

The Role of Subsurface Heat Storage in Climate Model Simulations

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Abstract:

Analysis of geothermal data reveals that all continental areas have absorbed large quantities of energy in the recent past. The total heat absorbed by the Northern Hemisphere's land surface is 4.8×10^{21} J and 13.3×10^{21} J for the last 50 and 200 years, respectively. Such large heat gains suggest that the continental subsurface is an important component of the global energy budget and should be adequately resolved in long-term climate simulations. Here we examine how simulations of subsurface heat storage are impacted by the bottom boundary condition placement in land-surface models. We find that the placement of the bottom boundary has effects as large as the total heat absorbed by each of the atmosphere and continental areas in the last 50 years. Results show that climate models should take subsurface thermodynamics into account whenever performing paleoclimatic simulations or projection estimates of future climate change.

Introduction:

Recent analyses indicate that the continents and atmosphere have absorbed a commensurate amount of energy in the latter half of the 20th century, [Levitus et al., 2005, Beltrami et al., 2006], each gaining approximately $7.0 - 9.0 \times 10^{21}$ J. These estimates underscore the importance of heat stored in the terrestrial subsurface as a component in the global energy budget [Seneviratne et al., 2006]. It is therefore essential to include a realistic representation of subsurface heat storage in state-of-the-art General Circulation Models (GCMs). Failure to do so may displace a large quantity of heat in the global energy budget that could be allocated to other climate system components, rather than being stored in the subsurface. Robust representations of the physical processes at and below the land surface are therefore important components of GCMs, and validation of these representations is an ongoing and significant area of research.

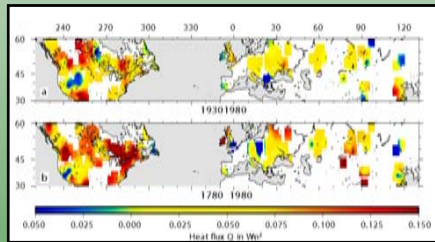


Figure 1. Spatial variation of the estimated ground surface heat flux from subsurface temperatures. a) Surface heat flux history for the 1930 to 1980 period. b) Cumulative ground heat flux for a 200 year period from 1780 until 1980. This time interval would include most of the time since industrialization. From Beltrami et al., 2006.

One current shortcoming of land-surface representations in GCMs involves the bottom boundary condition placement (BBCP) of the subsurface model layer. The location of this boundary must be set deep enough to avoid significantly perturbing subsurface thermodynamics. Given that the BBCP in most GCMs is between 3 and 10m the recent results suggest that the behavior of subsurface temperature fields in climate change scenarios are likely corrupted [Smerdon and Stieglitz, 2006].

Here we are principally concerned with how the BBCP affects the capacity of the subsurface to store heat. We carry out several experiments to test the sensitivity of subsurface heat storage to BBCP. For this purpose, a one-dimensional soil model (1DSM) was used to complete two experiments, each differing in surface boundary conditions, and consisting of multiple runs. The first experiment employs a synthetic, step-change in surface temperature, such that the resulting subsurface thermal profile can be checked analytically.

Since this boundary condition is a simple representation of past climate, a second experiment was conducted using the millennial output from a GCM as the surface boundary condition. Results show that the amount of heat storage calculated in the subsurface models of GCMs used in future scenario projections are likely compromised by shallow BBCP

Synthetic Experiment:

Synthetic surface temperature step-change experiments were performed using our 1DSM to estimate heat storage dependency on the BBCP. Five sets of 1000 simulations were conducted with no changes in the upper boundary condition; each set differed only in run duration, from 100 to 500 years in increments of 100 years. The 1000 simulations in each set imposed increasingly shallow BBCP from 1000m to 1m in intervals of 1m. For each run, the variation in temperature as BBCP increases arises because the subsurface thermal field must satisfy both top and bottom boundary conditions, and becomes skewed when the bottom boundary is too shallow.

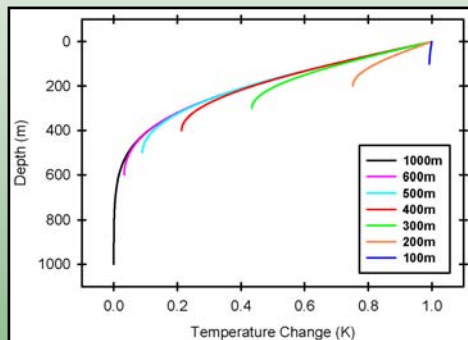


Figure 2. Temperature-depth profiles resulting from different placement of the bottom boundary after 500 years of simulation. As the BBCP becomes shallower, the thermal profile becomes increasingly warm.

