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Transient lateral heat flow due to land-use changes

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Abstract

Subsurface temperatures have been shown to be useful for obtaining robust reconstructions of climatic changes for the last five centuries. Recently, interest has focused on determining the effects of land-use changes on ground surface temperatures (GST), which could potentially create a bias on these records and should thus be considered in the interpretation of GST reconstructions. To date, studies have focused on the one-dimensional effect of land-use changes on heat flow. In this study, temperature anomalies resulting from lateral heat flow were assessed for different scales of land-use change. Numerical simulations indicate that land-use changes over large areas may cause significant changes in subsurface temperatures reaching beyond the extent of the affected area at the surface. We provide guidelines for future surveys and for correcting existing data.

Keywords: ground temperature; borehole temperatures; ground warming; land-use change

1. Introduction

Over the past two decades, analysis of temperature profiles measured in boreholes has become an accepted method of reconstructing past climate changes [1,2]. However, discrepancies between proxy constructions [3–8] have stimulated the examination of the processes that affect ground surface temperature (GST)–surface air temperature (SAT) coupling over long time scales. Recent works [9,10,2] have confirmed that borehole temperatures are robust indicators of past climate, such that general circulation modellers are beginning to explore borehole temperature data as a possible source of information for the validation of the long-term behaviour of general circulation models (GCMs) [11].

Borehole data provide a ground surface temperature (GST) history, which reflects the changes in the energy balance at the Earth's surface, rather than a measure of the surface air temperature (SAT) and subsurface temperatures may be a result of factors other than climate. Comparing GST and SAT may be problematic in cases where land-use changes have occurred as they can alter the surface energy balance. Numerous studies have measured an increase in subsurface temperatures following deforestation [12–16]. This occurs for a number of reasons: changes in albedo; changes in evapotranspiration; and changes in the thickness of the forest floor organic matter layer [17,18]. A first attempt to model and correct for these changes was presented by [19], who assumed a step change in temperature to attempt to explain the subsurface warming found in several boreholes in a deforested area of British Columbia, Canada.

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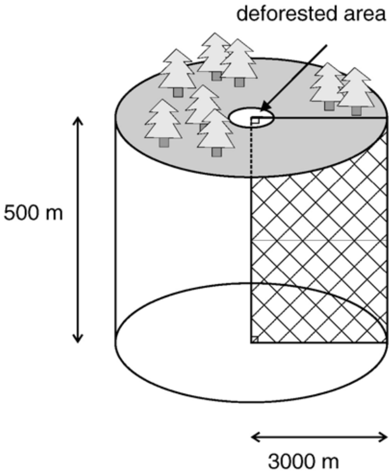

Fig. 1. Dimensions of region modeled. Small circle in center represents deforested area and has radii of 10, 50 and 250 m in the various models conducted in this study.

However, in many cases the GST response to a deforestation cannot be described adequately by a step change due to the gradual regrowth of the organic matter layer as vegetation recovers. Nitoiu and Beltrami [2005] presented a more detailed empirical method that allows for separation of changes in temperature, due to variations in climate from those that occur due to changes in the litter layer of the forest floor as well as associated energy balance rearrangement at the surface. Both of these analyses assumed one-dimensional heat flow while neglecting the effects of lateral heat flow; such effects have been shown to occur in urban environments [20] and due to topography [21].

In the current study, the lateral extent of the temperature anomaly resulting from deforestation was analyzed using numerical models. These numerical simulations serve as a basis for possible corrections to measured temperature profiles, prior to GST reconstruction, and will also provide guidelines for future temperature profile surveys by providing estimates of temperature changes due to lateral heat flow.

2. Analysis

To analyze the lateral effects of deforestation on subsurface temperatures, a series of finite difference conductive heat flow models were created. The finite difference equation used in these models is a solution of the differential equation describing conductive flow of heat in a solid [22]:

$$\frac{c\rho}{\lambda}\frac{\partial T}{\partial t} = \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial z^2}, \tag{1}$$

where T is temperature, c is specific heat capacity, ρ is density, and λ is thermal conductivity. These models were constructed for a region 500 m deep and 6000 m across (Fig. 1). Changes in surface cover for areas 20, 100, and 500 m in width were examined, which approximately correspond to forest clearing for access by a drill rig, a small clearcut and a larger clearcut typical of those found in commercially logged areas of Canada. The cells of the finite difference models were 1 m across vertically and had widths ranging from 1 m in the vicinity of the transition between clearcut and unaffected area to 200 m across near the outer edge of the model. Time steps were determined automatically in the model and ranged from under 1 s at the start of the model to several years near the end of the 100 year modeled period. In maintaining convention in borehole climatology, only deviations in temperature were examined and the background geothermal gradient was neglected [23]. A reference temperature was assigned to the entire problem domain. The lateral boundaries were assigned zero heat flux boundary conditions and the upper and lower boundaries were assigned fixed temperatures equal to the reference temperature. A thermal diffusivity of 1.0×10^{-6} m^2 s^{-1} and a thermal conductivity of 3.0 W m^{-1} K^{-1} were used, both of which are typical of geological materials [24].

