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LETTER TO THE EDITOR

Reply to L. Kutzbach

By D. V. KHVOROSTYANOV[1*], G. KRINNER[2], P. CIAIS[3], M. HEIMANN[4] and S. A. ZIMOV[5],
[1]*Laboratoire de Météorologie Dynamique, Palaiseau, France;* [2]*Laboratoire de Glaciologie et Géophysique de l'Environnement, St Martin d'Hères, France;* [3]*Laboratoire des Sciences du Climat et l'Environnement, Saclay, France;* [4]*Max-Planck Institute of Biogeochemistry, Jena, Germany;* [5]*Northeast Science Station, Cherskii, Russia*

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We thank Dr. Kutzbach for providing us with an opportunity to clarify a detail of our model recently presented in (Khvorostyanov et al., 2008, hereafter K08). The comment by Kutzbach (2009) is based on the assumption that the surface heat balance (SHB) in eq. (2) of K08 is a function of the prescribed atmospheric forcing only, thereby neglecting the diffusive ground heat flux $\Phi_G = -k\,\partial T/\partial z|_{z=0+}$ (with z and Φ_G being defined positive downwards). However this is not true.

Our model calculates the surface heat balance as:

$$B = S_{\downarrow}(1-\alpha) + L_{\downarrow} - L_{\uparrow} - \Phi_L - \Phi_S + \Phi_G,$$

where $S_{\downarrow}$ is the downwelling solar radiation, $L_{\downarrow}$and $L_{\uparrow}$ are down- and upwelling longwave radiation fluxes, Φ_S and Φ_L are the turbulent sensible and latent heat fluxes, respectively (positive upwards), and Φ_G is the ground heat flux (positive downwards).

The ground heat flux Φ_G is calculated when solving eq. (1) of K08 for the soil temperature $T(z, t)$. In other words, the model is formulated as Kutzbach (2009) suggests it should be, taking into account the $T|_{z=0}$ increase in case of the soil warming by microorganisms. We should probably have stated this explicitly; to us it went without saying that Φ_G is to be taken into account, as is the case for climate models. The ground heat flux Φ_G to the atmosphere does not increase by more than 5 W m^{-2} during the phase of intense soil warming in Fig. 3 of K08, compared to a simulation without biogenic soil heating. Given that soil warming occurs on very limited spatial scales, and the ground heat flux dissipates quickly in the atmosphere through advection, away from the heated soil patches, this microbial heating cannot significantly change the atmospheric temperature. At the same time neglecting Φ_G in the SHB calculation *does* change the soil heat balance and the soil response to atmospheric warming.

However the effect of neglecting Φ_G on the soil warming in our model is the opposite to that anticipated by Kutzbach (2009). In the additional simulation that does not take into account Φ_G in the SHB calculation, the soil warming is smaller than in the original simulation. For the case corresponding to Fig. 3 of K08, permafrost thaws only above 2 m, with maximum soil temperatures at the surface layers, due to heat diffusion from the atmosphere in summer. With neglected Φ_G the upper soil is a few degrees colder than with the ground heat flux taken into account, and the deep soil remains frozen.

The point is that the heat loss from the soil to the atmosphere is proportional to the vertical temperature gradient $\frac{\partial T}{\partial z}$ in the upper soil. If the surface gets colder due to the SHB that neglects the ground heat flux (as assumed by Kutzbach, 2009), then $\frac{\partial T}{\partial z}$ increases due to soil biogenic warming, and the soil looses more heat compared to the original case. Mathematically, taking into account the ground heat flux in the SHB calculation can be simplistically seen as adding another surface-layer resistance r_S between $T|_{z=0}$ and the prescribed atmospheric forcing temperature T_a. The boundary condition at $z = 0$ is then

$$r_S(T_a - T|_{z=0}) = -k\frac{\partial T}{\partial z}|_{z=0},$$

where k is the heat conductivity. Adding this additional resistance effectively insulates the soil more than if it were absent and thus confines the internal heating more to the soil and enhances its warming.

To summarize, the SHB in eq. (2) of K08 does take into account the ground heat flux Φ_G, while neglecting the latter would

*Corresponding author.
e-mail: dmitry.khvorostiyanov@lmd.polytechnique.fr
Institut Pierre-Simon Laplace, Laboratoire de Météorologie Dynamique, Ecole Polytechnique, 91128 Palaiseau, France.
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require a greater atmospheric warming to trigger the intense deep-soil respiration and permafrost thaw.

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