On the formation of high-latitude soil carbon stocks: Effects of cryoturbation and insulation by organic matter in a land surface model

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Received 22 July 2009; revised 17 September 2009; accepted 24 September 2009; published 12 November 2009.

[1] We modify the soil component of the ORCHIDEE terrestrial carbon cycle model to include vertically-discretized soil carbon. With this model, we investigate the feedback of considering thermal insulation by soil carbon, which modifies the soil thermal regime by lowering the thermal conductivity and increasing the heat capacity of a carbon-rich soil, on the total carbon stocks the model builds up. In addition, we demonstrate the effects of diffusive vertical mixing of soil organic matter by cryoturbation on the total carbon stocks that the model builds up in mineral soils in equilibrium with a steady climate. We show that including these two effects together leads to up to 30% higher soil carbon stocks in the top meter of permafrost soils, as well as large stocks of carbon below 1m in the upper permafrost soil layers. The vertical profile of partitioning of carbon between different lability pools is also affected, as the slower pools are more deeply mixed; also the time to reach equilibrium lengthens considerably. These effects are largest in the coldest regions such as Eastern Siberia. The inclusion of cryoturbative mixing and insulation by soil carbon leads to better agreement with estimates of high-latitude soil carbon stocks, where substantial amounts of carbon are found in permafrost regions, to depths of three meters; however we do not include peat, Yedoma, or alluvial deposition processes here, so the total carbon stocks are still lower than observed.
Citation: Koven, C., P. Friedlingstein, P. Ciais, D. Khvorostyanov, G. Krinner, and C. Tarnocai (2009), On the formation of high-latitude soil carbon stocks: Effects of cryoturbation and insulation by organic matter in a land surface model, *Geophys. Res. Lett.*, *36*, L21501, doi:10.1029/2009GL040150.

1. Introduction

[2] Permafrost soils hold enormous quantities of organic carbon: 1024 Pg in the top 3 meters, and another 241 Pg in deltaic deposits and 407 Pg in Yedoma loess soils [*Tarnocai et al.*, 2009]. Together, these carbon stocks represent a large fraction of the terrestrial carbon pool, thus it is important to consider the processes responsible for both their formation as well as their possible stability in future climates. Warming in arctic regions has the potential to lead to large greenhouse gas feedbacks due to two related but separate processes: as soils warm, the residence time of carbon in surface layers decreases, thus the equilibrium carbon balance shifts to release more CO_2 and/or CH_4 for a given carbon input by vegetation; in addition active layers are likely to deepen, thus thawing and allowing respiration of older, currently inactive carbon stores [*Schuur et al.*, 2009]. Current terrestrial biosphere models that use vertically-integrated soil carbon pools do not include this perennially frozen carbon, thus they are unable to represent the effects of active layer thickening on carbon balance. In this paper, we investigate the relationship between high-latitude soil processes and carbon stocks, in particular on the processes that lead to the existence of large carbon stocks both in the active layer and in the upper permafrost of arctic soils.

[3] We have incorporated the detailed one-dimensional permafrost soil carbon model POPCARN [*Khvorostyanov et al.*, 2008a, 2008b] into the global land surface/carbon cycle model ORCHIDEE [*Krinner et al.*, 2005]. ORCHIDEE is a land surface model which calculates the fluxes of carbon, water, and energy for terrestrial ecosystems. POPCARN is a soil carbon model, which calculates vertically-resolved input of soil organic matter (SOM) from litter, first-order decomposition processes at each model level, moisture-dependant diffusion of oxygen and methane in soils and anoxic decomposition processes. SOM is separated into three pools with different residence times, each a function of soil temperature and texture (active = 0.85 yr, slow = 31 yr, and passive = 1400 yr at 5°C).

[4] We have added two key processes relevant to the carbon cycling of permafrost soils. The presence of organic matter has a strong influence on soil thermal properties both in models [*Lawrence and Slater*, 2008] and in the field [*O'Neill et al.*, 2002] because it is more insulating than soil minerals. The presence of SOM can also change surface energy fluxes and thus modify the climate [*Lawrence and Slater*, 2008; *Rinke et al.*, 2008]. Here we model the effect of SOM on soil temperatures, using the prognostic soil carbon stocks in ORCHIDEE to define the soil thermal conductivity and heat capacity. This creates the opportunity for a feedback in soil carbon accumulation, in which additions of soil carbon modify the soil thermal regime and thus the residence time of soil carbon, which leads to a new steady-state soil carbon stock.

