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Effects of bottom boundary placement on subsurface heat storage: Implications for climate model simulations

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[1] A one-dimensional soil model is used to estimate the influence of the position of the bottom boundary condition on heat storage calculations in land-surface components of General Circulation Models (GCMs). It is shown that shallow boundary conditions reduce the capacity of the global continental subsurface to store heat by as much as 1.0×10^{23} Joules during a 110-year simulation with a 10 m bottom boundary. The calculations are relevant for GCM projections that employ land-surface components with shallow bottom boundary conditions, typically ranging between 3 to 10 m. These shallow boundary conditions preclude a large amount of heat from being stored in the terrestrial subsurface, possibly allocating heat to other parts of the simulated climate system. The results show that climate models of any complexity should consider the potential for subsurface heat storage whenever choosing a bottom boundary condition in simulations of future climate change. **Citation:** Stevens, M. B., J. E. Smerdon, J. F. González-Rouco, M. Stieglitz, and H. Beltrami (2007), Effects of bottom boundary placement on subsurface heat storage: Implications for climate model simulations, *Geophys. Res. Lett.*, *34*, L02702, doi:10.1029/2006GL028546.

1. Introduction

[2] Recent analyses indicate that the continents and atmosphere have absorbed a commensurate amount of energy in the latter half of the 20th century [*Beltrami et al.*, 2002; *Beltrami*, 2002; *Levitus et al.*, 2005; *Beltrami et al.*, 2006a; *Huang*, 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 therefore is 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.

[3] Calculations of terrestrial heat flux and thermodynamics in GCMs are performed by the land-surface component within the GCM structure. This component is important for numerous reasons, including the determination of water and energy fluxes at the land-surface boundary [e.g., *Henderson-Sellers and Hopkins*, 1998; *Stieglitz et al.*, 2001], for model calibration [e.g., *Koster and Suarez*, 1992; *González-Rouco et al.*, 2003, 2006; *Beltrami et al.*, 2006b], for assessments of biogeochemical processes important in soil-profile CO_2 dynamics and long-term soil carbon storage [*Knorr et al.*, 2005], as well as for providing a metric of planetary energy imbalance [e.g., *Hansen et al.*, 2005; *Beltrami et al.*, 2006a]. 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.

[4] One current shortcoming of land-surface representations in GCMs involves the bottom boundary condition placement (BBCP) of the subsurface model. The location of this boundary must be set deep enough to avoid significantly perturbing subsurface thermodynamics. Several studies have worked to quantify the effect of BBCP on subsurface thermodynamic calculations. *Lynch-Stieglitz* [1994] investigated the behavior of annual temperature signals in a land-surface model with a BBCP at 2.3 m. *Sun and Zhang* [2004] have also investigated the effect of BBCP on annual temperature signals using variable boundary depths. Both of these studies noted that simulations of annual temperature signal propagation were affected by the BBCP. In particular, for shallow BBCP, subsurface temperatures were warmer in the summer and colder in the winter, with maximum temperatures occurring later in the year, relative to expected results in which the bottom boundary condition does not influence the propagation of the annual temperature signal.

[5] *Smerdon and Stieglitz* [2006] have further investigated the effect of BBCP on subsurface thermodynamics using analytic solutions to the one-dimensional heat conduction equation. This study investigated signals with diurnal to millennial periods and noted that appropriate BBCP is dependent on the time scale of interest. Errors in amplitude and phase of downward propagating signals ranged from 0 to almost 100% and depended on the frequency of surface oscillations, the depth of the BBCP and the thermophysical properties of the subsurface. Given that the BBCP in most GCMs is between 3 and 10 m [see *Smerdon and Stieglitz*, 2006, and references therein], the *Smerdon and Stieglitz* [2006] results suggested that the behavior of subsurface temperature fields in climate change scenarios are likely corrupted.

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[6] Here we are principally concerned with how the BBCP affects the capacity of the subsurface to store heat. In contrast to earlier studies that have investigated the effects of the BBCP on downward propagating temperature signals, we seek to quantify the amount that heat storage capacity is affected by the location of the lower boundary in a thermodynamic model. 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. The choice of GCM temperature data as a surface boundary condition is unrelated to the thesis of this paper, ie., quantification of the corrupting influence of BBCP on heat storage in the subsurface component of state-of-the-art GCMs. 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 BBCPs.

