Impact of horizontal groundwater flow and localized deforestation on the development of shallow temperature anomalies

Victor Bense\textsuperscript{1} and Hugo Beltrami\textsuperscript{2}

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[1] In this paper we discuss temperature anomalies that develop in the shallow subsurface as a result of localized deforestation in combination with shallow horizontal groundwater flow. Model results show how a patch-wise pattern of deforestation at the surface induces significant lateral temperature gradients in the subsurface. Results also indicate that lateral heat transport by advection via horizontal groundwater flow becomes significant above flow rates of about \(10^{-8}\) m/s. In a steady state situation, reached 1750 a after deforestation, an anomaly of 0.1 K is still present at a distance of \(\sim 2.5\) km downstream of the deforested patch at depths between 200 and 575 m for horizontal groundwater flow velocities between \(10^{-7}\) m/s and \(10^{-8}\) m/s, respectively. We carried out transient simulations to examine the impact of deforestation on subsurface temperatures during the last century. These experiments include a study of the effects of regional surface warming on the thermal regime of the subsurface. In these scenarios, 100 a after localized deforestation, significant temperature anomalies occur hundreds of meters downstream of the deforested areas. Results show that ground surface temperature history reconstructions based upon synthetic temperature versus depth profiles up- and downstream of the deforested patches fail to recover the timing and magnitude of the warming event imposed at the surface. Results from our numerical simulations indicate that lateral heat flow effects should be considered when using subsurface thermal data for constraining land surface schemes in general circulation models.


1. Introduction

[2] The temperature distribution in the upper kilometer of the continental landmasses is in quasi-equilibrium and is determined by the long-term surface temperature and the heat flowing from the Earth’s interior. Under these conditions, subsurface temperature increases in a predictable way with depth. If the temperature at the Earth’s surface changes, a quantity of heat flows in or out of the ground in such a way that the continuity of heat flowing across the ground surface is maintained. These changes propagate into the ground and appear as perturbations to the quasi–steady state thermal regime of the subsurface. Analysis of these subsurface temperature anomalies allow borehole climatologists to reconstruct climate-induced ground surface temperature (GST) histories for the last millennium. Indeed, geothermal data have been widely used at local, regional and global scales to reconstruct past GST changes [Harris and Chapman, 1995, 2001; Pollack and Huang, 2000; Bodri et al., 2001; Beltrami, 2001; Beltrami and Boulron, 2004], to obtain ground surface heat flux histories, and to estimate the amount of heat absorbed by the ground over past centuries [Beltrami et al., 2002, 2006a]. Recent studies have further confirmed that GST, as recorded in the Earth’s thermal regime by conduction of heat, can be assumed to be closely coupled to surface air temperature (SAT) over periods of the order of centuries [Huang et al., 2000; González-Rouco et al., 2003, 2006; Beltrami et al., 2005] and decades [Marshall et al., 2006]. The robustness of borehole climatology has received increased attention in the light of several developments: (1) an eventual reconciliation of borehole and proxy paleoclimatic records for the last five centuries [Esper et al., 2002; Moberg et al., 2005; Harris and Chapman, 2005], (2) because borehole climatology provides an estimate for the magnitude of heat gained by the subsurface over past centuries which is difficult to obtain from meteorological data [Beltrami et al., 2002; Levitus et al., 2005], and (3) the important role this quantity may play when it is included in general circulation models (GCMs) for future climate projections [Beltrami et al., 2006a, 2006b; Smerdon and Stieglitz, 2006; Hansen et al.,...
2. Modeling Approach

2.1. Model Setup

[7] We use suites of two-dimensional cross-sectional models to illustrate the combined thermal effects of horizontal groundwater flow, and lateral variations in surface temperature. The equation for transient heat flow through conduction and advection as a result of horizontal groundwater flow is [Bredehoef and Papadopoulos, 1965]:

\[ c_b \rho_b \frac{\partial T}{\partial t} - \kappa \nabla^2 T + c_w \rho_w q_i \nabla T = 0 \]  

in which \( T \) [°C] is temperature, \( \kappa \) [W/m°C] is thermal conductivity, \( c_w \) [J/kg°C] is the specific heat of water, \( q_i \) [m/s] is the horizontal component of the Darcy velocity, \( \rho_w \) [kg/m³] is the density of water and \( c_b \) and \( \rho_b \) are the bulk specific heat and density of the aquifer. It is further assumed that the aquifer is fully saturated and that, hence, no unsaturated zone is present near the surface. This is likely to be a reasonable assumption for topographically flat areas with shallow groundwater tables. Equation (1) is solved using the generic finite element code FlexPDE (http://www.pdesolutions.com) that has been tested and applied in earlier studies to simulate combined heat and fluid flow [Bense and Kooi, 2004]. For the parameters summarized above, we use typical literature values [Stolk, 2000; Bense and Kooi, 2004] representative of sandy sediments. These are, \( \kappa = 2.5 \) [W/m°C], \( c_w = 4190 \) [J/kg°C], \( \rho_w = 1000 \) [kg/m³], \( c_b = 2013 \) [J/kg°C] and \( \rho_b = 2105 \) [kg/m³].