[5] We have also added a simplified vertical mixing scheme to account for the effects of cryoturbation on the redistribution of SOM. Cryoturbation is a physical mixing process driven by ice growth and soil density changes that

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0094-8276/09/2009GL040150

accompany freeze-thaw cycles. This mixing allows the soil carbon, which is generated near the soil surface, to move downwards into colder regions of the soil [*Bockheim*, 2007]. The deeper SOM, extending well below the active layer and into the permafrost region of soils, can exceed the quantity of carbon in the top meter [*Tarnocai et al.*, 2009]. Significant SOM stocks below the top meter of soil are ubiquitous in many biomes [*Jobbágy and Jackson*, 2000], however we focus on high-latitude regions here because the vertical profile of carbon may be especially important in permafrost regions if, as expected under global warming, active layers deepen and allow buried frozen carbon to be respired.

2. Permafrost Modifications to ORCHIDEE

2.1. Thermal Insulation by Soil Organic Matter

[6] Soil temperature in ORCHIDEE is calculated by a simple thermal diffusion, with an upper boundary condition of a surface layer that exchanges latent and sensible heat with the atmosphere. To account for the effects of ice and latent heat of fusion, we follow *Poutou et al.* [2004], in which the latent heat is added as an effective heat capacity. To consider the effect of snow on soil temperature, we follow the method of *Khvorostyanov et al.* [2008a], in which a separate snow column, with 7 layers of variable thickness depending on the current mass of snow, lies above the constant-thickness soil column. In order to include the thermal inertial of deep layers on soil temperatures [*Alexeev et al.*, 2007], we deepen the ORCHIDEE soil thermal column to 32 layers, with an exponential grid and total depth of 47.5 m.

[7] The presence of SOM strongly alters the soil temperature regime, particularly in arctic regions [*Nicolsky et al.*, 2007; *Lawrence and Slater*, 2008; *Rinke et al.*, 2008]. Following *Lawrence and Slater* [2008], we use the method of *Farouki* [1981], in which soil thermal diffusivity and heat capacity at each layer of each gridcell at each timestep is a function of the SOM:

$$\frac{\partial T}{\partial t} = \frac{1}{c}\frac{\partial}{\partial z}\left(\lambda\frac{\partial T}{\partial z}\right)c, \lambda = f(ice, SOM, water, clay, T) \qquad (1)$$

where λ is the thermal conductivity of the soil, and c is the heat capacity (see auxiliary material for parameter values used).[1]

[8] Here, we consider only the effect of SOM on soil thermal properties, not on soil hydrologic properties as well as was done by *Lawrence and Slater* [2008]; this is a first step, and also serves to isolate the thermal and hydrological effects. *Lawrence and Slater* [2008] and *Rinke et al.* [2008] show large effects in a coupled atmosphere-ocean model due to changes in latent heat exchange when changing the soil hydrological properties, however we expect these effects to be relatively smaller than the thermal effects here on the soil carbon dynamics in the offline model we use here.

2.2. Vertical Mixing of Soil Organic Matter by Cryoturbation

[9] Physical mixing by cryoturbation is widespread in permafrost-affected soils, and redistributes organic matter from the surface to deeper within the soil [*Bockheim*, 2007]. Cryoturbation leads to heterogeneous soils, both horizontally and vertically, with warped organic horizons that may extend well into the permafrost layers [*Kaiser et al.*, 2007]. Transport into the permafrost layers is possible due to a dynamic permafrost table, which can deepen greatly in response to fire or other disturbance, allowing mixing to layers that are then subsequently frozen by a slowly rising permafrost table. There exist several field-scale mechanistic cryoturbation models [e.g., *Swanson et al.*, 1999; *Peterson and Krantz*, 2003; *Nicolsky et al.*, 2008] here we are limited from using a fully mechanistic cryoturbation model by the low spatial resolution (GCM-scale) of ORCHIDEE, and the computation cost and general applicability of embedding a cryoturbation model within a global scale model. Thus, rather than explicitly modelling cryoturbation processes, we try to capture the effect of cryoturbation on the vertical profile of SOM stocks by considering a simple diffusion scheme:

$$\frac{\partial C_i}{\partial t} = D\frac{\partial^2 C_i}{\partial z^2} \qquad (2)$$

where C_i is the carbon concentration of carbon pool i, and D is the diffusion constant resulting from the mixing due to cryoturbation. Carbon is initially added to the soil column as an exponential function of depth through the active layer, with PFT-dependent (based on rooting depth) e-folding depth between 0.8 and 1.0 m. We assume that the depth of mixing is a function of the active layer thickness, with mixing rates constant through the active layer and tapering linearly to zero at a depth of some constant times the active layer thickness:

$$D = \begin{cases} D_0 & \text{for } z < z_{ALT} \\ D_0\left(1 - \left(\frac{z - z_{ALT}}{(k-1)z_{ALT}}\right)\right) & \text{for } z_{ALT} < z < kz_{ALT} \\ 0 & \text{for } z > kz_{ALT} \end{cases} \qquad (3)$$

where z_{ALT} is the depth to the base of the active layer. The cryoturbation diffusive constant used here, D_0, of 10^{-3} $m^2 y^{-1}$, gives an approximately 1000 yr mixing timescale over the top meter of soil; this timescale is supported by radiocarbon dates from subducted O horizons in cryoturbated soils [*Kaiser et al.*, 2007], and allows mixing of the longer term carbon pools into the upper permafrost, while the rapidly cycling active pool carbon is not strongly affected. The maximum mixing depth is a fixed multiple, k of the active layer; here we use a k value of 3, i.e., the maximum mixing depth is 3 times the active layer thickness. This value is chosen to give approximately the observed partitioning of 38% of turbel SOM in the top 1 m, 33% at 1–2 m, and 28% at 2–3 m [*Tarnocai et al.*, 2009], given typical active layer thickness of <1 m (e.g., median active layer thickness from CALM stations [*Brown et al.*, 2000] of 77 cm), however this value is poorly constrained due to the sparcity of vertically-resolved soil carbon observations in general, and in particular observations of the maximum depth of mixing of organic matter into permafrost soils. The use of a vertical diffusion term to represent mixing is similar to that of *Elzein and Balesdent* [1995], who model vertical SOM transport in temperate soils using an advection-diffusion equation. The presence of a permafrost table is likely to strongly inhibit vertical advection of dissolved carbon in groundwater, thus

[1]Auxiliary materials are available in the HTML. doi:10.1029/2009GL040150.

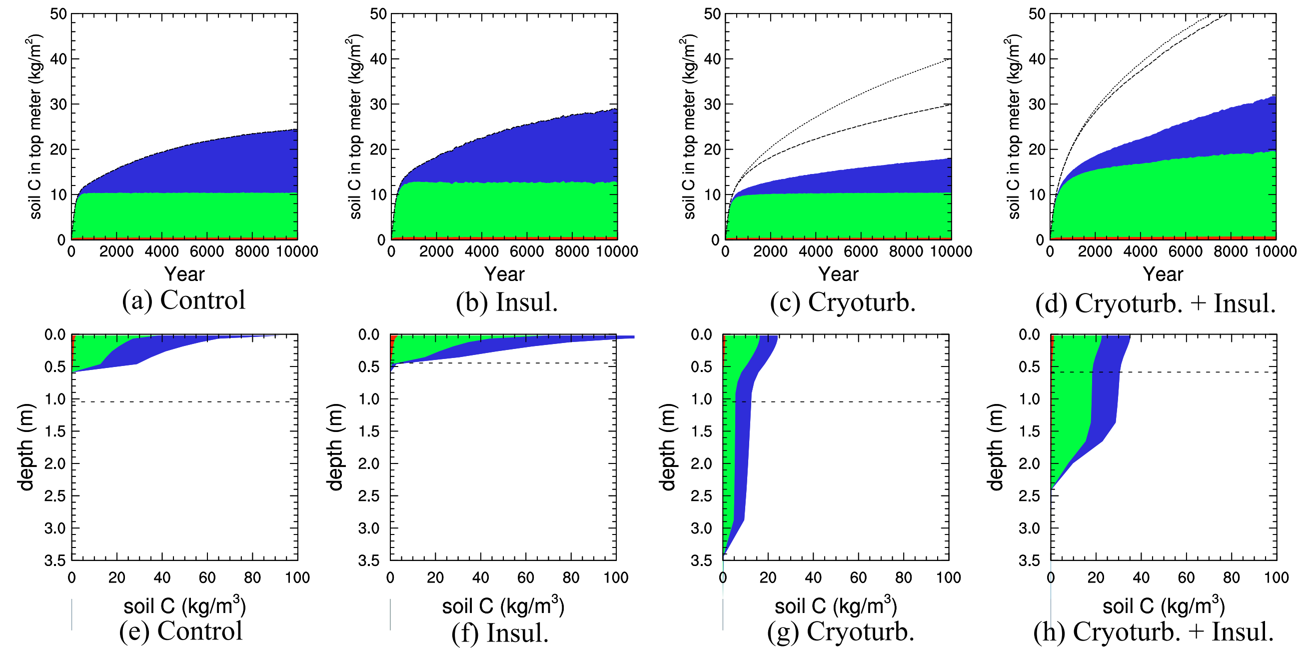


Figure 1. Time series of carbon accumulation in the upper meter of soil at Cherskii: (a) no insulation by organic or cryoturbation, (b) insulation by organic, (c) cryoturbation, (d) both insulation by organic and cryoturbation. Shaded area corresponds to: active pool(red), slow pool(green), passive pool(blue). Dashed line in Figures 1a–1d corresponds to total carbon in top 2 meters of soil, dotted line corresponds to total carbon in top 3 meters. (e–h) Same as Figures 1a–1d but for vertical profile of carbon at end of run. Dashed line corresponds to mean modelled active layer depth for each experiment.