After the deforestation, the upper boundary condition of the deforested area was assigned a temperature corresponding to a step increase in temperature, as suggested by [19] in the first set of models (Fig. 2). In the second set of models, a temperature increase corresponding to the curve given by [16] (hereafter referred to as the NB model) was assigned to the

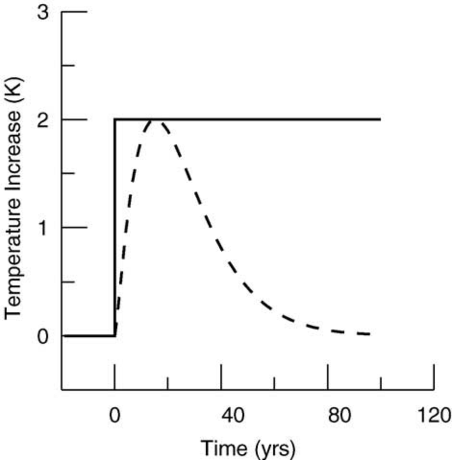

Fig. 2. Ground surface temperature forcing used in numerical models with time in years after deforestation. Solid line represents step function and dashed line represents the model of [16].

upper boundary. The NB model is based on field data as well as changes in the forest floor organic matter layer [25] which serves as a proxy to emulate the rearrangement in the surface energy balance that follows deforestation. This energy rearrangement is the result of an increase in albedo and decrease in evapotranspiration that leads to a net increase in the amount of energy absorbed by the ground in the years immediately following deforestation. As the forest regenerates and recovers to its original state, the ground surface temperature returns to its initial value [16]. In both sets of models, a maximum increase in GST of 2.0 K above the reference was used. This is consistent with observed temperature difference between forest and grassland [15].

The transient temperature anomalies, resulting from land-use changes modeled in a step increase in ground surface temperature, are predicted to extend beyond the affected area at the surface (Fig. 3). For a step function change of 2 K over an area 20 m in width, the 0.1 K isotherm, extends only 10 m beyond the edge of the affected area and penetrates less than 30 m. The anomaly approaches a near equilibrium state after only 20 years. The same change in GST over an area with a diameter of 100 m affects the subsurface 30 m beyond the edge of the affected area at the surface after 20 years. As the anomaly continues to grow, it will extend nearly 50 m beyond the edge of the deforested area after a century. Similar trends are observed for a change in GST over an area with a width of 500 m, where the thermal anomaly in the subsurface is predicted to extend beyond the surface-anomaly laterally by 70 m after 100 years.

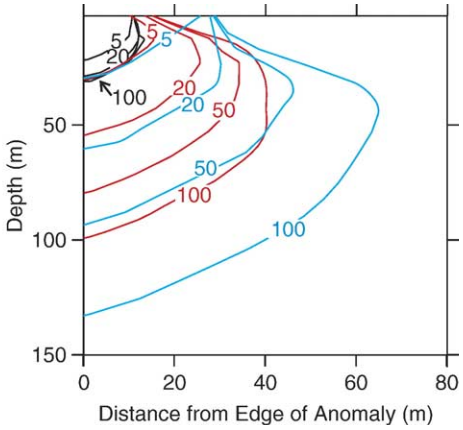

Fig. 3. Position of 0.1 K isotherm for of temperature anomaly for 2 K step function boundary condition resulting from land surface changes of 20 (black line), 100 (red line) and 500 (blue line) m widths. Contour labels indicate time in years after deforestation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