[8] Two patches (I and II) represent areas that are deforested (Figure 1). These patches are 300 m wide and are separated by 300 m. The left- and right-hand sides of the

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[5] Although clear-cutting is often followed by regrowth, in other locations deforestation has been permanent and was initiated centuries ago. However, while parts of Europe were deforested between 1000 and 1500 CE, most deforestation of the Amazonian rain forest is confined to the 20th century [Williams, 2000]. Under the conditions found in Europe and North America, a steady state temperature condition may have developed.

[6] In this paper, we first consider the characteristics of such steady state conditions for different regimes of horizontal groundwater flow. Then we evaluate the evolving temperature distribution within the shallow (<500 m) subsurface over the course of one century under the influence of localized land use changes in combination with horizontal groundwater flow. In addition to examining the temperature effects of deforestation within patches, we used numerical models to also examine the effects of a climate-driven surface temperature increase. These two scenarios of temperature changes at the surface are evaluated for three regimes of horizontal groundwater flow. We further tested how lateral groundwater flow in combination with patchy deforestation would impact ground surface temperature history (GSTH) reconstructions if temperature data from such areas were to be used to estimate recent climate changes.

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[4] Geothermal data collected at sites affected by deforestation or forest fires are usually discarded for paleoclimate analysis [Guillou-Frottier et al., 1998; Beltrami et al., 2003] since such surface events create transient and persistent energy imbalances at the air-ground interface [Geiger et al., 1995]. Post deforestation, more solar radiation reaches the ground surface. Since the decrease in evapotranspiration is not compensated by an increase in surface albedo, the ground gains energy increasing its surface temperature [Lean et al., 1996]. Observations show that the removal of vegetation results in a significant increase of surface temperature of the order of several degrees Celsius [e.g., Bond-Lamberty et al., 2005]. These effects can be traced back in borehole geothermal data [Lewis and Wang, 1998; Taniguchi et al., 1999b]. It has been shown that localized deforestation can lead to significant lateral conductive heat flow resulting in temperature anomalies away from the deforested area [Ferguson and Beltrami, 2006].
model domain are open for inflow and outflow of heat as controlled by the temperature at that boundary and the horizontal groundwater flux. Basal heat flow was set to zero to isolate the temperature anomalies resulting from the variations in surface temperature and groundwater flow [Lachenbruch and Vaughn Marshall, 1986]. For the steady state models we used a model domain of 4000 m long and 3000 m deep, and for the set of transient simulations in which a smaller spatial scale is considered, we used a domain of 2000 m long and 500 m deep. Results for the transient simulations are examined for $t = 100$ a.

2.2. Surface Temperature Scenarios

In the set of steady state models surface temperatures in the cleared patches were fixed at 2 K higher than in surrounding areas. These model results show the maximum subsurface temperature effect that can be expected from a permanently existing lateral temperature contrast at the surface as a result of variations in land use. We also estimated the time the system takes, after patch deforestation, to reach its steady state.

For the transient simulations, at the surface boundary in the model, the temperature effects of localized deforestation are conceptualized as follows: (1) inside area I and II, temperature increased stepwise by 2 K at $t = 0$ and (2) outside these patches the temperature is fixed at its initial value. This approach is assumed to realistically represent a localized clearing of vegetation when no significant regrowth of vegetation is occurring [Lewis and Wang, 1998]. A scenario like this is typical when forest is transformed into agricultural land.

For the transient models we consider two different scenarios. One set of numerical experiments was run considering only the temperature effect of the removal of vegetation (scenario 1). In a second set of simulations the additional effect of a regional increase in temperature due to a warming climate was included (scenario 2). This was done by adding a linear temperature increase of 1 K per 100 a over the entire surface boundary. As a result, in scenario 2 the total increase in temperature (after 100 a) in the clear-cut patches is 3 K, of which 2 K is imposed at $t = 0$ of the simulation, while outside of these areas the total increase is 1 K as gradually applied over the course of one century.