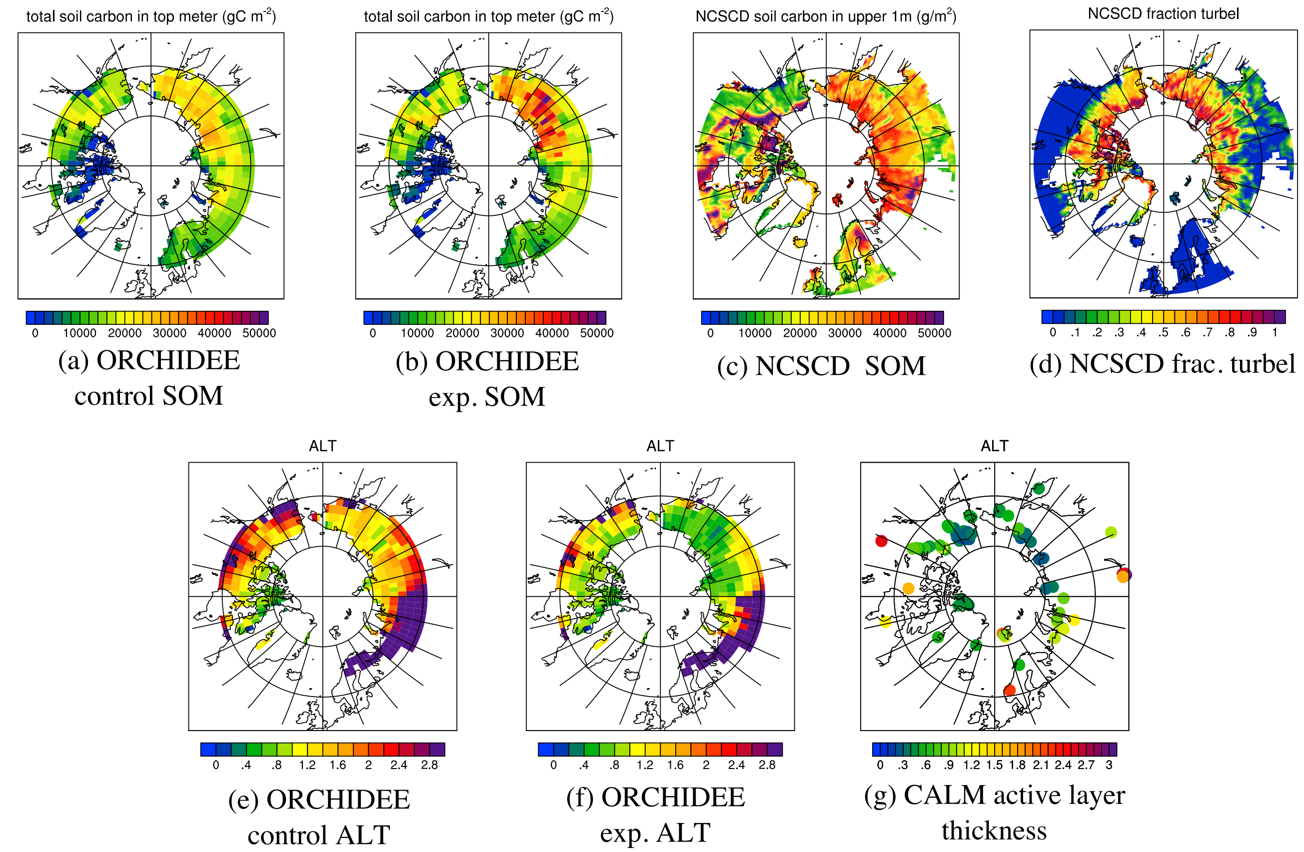
we do not include an advection term here; however advection may be critical in loess or alluvial depositional areas and allow buildup of, e.g., Yedoma SOM stocks [*Zimov et al.*, 2009]. We further assume here that cryoturbation only occurs where permafrost exists within the top meter of soil, as this corresponds roughly with the geographic extent of cryoturbated soils (see discussion below and Figure 2d), and calculate no vertical mixing outside this region.