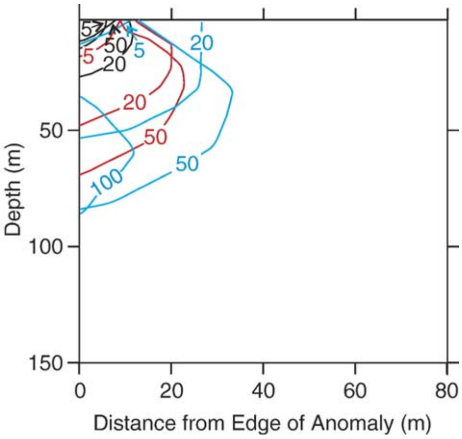

Fig. 4. Position of 0.1 K isotherm for of temperature anomaly for 2 K based on the GST boundary condition described by the NB model resulting from land surface changes of (black line), 100 (red line) and 500 (blue line) m widths. Contour labels indicate time in years after deforestation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The NB model predicts smaller anomalies than those obtained using the step change model and are of shorter duration (Fig. 4). For a change in GST over an area with a width of 20 m, subsurface temperature anomaly, as defined by the 0.1 K isotherm is approximately extends 10 m beyond the edge of the deforested area after 20 years. A much smaller anomaly is predicted after 50 years and the maximum temperature change after 100 years is less than 0.1 K. When the same transient change in GST is applied to an area with a width of

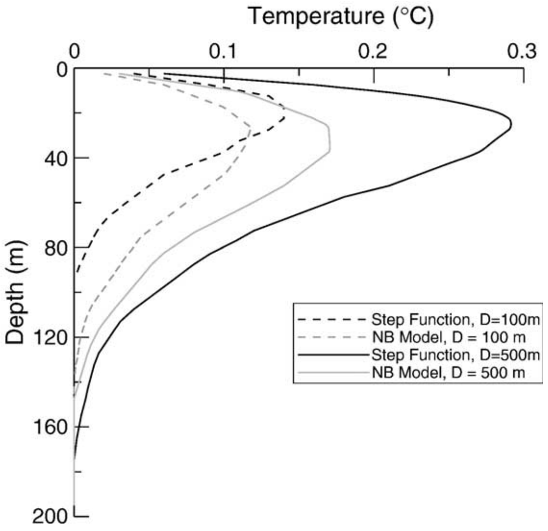

Fig. 5. Temperature profiles for a position 20 m outside the edge of the affected area at the surface 50 years after deforestation.

100 m, the maximum extent of the subsurface temperature anomaly is approximately 20 m beyond the edge of the deforested area and occurs after 20 years. The predicted anomaly at 50 years is of similar width but penetrates about 20 m further into the subsurface; in this instance, the anomaly is of insignificant magnitude after 100 years. If the same GST forcing is applied to an area with a width of 500 m, the subsurface anomaly attains a maximum extent that reaches approximately 30 m beyond the edge of the deforested area between 20 and 50 years. A thermal anomaly, defined by an increase of 0.1 K extending approximately 10 m beyond the deforested area is predicted to occur after 100 years, with the maximum temperatures occurring at approximately 60 m below ground surface.

Temperature profiles 20 m outside the edge of the disturbed area at the surface were modeled 50 years after the change in land-use occurred (Fig. 5). At this time, the maximum temperature anomalies for a 500 m width change in surface cover are approximately 0.3 and 0.17 K for the step GST change and NB model, respectively. For a 100 m width change in surface cover, a maximum subsurface temperature anomaly of 0.14 K occurs for a step change in temperature and a 0.11 K maximum subsurface temperature anomaly occurs if a GST anomaly following the NB model occurs. These maxima occur between 20 and 40 m depths at this time, and temperatures decrease sharply both above and below this region of the temperature profile.

3. Discussion and conclusions

The results of this study emphasize the importance of considering the effect of land-use changes on the transient portion of subsurface temperature profiles. Although this study examines the input in isolation, forest harvesting usually takes place within a larger area with a complex history. Harvesting will have occurred at various times by various techniques in this larger area and at any given time there will be varying degrees of recovery in different areas of the forest. The cases examined in this study only considered changes in land-use that will cause a rise in GST, but it is also possible for land-use changes could to a decrease in GST. This has occurred in many areas of North America over the past century where subsistence farming has been discontinued and agricultural land has been replaced by forest. GST reconstructions from temperatures profiles measured in these areas will display an apparent cooling and will to some extent balance bias introduced by analysis of profiles measured in recently deforested areas. However, there is insufficient information on temperature profile locations in the International Heat Flow Commission Database to comment on how this may bias estimates of climate change.