2.3. Horizontal Groundwater Flow

For the steady state models as well as for both surface temperature histories discussed above the impact of horizontal groundwater flow on the calculated temperature distributions is evaluated for three different magnitudes of horizontal groundwater flow. Groundwater flow is considered to be in a steady state, and flow velocity is independent of variations in fluid viscosity or density that might arise from temperature variations. Horizontal groundwater velocities are varied over a range of one order of magnitude between $10^{-8}$ and $10^{-7}$ m/s. We assume groundwater flow to be purely horizontal and to be directed from the left- to the right-hand side of the domain. These values for horizontal flow velocities are reasonable for relatively flat areas where a generic hydraulic gradient of $10^{-3}$ m/m is a good assumption [e.g., Bense et al., 2003]. For such a hydraulic gradient the variation in groundwater flow velocity used here corresponds to a variation in hydraulic conductivity between $10^{-5}$ and $10^{-4}$ m/s. Such values of hydraulic conductivity are typical for shallow sedimentary aquifers [Freeze and Cherry, 1979].

3. Simulation Results

3.1. Steady State Temperature Distributions

Simulated steady state temperature distributions are shown in Figure 2. In addition, temperature-depth profiles extracted from the right-hand side boundary of the model domain are shown in Figure 3. These plots show that with increasing horizontal groundwater flow the maximum tem-
temperature perturbation originating at the patches is found at more shallow depths. However, with increasing distance from the deforested areas the maximum temperature anomaly is found deeper. At a distance of \(~2.5\) km downstream of the edge of the deforested area, a maximum temperature anomaly of \(0.1\) K is found at depths of \(200\) and \(575\) m for horizontal groundwater flow velocities of \(10^{-7}\) m/s and \(10^{-8}\) m/s respectively.

One transient simulation was carried out, in which at the start of the simulation the temperatures in the cleared patch are stepwise increased by \(2\) K, for a horizontal groundwater flux of \(5 \cdot 10^{-8}\) m/s. This simulation was run until a steady state temperature distribution was reached. Profiles taken in this second model (Figure 3b) illustrate that it takes about \(1750\) a to reach a steady state after which the temperature distribution in the model is indistinguishable from steady state conditions.

Figure 2. Steady state temperature distributions considering elevated temperatures (+2 K) in two patches at the surface for three different values of horizontal groundwater flow.
3.2. Transient Temperature Patterns

[15] Figure 4 shows the transient temperature distributions considering the surface temperature scenario 1. The calculated temperature anomaly distributions are shown for \( t = 100 \) a. Figure 5 shows the distribution of temperature anomalies, also for the different regimes of groundwater flow, when surface temperature scenario 2 is considered. Next to the cross-sectional distributions of temperatures shown in Figures 4 and 5, three temperature-depth profiles (1–3; for location see Figure 1) were extracted from the calculated temperature fields. These profiles are shown in Figure 6 and Figure 7. Profiles 1 and 3 are located at a distance of 30 m respectively up- and downstream of the edge of patch I. Profile 2 is located in the middle of patch I.

[16] Comparison of Figures 4a–4c show that the 0.1 K isotherm is found at a similar depth of about 150 m for each groundwater flow regime. However, while for scenario 1 (Figure 4a) heat is still more or less equally distributed upstream and downstream (left and right respectively) of each cleared patch. For stronger groundwater flow there is progressively less excess heat present upstream of the patch (Figures 4b and 4c) as the temperature distribution becomes more asymmetric around each patch. This happens because heat is transported downstream of the patch by advection through groundwater movement. The plumes of anomalously warm groundwater that originate in the deforested areas are propagating downward as a result of heat conduction and migrate laterally by additional advection of heat through groundwater flow. The simulation results for scenario 2 (Figure 5) show how the subsurface temperature distribution is further affected when regional warming is superimposed on land use change induced local warming. The development of heat plumes as seen in scenario 1 (Figure 4) is not as striking. However, the impact of the various groundwater flow regimes is clearly reflected in the distribution of subsurface heat.