2. Model Descriptions and Analysis

2.1. One-Dimensional Soil Model

[7] The 1DSM used in this work was designed to study snow-ground thermal interactions [*Goodrich*, 1982; *DeGaetano et al.*, 1996; *Zhang et al.*, 1996] and the thermal regime of the subsurface. The major heat transfer mechanism in the soil system is assumed to be conduction, although the model can take into account hydrologic phase changes and prescribed snow-soil layer thermal properties. The variable thermal properties and latent heat during phase changes are taken into account separately, so that the model can be applied in this experiment with no latent heat. Such a representation of subsurface heat transport is a reasonable approximation in many cases [e.g., *Smerdon et al.*, 2003]. To carry out the simulations, upper and lower boundaries and physical and thermal properties of the soil system need to be prescribed. We ignore snow cover and thus the upper boundary can be defined as temperature or heat flux at the ground surface. The lower boundary can be set at a specific depth with a constant temperature or heat flux; here we apply a zero-flux lower boundary conditions.

2.2. ECHO-g GCM

[8] The ECHO-g data used here are the mean Northern Hemisphere land-surface temperatures derived from a transient simulation of the climate of the last millennium [*González-Rouco et al.*, 2003]. This simulation was forced by plausible estimations of the evolution of external forcing factors (solar irradiance, radiative effects of stratospheric volcanic aerosols and greenhouse gas concentrations) through the period 1000–1990 CE [*Crowley*, 2000] and continued under the IPCC A2 and B2 scenarios up to 2100 CE [*Intergovernmental Panel on Climate Change*, 2001].

[9] ECHO-g [*Legutke and Voss*, 1999] consists of the atmospheric and ocean GCM components ECHAM4 and HOPE-g, respectively. ECHAM4 [*Roeckner et al.*, 1996] is used with a T30 horizontal resolution (ca. 3.75°) and 19 vertical levels. HOPE-g [*Wolff et al.*, 1997] is used with a T42 horizontal resolution (ca. 2.8°) that increases toward low latitudes reaching a minimum grid point separation of 0.5° for a better representation of equatorial and tropical ocean currents. The ocean model contains 20 discrete vertical levels.

[10] ECHO-g's land-surface scheme comprises a soil model, hydrology, snow cover physics and vegetation effects on surface evapotranspiration. The soil model [*Warrilow et al.*, 1986] is a five-layer finite-difference approximation of the diffusion equation that operates on the T30 land-sea-mask grid of ECHAM4. Ground temperatures are simulated at five levels with depths at 0.06 m, 0.32 m, 1.23 m, 4.13 m and 9.83 m. A zero heat flux is the prescribed BBCP at the lowest layer. Further discussion and results with these simulations can be found elsewhere [*Fischer-Bruns et al.*, 2005; *Zorita et al.*, 2005; *González-Rouco et al.*, 2006; *Beltrami et al.*, 2006b].

3. Results

3.1. Synthetic Step-Change Experiment

[11] Synthetic surface temperature step-change experiments were performed using the 1DSM to estimate heat storage dependency on the BBCP. Since we are interested in changes in the thermal regime of the subsurface, the subsurface was initialized to a temperature of 0°C at all depths prior to model execution. Temperature calculations were performed at constant 1 m intervals throughout the subsurface. In order to clearly assess the effects of BBCP, the system was allowed to "spin-up" for 500 years. A 1 K step increase in surface temperature was imposed at the beginning of the spin-up period, and the bottom boundary condition was set at 1000 m. For all practical purposes, heat propagating downward does not reach the maximum depth of 1000 m for the timescales involved here. The BBCP remains causally detached, and therefore does not influence the results of our experiments. The temperature profile at the end of the spin-up run was used as the initial temperature profile for the synthetic experiments.

[12] Five sets of 1000 simulations were conducted after the spin-up was completed 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 1000 m to 1 m in intervals of 1 m. Figure 1a shows the resulting temperature-depth profiles for eight sample BBCPs for the 500 year runs. It is clear that the subsurface temperature field and thus the heat stored in the subsurface are sensitive to the placement of the bottom boundary. 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. The quantification of this sensitivity in the underground heat storage is what we seek to examine in this note.