The shape of the temperature profile, predicted in areas adjacent to regions subjected to land-use changes indicates, that warming occurs at depths of 20 to 100 m, which is the depth range affected by variations in GST due to climate over the past century. This anomaly is expected to grow unrealistically over time in the case of a step function because empirical evidence indicates that the GST anomaly becomes negligible after only a few decades. This implies that the NB model is more realistic. Intermediate results are also possible if the forest does not recover to its original state [16]. The results of this study indicate that the thermal effects of land-use changes over moderately large areas will only extend approximately 50 m beyond the affected area at the surface. The lateral extent of the anomaly increases at an approximately exponential rate proportional to the size of the disturbance (a linear superposition of two complimentary error functions) [26]. The temperature gradient reversal, observed in the upper few metres in Fig. 5, would not be observed in most measured temperature profiles because in the majority of areas these temperatures will occur in the unsaturated zone, where temperature measurements are rarely made due to problems of thermal stability. Our results may enable analysis of temperature profiles which were thought to be too close to the areas affected by land-use changes. Also, the results may allow for measurement of boreholes not visited because of suspected contamination. It may also be possible to account for changes in subsurface temperature prior to inversion of the temperature profile by constructing a numerical model to assess the effect of the lateral heat flow from a change in land-use on a temperature profile. A correction can then be applied to the profile prior to inverting the data to retrieve past GST changes. However, this correction requires that there is some knowledge of previous land-use changes; and until there is a more complete understanding of the relationship between land-use changes and subsurface temperature, this correction will only be an approximation. These results also provide guidelines that can be used in future surveys of subsurface temperatures. In general for anomalies with a width of 20 m, there will be no measurable effect on subsurfaces temperatures for either model examined in this study. For a 100 m width anomaly, measurements should be made at least 40 and 20 m from the anomaly for a step change in GST and NB model, respectively. For anomalies with widths of 500 m, temperature measurements should be made at least 60 m from the edge of the anomaly if GST undergoes a step change, and at least 30 m away if the GST follows the NB model.

An alternative method of analyzing climatic change from underground temperatures is to examine the amount of heat contained in the subsurface [27]. The total heat anomaly imprinted on the ground by these models is different. The total heat associated with each model can be estimated as

$$Q \propto \int_{t=0}^{t} T(t)\mathrm{d}t, \qquad (2)$$

where Q is heat. In addition, the heat is proportional to the area under the curve of each model in Fig. 1. Clearly, the differences in ground heat are time dependent and response of GST following changes in land-use will have an effect on the amount of energy contained in the subsurface, which is known to have increased over the past century [28]. Separating land-use change contributions to the increase in subsurface heat from that due to climate change will require that one chooses the appropriate model. However, at this point it is not known whether land-use changes are responsible for a significant amount of this recent increase in heat contained within the continental crust.

Understanding the extent of lateral subsurface heat flow associated with land-use changes may also have applications to spatial studies of GST variations [7,29]. The results of this study indicate that changes in GST associated with land-use changes found in previous studies could be important. To date, there have been no studies that have rigorously addressed the effect of land-use on GST on a regional basis. Such a study may provide valuable insight into correlations between GST reconstructions, other proxies and the results of GCMs.

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References

[1] H. Beltrami, R.N. Harris (Eds.), Inference of Climate Change from Geothermal Data, Glob. Planet. Change, vol. 29, 2001. pp. 148–352.

[2] H. Beltrami, G. Ferguson, R. Harris, Long-term tracking of cliamte change by underground temperatures, Geophys. Res. Lett. 32 (2005), doi:10.1029/2005GL023714.

[3] M.E. Mann, A.G. Schmidt, Ground vs. surface air temperature trends: implications for borehole surface temperature reconstructions, Geophys. Res. Lett. 30 (12) (2003) 1607, doi:10.1029/2003GL017170.

[4] M.E. Mann, S. Rutherford, R.S. Bradley, M.K. Hughes, F.T. Keim-ing, Optimal surface temperature reconstructions using terrestrial borehole data, J. Geophys. Res. 108 (2003), doi:10.1029/202JD002532.

[5] D.S. Chapman, M.G. Bartlett, R.N. Harris, Comment on 'ground vs. surface air temperature trends: implications for borehole surface temperature reconstructions' by M. E. Mann and G. Schmidt, Geophys. Res. Lett. 31 (2004) L07205, doi:10.1029/2003GL019054.

[6] P.D. Jones, M. Mann, Climate over past millennia, Rev. Geophys. 42 (1–42) (2004) RG2002, doi:10.1029/2003RG000143.

[7] H.N. Pollack, J.E. Smerdon, Borehole climate reconstructions: spatial structure and hemispheric averages, J. Geophys. Res. 109 (2004) D11106, doi:10.1029/2003JD004.