[17] For a horizontal groundwater flow velocity of \( 10^{-8} \) m/s (Figure 6a), and in the case when no regional surface warming is considered (scenario 1), profiles 1 and 3 show a maximum temperature anomaly around a depth of 38 m that has a value of about 0.12 K and 0.34 K respectively. For a larger value of horizontal groundwater of \( 5 \cdot 10^{-8} \) m/s (Figure 6b) the temperature anomaly in the upstream profile (dashed line) almost disappears while the downstream profile (3; grey line) now shows a temperature anomaly of 0.8 K at a depth of \( \sim 40 \) m. Interestingly, below a depth of 55 m the anomaly in the downstream profile is even larger than in profile 2 from the middle of the deforested patch. When the groundwater velocity increases to \( 10^{-7} \) m/s (Figure 6c), the patterns in the profiles change further. The maximum temperature anomaly in profile 3 is now almost 1 K and this maximum occurs at a shallower depth of around 30 m. Also, the temperature anomaly in profile 2 appears to propagate downward at a decreased rate for stronger groundwater flow. As a result, the temperature anomaly in the downstream profile is larger than in profile 2 starting at a more shallow depth (\( \sim 30 \) m). The profiles extracted from the last set of simulations (Figure 7), in which the signal of transient uniform warming at the surface was included (scenario 2), show similar characteristics as those for scenario 1. The patterns visible in the first simulations are partly overprinted in this scenario. For
example, for a groundwater flow velocity of $1 \times 10^{-8}$ m/s (Figure 7a), the shallow temperature anomaly that was visible in profile 1 and 3 (Figure 6a) is here dominated by the signal of regional surface warming (Figure 7a). However, for larger groundwater velocities, in profile 3, the temperature anomaly due to horizontal groundwater flow is too large to be fully overprinted by the signal of regional surface warming (Figures 7b and 7c).

### 3.3. Ground Surface Temperature History Reconstructions

[18] We used the synthetic temperature-depth profiles presented in Figures 6 and 7 to test how lateral groundwater flow in combination with patchy deforestation at the surface would impact ground surface temperature history (GSTH) reconstructions from borehole temperatures in areas where these processes play a role. Such reconstructions are usually carried out under the assumption that anomalies in the temperature-depth profile would be solely due to stepwise variations in surface temperature in combination with purely vertical conduction of heat. For this analysis we used a singular value decomposition algorithm using an eigenvalue cutoff of 0.025 and assuming a white noise of standard deviation of 20 mK in the temperature data. A detailed description of this procedure can be found elsewhere [Mareschal and Beltrami, 1992; Beltrami et al., 1997]. The GSTH model used here consists of a series of twenty 10-a duration step-wise temperature change model parameters.

[19] The resulting GSTH reconstructions are shown in Figures 8 (scenario 1) and 9 (scenario 2). The standard errors of the model parameters in these reconstructions are equal or smaller than $<0.06$ K and are not shown in the plots. In both scenarios, the inversion results for the profile (2) in the center of the cleared patch shows that the advective inflow of heat from the side dampens the downward propagation of the temperature anomaly. As a result, for an increasing groundwater flow, the apparent timing of the warming event at the surface would be interpreted to be

![Figure 4](image-url)
Figure 5. Modeling results for the second surface temperature boundary scenario discussed in the text. In this scenario, we apply, in addition to the initial step change in temperature in the deforested patches of 2 K, a linear increase in surface temperature of 0.01 K/a that is uniformly distributed along the surface (scenario 2). Model results are for $t = 100$ a.

Figure 6. Temperature-depth profiles for the modeling results presented in Figure 4. The locations of profiles 1 (dashed black line), 2 (black line), and 3 (shaded line) are indicated in Figure 1.
in the more recent past than actually happened. For example, in Figure 8b for a groundwater flow velocity of $10^{-7}\text{ m/s}$, it appears that a warming event happened at a progressively shorter time ago. In the profile downstream of the deforested patch (3; Figure 8c and Figure 9c) the enhanced transport of heat downstream due to groundwater flow results in a strong apparent recent warming event with a magnitude of several K while in fact at this location surface temperature never varied over time (scenario 1) or only experienced a gradual increase in temperature to 1 K during the last century (scenario 2). Upstream of the cleared patches apparent temperature anomalies as a result of lateral heat diffusion occur and could be misinterpreted as recent warming events at the surface with a range of timing and magnitudes that are a function of horizontal groundwater flow.

4. Discussion and Conclusion

The results of the models presented above show the development of anomalously warm heat plumes that slowly penetrate the subsurface from areas that have experienced a recent increase in surface temperature, representing the effects of deforestation. Under conditions of sufficient horizontal groundwater flow (stronger than $10^{-8}\text{ m/s}$), these warm plumes become significantly asymmetric around the source area. As a result, one-dimensional analysis of temperature-depth data from both sides of one of the deforested areas is no longer in agreement with the magnitude and timing of recent surface warming (Figure 8 and Figure 9), although both localities experienced the same history of surface temperature change. We also showed the complex thermal patterns that arise when the temperature signal of localized changes in land use is considered in combination with a regional increase in surface temperature (Figure 5). As shown in field data [Taniguchi et al., 1999a; Ferguson and Woodbury, 2004; Bense and Kooi, 2004] the regional climate signal uniformly overprints local temperature signals, and so dampens temperature anomalies resulting from land use changes and groundwater flow (Figure 7).