[13] We perform one-dimensional calculations of heat, Q, according to:

$$Q = \rho \, c_s \int T(z) \, dz \tag{1}$$

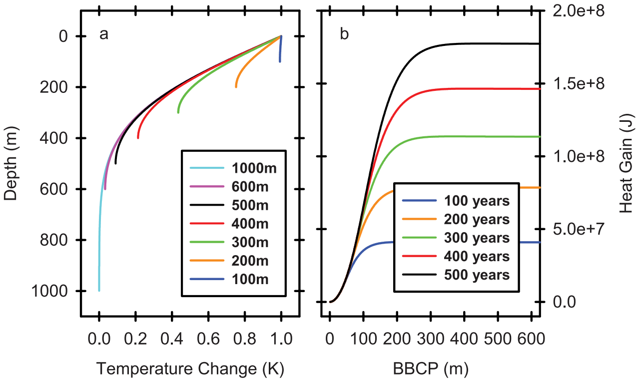

Figure 1. (a) Temperature-depth profiles resulting from different placements of the bottom boundary after 500 years of simulation. As the BBCP becomes shallower, the thermal profile becomes increasingly warm. (b) Total heat gain since spin-up as a function of BBCP for synthetic examples (see text). Each point on the curves represents the total heat gained by the subsurface for a given run duration and BBCP. Each of these curves approach an asymptotic value as a function of BBCP; this outlines the region of interference by the bottom boundary on subsurface thermodynamics.

where ρ is the density and c_s is the specific heat of the solid. Throughout this study, density and specific heat were set such that the thermal diffusivity remains fixed at $10^{-6}\text{m}^2\text{s}^{-1}$ and constant in both depth and time [*DeGaetano et al.*, 1996].

[14] Figure 1b shows the effects of insufficiently deep BBCP for a synthetic upper boundary condition. Each point on these curves represents the total heat gained by the subsurface since spin-up for a given run duration and BBCP. Each curve asymptotically approaches a greater value for heat storage as run duration increases. Also, due to the nature of heat diffusion, the depth at which the asymptotic convergence occurs is shallower for shorter run durations. According to Figure 1b, if the BBCP was at a depth of 120 m for the 500 year simulation, the total heat stored in the subsurface in 500 years (8.9×10^7 J) would be half of the asymptotic value (1.8×10^8 J).

3.2. Experiment With GCM Projections

[15] 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 [*Fischer-Bruns et al.*, 2005; *Zorita et al.*, 2005]. We initialized the experiment with the ECHO-g 1000-year paleoclimatic simulation acting as the spin-up run from 1000 to 1990 CE [*González-Rouco et al.*, 2003, 2006]. This paleoclimate simulation was used as the upper boundary condition, the bottom boundary was set at a depth of 1000 m, and the spin-up was initialized with a constant thermal profile. Application of the paleoclimatic simulation to the 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 Figure 2 shows the annual mean temperature for the millennial ECHO-g paleoclimatic simulation and the future temperature projections under scenarios A2 and B2 used in this experiment.

[16] As a practical guideline, Figure 2 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 200 m. In this case, a BBCP greater than 200 m would be sufficient to correctly estimate the ground heat content in response to the A2 and B2 simulations.

[17] Figure 2 depicts the results for 1000 simulations of the 1DSM for each scenario, and is the analog of Figure 1b 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 10 m, the total heat stored in the subsurface (1.9×10^8 J) would be less than one-quarter of the asymptotic value (8.8×10^8 J). If scaled over the entire continental surface (1.5×10^{14} m^2), 1.0×10^{23} J, or 75% of the corresponding asymptotic value (1.3×10^{23} J) would not be stored in the terrestrial subsurface. 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 [*Beltrami et al.*, 2002; *Levitus et al.*, 2005; *Huang*, 2006; *Beltrami et al.*, 2006a].

[18] Figure 3 restates the total subsurface heat gain in the 1DSM for the A2 and B2 scenario simulations as a ratio of the heat gain for each BBCP case to that of the respective 10 m case, as in ECHO-g. Note that the B2 scenario approaches a greater ratio than A2 because the heat gain at 10 m is smaller in the B2 scenario. We show the results down to a BBCP at 120 m where we observe an asymptotic convergence. For the A2 scenario, the 1DSM stores approximately 4.5 times less heat with a BBCP at 10 m than with a causally detached BBCP (8.8×10^8 J), and 12.5 times less heat for a BBCP at 3 m.

