep basin of the same length, a fluid flux of $q > 3.3 \times 10^{-9}$ m/s (102 mm/yr). This temperature perturbation is significantly lower than a typical climate induced GST perturbation [*Beltrami and Bourlon*, 2004; *Pollack and Smerdon*, 2004]. GWF of approximately three times this amount (1050 and 330 mm/yr for 100 and 200 m deep cases respectively) would be required to cause an apparent GST signal of 1.0 K, which would be of the same order magnitude as climate signals in most areas. Much greater Darcy fluxes would be required in shallower and/or longer basins.

[10] The Darcy flux required to cause a noticeable perturbation can result from an infinite number of combinations of hydraulic conductivities and hydraulic gradients (Figure 4) but only a subset of these values is reasonable in natural environments. Moreover, hydraulic gradients are most commonly a few orders of magnitude less than unity. If one assumes that the hydraulic gradient, $\frac{\Delta h}{\Delta z}$, is less than one, then a hydraulic conductivity, K, of more than approximately 10^{-8} m/s is required for advective heat transport to create a significant perturbation to a GST reconstruction. This assumption is reasonable because the under gravity drainage, a unit gradient is the maximum possible gradient and under other flow conditions, fluidization is likely at higher gradients [*Bear*, 1972]. Such restrictions would decrease the probability of finding perturbations to the GST signals in most igneous and metamorphic rocks, shales, siltstones and a variety of other low permeability rocks. See *Freeze and Cherry* [1979] for typical permeabilities in various rock types. This result is consistent with that of [*Smith and Chapman*, 1983], who suggest that the transition from environments dominated by conduction to those where advection is measurable, occurs at a hydraulic conductivity of approximately 10^{-9} m/s. This critical hydraulic conductivity was found to be much greater in basins with lower length to depth ratios. Using the same arguments as above, a hydraulic conductivity of 8×10^{-6} m/s would be required to cause the anomaly of 0.08 K found in the 500 m by 100,000 m basin (Figure 3). Conversely, basins with greater depth to length ratios will require lower Darcy fluxes to cause significant temperature perturbations. However, such situations are rare in nature.

[11] A further constraint for groundwater flow induced subsurface thermal anomalies comes from meteorological data. To achieve the critical darcy fluxes, a greater or equal amount of precipitation is required in the absence of GWF focusing mechanisms. Thus, according to our results, errors in GST reconstructions due to groundwater flow in areas with less annual precipitation than these critical values are unlikely. This is conservative because advective effects will be further reduced when evapotranspiration and surface runoff are considered, since these processes decrease the amount of water available for infiltration. *Schwartz and Zhang* [2003] suggest that only 5% of total precipitation may be available for groundwater recharge, suggesting that the precipitation must be twenty times greater than the critical Darcy flux (e.g., a minimum of 2000 mm/yr for the cases described above) for a significant temperature perturbation to occur. This indicates that groundwater flow may affect GST reconstructions in humid environments where rocks of at least moderate permeability occur. In areas where groundwater recharge is focused in depressions or high permeability zones, hydraulic conductivity criteria should be invoked to determine if GWF might be problematic.

[12] An examination of the hydrogeology of the area may reveal areas where Darcy fluxes are sufficiently high to warrant attention. This examination should focus on the geometry of any aquifers present and distribution of hydraulic conductivity. Using temperature profiles from different areas will help to address this issue. The magnitude and orientation of Darcy flux will differ with location in a

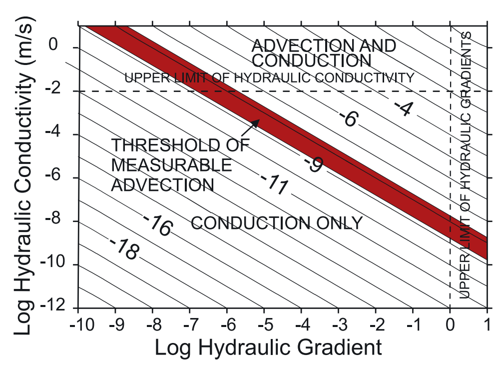

Figure 4. Range of hydraulic conductivities and hydraulic gradients where GWF induced GST history perturbations are possible is bound by the red zone indicating the range of minimum Darcy fluxes, the horizontal line indicating the upper limit of hydraulic conductivity and the vertical dashed line indicating the maximum possible hydraulic gradient. Contour labels indicate the log of Darcy flux. In this case, the red line represents models for 1000 m long basins with depths of 100 to 200 m.

given aquifer and this will effect the observed temperature perturbations at these locations. In aquifers with sufficiently high depth to length ratios, the majority of the central part of the model will be dominated by conduction and these will provide a basis for identifying profiles affected by GWF. In general, temperature profiles should be deep enough to encounter a conductive environment to assess the background heat flux [*Smith and Chapman*, 1983] and assess the nature of perturbations at shallower depths.

[13] Advection will only have a noticeable effect on GST reconstructions where there is a significant amount of precipitation (>2000 mm/yr), moderately permeable rocks ($K > 10^{-8}$ m/s) and aquifers with a high depth to length ratio. In the Canadian portion of the data set, these factors do not coincide in many locations. Most temperature profiles were measured in the Canadian Shield, where bulk permeability will be below the threshold value. In other regions, such as the Western Canada Sedimentary Basin, rocks may be permeable enough but precipitation values are quite low and in many areas soil moisture deficits exist. A study by *Majorowicz et al.* [2006] indicated that recharge rates, which are a small percentage of precipitation, were not sufficient to cause a noticeable effect on temperature profiles. Only in Western Canada does GWF have serious potential for disrupting GST reconstructions due to the presence of relatively permeable rocks and high precipitation values in some areas. However, there is no clear evidence that profiles from this area are affected by GWF. In suspect areas, a detailed analysis of precipitation records, drilling records and geological maps may be warranted. Our results indicate that it is unlikely that groundwater flow is a major concern in reconstructions of GST changes that utilize the IHFC global database [*Huang et al.*, 1999] or those that use a significant number of profiles from that database.

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