[8] G.A. Schmidt, M.E. Mann, Reply to comment on 'ground vs. surface air temperature trends: implications for borehole surface temperature reconstructions' by M. E. Mann and G. Schmidt, Geophys. Res. Lett. 31 (2004) L07206, doi:10.1029/2003GL019144.

[9] J. Esper, E.R. Cook, F.H. Schweingruber, Low-frequency signals in long tree-ring chronologies for reconstructing past temperature variability, Science 295 (2002) 2250–2253.

[10] A. Moberg, D.M. Sonechkin, K. Holmgren, N.M. Datsenko, W. Karlen, Highly variable Northern Hemisphere temperatures reconstructed from low-and high-resolution proxy data, Nature 433 (2005) 613–617.

[11] H. Beltrami, E. Zorita, J.F. Gonzalez-Rouco, H. von Storch, Comparison of last millenium global climate model simulations and borehole temperatures, Geophys. Res. Abstr. 7 (2005) 08750.

[12] G.G. Murtha, J. Williams, Measurement, prediction and interpolation of soil temperature for use in soil taxonomy: tropical Australian experience, Geoderma 37 (1986) 189–206.

[13] V. Cermak, L. Bodri, J. Safanda, Recent climate change recorded in the underground: evidence from Cuba, Glob. Planet. Change 98 (1992) 219–223.

[14] J. Majorowicz, W. Skinner, Potential causes of differences between ground and surface air temperature warming across different ecozones in Alberata, Canada, Glob. Planet. Change 15 (1997) 79–91.

[15] H. Beltrami, L. Kellman, An examination of short-and long-term air-ground temperature coupling, Glob. Planet. Change 98 (2003) 167–184.

[16] D. Nitoiu, H. Beltrami, Subsurface thermal effects of land use changes, J. Geophys. Res. 110 (2005), doi:10.1029/2004/JF000151.

[17] J. Lean, C.B. Bunton, C.A. Nobre, P.R. Rowntree, The simulated impact of Amazonian deforestation on climate using measured ABRACOS vegetation characteristics, in: J.H.C. Gash, C.A. Nobre, J.M. Roberts, R.L. Victoria (Eds.), Amazonian Deforestation and Climate, Wiley, New York, 1996, pp. 549–576.

[18] J. Ogée, Y. Brunet, A forest floor model for heat and moisture including a litter layer, J. Hydrol. 255 (2002) 212–233.

[19] T. Lewis, K. Wang, Geothermal evidence of deforestation-induced warming: implications for the climatic impact of land development, Geophys. Res. Lett. 25 (1998) 535–538.

[20] G. Ferguson, A.D. Woodbury, Subsurface heat flow in an urban environment, J. Geophys. Res. 109 (2004) B02402, doi:10.1029/2003JB002715.

[21] T. Kohl, Transient thermal effects below complex topographies, Tectonophysics 306 (1999) 311 – 324.

[22] H.S. Carslaw, J.C. Jaeger, Conduction of Heat in Solids, 2nd ed., 1959. 510 pp.

[23] A. Lachenbruch, B.V. Marshall, Changing climate: geothermal evidence from Permafrost Areas of Alaska, Science 234 (1986) 689 – 696.

[24] V., Cermak, L. Rybach, Thermal conducitiy and specific heat of minerals and rocks, in Landolt-Bornstein: Zahlenwerte und Fuktionen aus Naturwissenschaften und Technik. (Hrsg): Bd. 1, Physikalische Eisgen-schaften der Gesteine, Teibd. a., in: G. Angenheister. Spring-Verlag, Berlin, Heidelberg, New York, 1982, pp. 305–343.

[25] W.W. Covington, Changes in forest floor organic matter and nutrient content following clear cutting in northern hardwoods, Ecology 62 (1981) 41 – 48.

[26] A.H. Lachenbruch, Three-dimensional heat conduction in permafrost beneath heated buildings, U.S. Geol. Surv. Bull. 1052-B (1957) 51 – 69.

[27] H. Beltrami, Surface heat flux histories from inversion of geothermal data: energy balance at the earth surface, J. Geophys. Res. 106 (2001) 21,979 – 21,994.

[28] H. Beltrami, J.E. Smerdon, H.N. Pollack, S. Huang, Continental heat gain in the global climate system, Geophys. Res. Lett. 29 (2002), doi:10.1029/2001GRL014310.

[29] H. Beltrami, E. Bourlon, Ground warming patterns in the northern hemisphere during the last five centuries, Earth Planet. Res. Lett. 227 (2004) 169 – 177.