[19] Most GCMs have shallow BBCPs; Figure 3 can serve as a guide to scale results from other models. For any

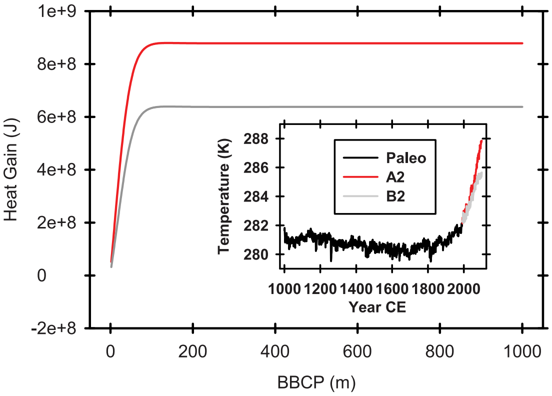

Figure 2. Each point on these curves represents the total amount of heat gained by the subsurface as a function of BBCP from 1990 to 2100 CE for both the A2 and B2 IPCC scenarios. For shallow BBCPs, soil models will underestimate the amount of heat being stored in the ground. Inset: ECHO-g annual land-surface temperature time series from the millennial paleoclimatic simulation and A2 and B2 scenario projections for the Northern Hemisphere.

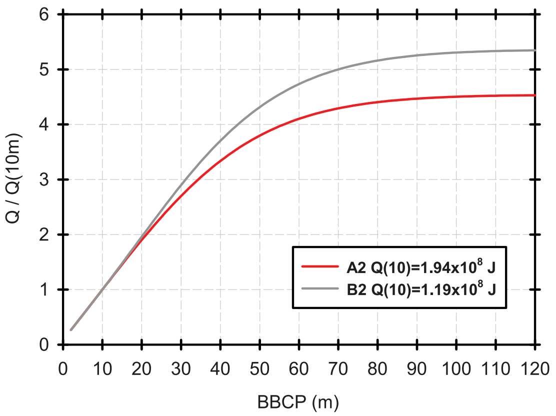

Figure 3. Shown are the same results as Figure 2, but expressed as a ratio of the heat gained for a BBCP at 10 m, as in ECHO-g. These curves show the ratio of total heat gain with BBCP set at *z* meters compared to a BBCP set at 10 m. Existing GCMs have BBCPs typically imposed between 3 and 10 m.

soil model, if the BBCP is at a depth that is too shallow, the amount of energy stored in the ground may be underestimated. As shown in Figure 3, an increase in BBCP from 10 m to 100 m could result in a four- to five-fold increase in heat storage potential. Furthermore, if there is a feedback mechanism involved between land surface and atmosphere, this unabsorbed quantity of heat may partition to other model subsystems. This is potentially a very important issue for climate models since ascertaining the energy balance of the climate system and all its components is a fundamental requirement for proper evaluations of future climatic trends [*Shin et al.*, 2006, and references therein].

4. Discussion and Conclusions

[20] 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 [*Levitus et al.*, 2005; *Beltrami et al.*, 2006a]. If the BBCP is too shallow, there is a significant perturbation to the subsurface temperature field and thus to the magnitude of underground heat storage. 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. Placement of the bottom boundary condition has significant effects on the surface and subsurface energy regime; if ground surface feedback mechanisms are to be included, or soil biogeochemical processes are to be examined in a future climate scenario, the bottom boundary condition cannot be arbitrarily placed. A quantity of heat that is one order of magnitude greater than that absorbed by the atmosphere may remain displaced in the global energy budget, at the risk of making additional energy available to other climatic components, rather than being stored in the terrestrial subsurface. Details of how this energy will affect the climate subsystems will be model dependent. Because of this, quantifying the effect in every GCM is outside the scope of this paper.

[21] It should be noted that the estimates of heat storage obtained by forcing the 1DSM with the ECHO-g surface air temperature would actually represent maximum levels of heat storage. In a coupled model simulation with a deeper BBCP, the propagation of heat to the subsurface would contribute to reducing the amount of warming at the surface throughout the simulation. It is unclear, however, how the demonstrated effects will influence a coupled model with many other interactions and feedbacks. Nevertheless, the demonstrated effects warrant further investigation. We also note that borehole temperature data may provide a useful aid in constraining and validating long-term climate simulations and testing model fidelity [*González-Rouco et al.*, 2003, 2006; *Beltrami et al.*, 2006a, 2006b].

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