As a result of lateral heat flow by advection, and 100 a after land clearing, the temperature perturbations can extend several hundreds of meters away from the deforested area (Figures 4b and 4c). If heat transport is purely conductive, [Ferguson and Beltrami, 2006] estimated that the maximum extent of such an anomaly would only be around 50 meters. The model results presented here show that under conditions of horizontal groundwater flow velocity larger than $10^{-8}\text{ m/s}$ this distance extends to several hundreds of meters downstream of the deforested area. When steady state conditions are simulated, model results indicate that a steady state condition is reached in about

**Figure 7.** Temperature-depth profiles for the modeling results presented in Figure 5. The locations of profiles 1 (dashed black line), 2 (black line), and 3 (shaded line) are indicated in Figure 1.

**Figure 8.** GSTH reconstructions for the synthetic temperature-depth profiles obtained at locations (a) 1, (b) 2, and (c) 3 considered for different magnitudes of horizontal groundwater flow for scenario 1. The standard errors of the model parameters in these reconstructions are equal to or smaller than $\sim0.06\text{ K}$ and are not shown in the plots.
1750 a after deforestation, and that several kilometers downstream from the deforested area temperature anomalies as high as 0.1 K occur at depths between 275 and 500 meters depending on the magnitude of the horizontal groundwater flow. Such anomalies could be interpreted as past warming events in GSTH reconstructions. Although, the models we present here are highly simplified (e.g., uniform, purely horizontal, time-invariant groundwater flow and homogeneous physical properties of the subsurface), for the evaluation of subsurface temperature data they nevertheless give insight to the possible nature of temperature anomalies in the subsurface. The characteristics of the patterns shown in the models may be present in subsurface temperature distributions found globally. However, more complex models would further consider the effects of a full or partial regrowth of vegetation after forest clearing (e.g., Nitoiu and Beltrami, 2005), the effect of vertical components of groundwater flow, lithological heterogeneity in the subsurface that impacts both flow and thermal properties (e.g., Smith and Chapman, 1983), and the effects of varying the width of the deforested areas (e.g., Ferguson and Beltrami, 2006). Based upon the results of such sensitivity studies, isolating the individual contributions of these temperature signals in field data sets may be possible if a number of these signals are independently constrained from, for example by meteorological records, historical land use maps or proxy data.

[22] There will be many sedimentary aquifer systems to which the situation will apply as described in this paper, with sufficient horizontal groundwater flow near the surface and recent land use changes. Such areas are usually also far more densely instrumented with observation wells, for example in the Netherlands (e.g., Van Dalfsen, 1983), than remote areas where groundwater flow will be minimal and significant land use changes might not have occurred over the last centuries. The latter type of study area is typically the one for which regional scale climate reconstructions using borehole data have been carried out, for example the Canadian Shield [Beltrami et al., 2003]. Nevertheless, shallow groundwater observation wells (up to several hundreds of meters deep) are well suited to complement geothermal measurements (e.g., Van Dalfsen, 1983; Bense and Kooi, 2004; Bodri and Cermak, 2005) and potentially yield a wealth of data on the temperature effects of land use changes, urbanization (as a special category of land use change), regional climate change and the spatial variability and timing of those processes.

[23] The analysis presented in this paper shows that horizontal heat transport by groundwater flow is especially important for the understanding of the shallow geothermal regime in areas where land use changes have occurred. The model results show that a simple one-dimensional analysis of data taken in a system such as modeled here will not suffice to reconstruct a realistic local surface temperature history at the location of a single borehole. Hence shallow horizontal groundwater flow has the potential to considerably complicate the interpretation of the shallow thermal regime for recent changes in land use and climate. A more extensive sensitivity analysis than carried out here would be needed to further improve the understanding of shallow thermal data for these effects. Such studies will contribute momentum in proceeding toward developing methodologies to include more geothermal data sets in climate change studies.

[24] The model results discussed above illustrate how the thermodynamics in the shallow thermal regime can vary as a function of horizontal groundwater flow and the heterogeneity of land use changes. Hence, where these processes are occurring, they play a role in controlling where and how quickly heat is stored in the subsurface during and after periods of land use change and/or regional surface warming. The thermal effects of horizontal groundwater flow and localized land use changes may be an important consideration when shallow thermal data, from an increasing number of localities, is used to test the performance of soil model components of GCMs to estimate the near-surface heat budget of the Earth’s continents [González-Rouco et al., 2006; Stevens et al., 2007].

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References