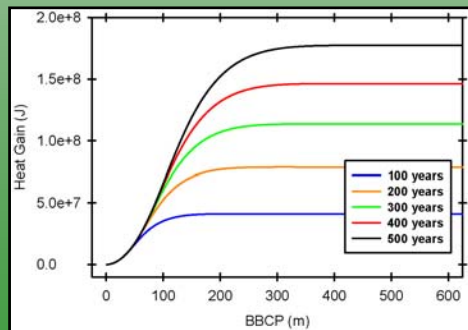


Figure 3. Total heat gain since spin-up as a function of BBCP for synthetic examples. Each point on the curves represents the total heat gained by the subsurface for a given run duration and BBCP. These curves each approach an asymptotic value as a function of BBCP; this outlines the region of non-interference by the bottom boundary on subsurface thermodynamics.

Experiment with GCM projections

In order to examine the possible consequences of misplacing the bottom boundary condition in models used to project future changes in climate, we used the Northern Hemispheric output from the ECHO-g model; specifically the A2 and B2 IPCC scenarios. We initialized the experiment with the ECHO-g 1000-year paleoclimatic simulation acting as the spin-up run from 1000 to 1990 CE.

This paleoclimatic simulation was used as the upper boundary condition, the bottom boundary was set at a depth of 1000m, and the spin-up was initialized with a constant thermal profile. Application of the paleoclimatic simulation to our 1DSM yields the temperature-depth profile that was used as the initial condition and reference state for all the future climate experiments. The inset plot in Fig. 4 shows the annual temperature for the millennial ECHO-g paleoclimatic simulation and the future temperature projections under scenarios A2 and B2 used in this experiment.

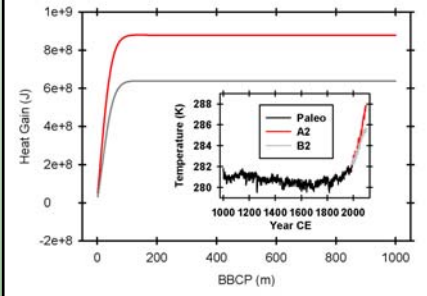


Figure 4. Each point on these curves represents the total amount of heat gained by the subsurface as a function of BBCP from 1990 to 2100 CE for both the A2 and B2 IPCC scenarios. For shallow BBCP, soil models will underestimate the amount of heat being stored in the ground. Inset: ECHO-g annual land-surface temperature time series from the millennial paleoclimatic simulation and A2 and B2 scenario future projections for the Northern Hemisphere.

As a guideline, Fig. 4 shows the total heat absorbed by the ground in the 1DSM between 1991 and 2100 CE for the ECHO-g A2 and B2 scenario simulations as a function of BBCP. Because of the duration of the A2 and B2 projections, the effects penetrate to less than 200m. In this case, a BBCP greater than 200m would be sufficient to correctly estimate the ground heat content in response to the A2 and B2 simulations.

Fig. 4 depicts the results for 1000 simulations of the 1DSM for each scenario, and is the analogue of Fig. 2 in the synthetic case. As the simulation depth in the 1DSM increases, so too does the potential for subsurface heat storage. For example, for a BBCP at a depth of 10m, the total heat stored in the subsurface (1.9×10^{23} J) will be less than one-quarter of the asymptotic value (8.8×10^{23} J) (see Fig. 5). If scaled over the entire continental surface (1.5×10^{14} m²), such underestimation would result in a displacement of 1.0×10^{23} J, or 75% of the corresponding asymptotic value (1.3×10^{23} J). This heat, absorbed over 110 years, is more than an order of magnitude greater than the heat absorbed by both the whole atmosphere and continental areas in the latter half of the 20th century [Levitus et al., 2005, Beltrami et al., 2006].

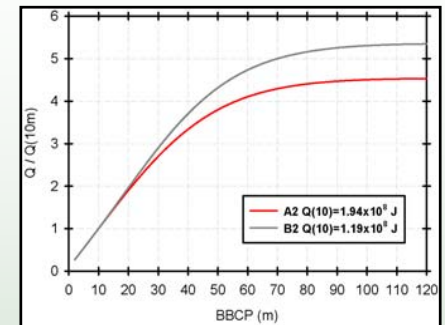


Figure 5. Shown are the same results as in Fig. 3, but expressed as a ratio of the heat gained for a BBCP at 10m, as in ECHO-g. These curves show the ratio of total heat gain with BBCP set at z meters compared to a BBCP set at 10m. Existing GCMs have BBCPs imposed between 3 and 10m.

Discussion and Conclusions:

We have shown that the bottom boundary placement is important when modeling subsurface heat storage. Improper placement of the bottom boundary in soil models could lead to energy discrepancies in subsurface heat storage of more than an order of magnitude greater than the heat absorbed by the atmosphere or by the continental areas in the last 50 years. In light of our findings, we suggest that GCMs' future climate change predictions should use realistic BBCP to estimate the changes in subsurface heat storage. Otherwise, a quantity of heat that is one order of magnitude greater than that absorbed by the atmosphere may remain displaced in the global energy balance, at the risk of making additional energy available to other climatic components, rather than being stored in the subsurface.

It is unclear, however, how the demonstrated effects will influence a coupled model with many other confounding influences. Nevertheless, the demonstrated effects warrant further investigation.

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