3. Results

[10] Figures 1a–1d show time series of SOM during runs at a single point in Eastern Siberia (Cherskii: 161°E, 69°N). In Figure 1a, the control simulation, the active and slow carbon pools quickly equilibrate, with the passive pool comprising the largest share, yet only approaching equilibrium at 10,000 years. Adding the insulation by SOM (Figure 1b), leads to higher (29 kg C/m^2 vs. 24 kg C/m^2 for the control run) SOM; this is uniformly spread about the three carbon pools, though the colder temperatures mean that all also take a longer time to reach equilibration. Adding cryoturbation alone (Figure 1c) actually leads to a reduction (18 kg C/m^2) in the SOM in the top meter, because the deep mixing has brought much of the carbon down below the 1m depth, so that SOM to 2 and 3 meters are 30 and 40 kg C/m^2, respectively. Because the passive pool, with a residence time much slower than the diffusion timescale, is mixed most fully, the ratio of slow pool to passive pool carbon in the top meter is now higher, leading to a net higher lability of the SOM in the top meter. Adding both processes (Figure 1d) leads to an increase in the SOM in the top meter to 32 kg C/m^2, and at the same time a lower fraction of passive pool SOM in the upper soil. Furthermore, SOM to 2 and 3 meters is now 55 and 57 kg C/m^2, respectively; indicating that a substantial SOM pool has been mixed below the active layer into the upper permafrost layers.

[11] The diffusive cryoturbation parameterization has a strong effect on the vertical profiles of SOM, as we show in Figures 1e–1h. The control run (Figure 1e) shows high SOM at the surface, a steep decline in SOM to the base of the active layer, and no SOM in the permafrost layers. Adding the insulation effect alone (Figure 1f) increases SOM everywhere with little change to the vertical profile of SOM; adding cryoturbation alone (Figure 1g) deepens the carbon profile considerably, mixing a substantial portion of SOM to 3 meters. The run with cryoturbation and insulation by organic matter (Figure 1h) also shows substantial SOM in the upper permafrost layers, but mixed less deeply because of the shallower active layer.

[12] Figure 2a shows the SOM after initializing ORCHIDEE over a 10,000 year period, without using the SOM to modify the insulation properties of the soil, while Figure 2b shows ORCHIDEE SOM using soil carbon insulation and cryoturbation. For comparison, Figure 2c shows the total soil carbon from the Northern Circumpolar Soil Carbon Database (NCSCD) [*Tarnocai et al.*, 2007]. Figure 2d shows the distribution of turbel soils (cryoturbated, permafrost-affected mineral soils), from the NCSCD database for comparison; most of the cryoturbated soils are in eastern and central Siberia and northernmost Canada and Alaska, and correspond to the highest non-peat soil carbon stocks. The modeled effect of the carbon thermal insulation and cryoturbation increases with increasingly cold conditions, with the largest accumulations of SOM in eastern Siberia. The maximum modelled SOM in Siberia is slightly to the south of the observed maximum. This is because the imposed mean



(a) ORCHIDEE control SOM (b) ORCHIDEE exp. SOM (c) NCSCD SOM (d) NCSCD frac. turbel

(e) ORCHIDEE control ALT (f) ORCHIDEE exp. ALT (g) CALM active layer thickness

Figure 2. (a) ORCHIDEE soil carbon stocks in top meter, without considering the insulation effect of SOM. (b) ORCHIDEE, with consideration of cryoturbation and insulation effect of SOM. (c) NCSCD Total carbon stocks in top meter of soil. (d) NCSCD fraction of soils in the turbel suborder (cryoturbated, permafrost-affected mineral soils). Active Layer Thickness [m]: (e) ORCHIDEE, without insulation by organic matter, (f) ORCHIDEE with insulation by organic matter, (g) observations from CALM [*Brown et al.*, 2000].

temperatures are coldest in this region, leading to buildup of highest carbon stocks there; in reality this region is somewhat mountainous, and thus erosion processes (which are not modelled here) may lead to less carbon accumulation than in northernmost Siberia.

[13] Because SOM acts as an insulator most effectively when it is thawed, it impedes the summer heat wave into the soil and thus thins the active layer. This is shown in Figures 2e–2g; here Figure 2e shows ORCHIDEE without the organic insulation, Figure 2f shows ORCHIDEE with insulation, and Figure 2g shows observations of mean ALT from the CALM network [*Brown et al.*, 2000]. The active layer is thinned wherever there is substantial SOM in the model; this brings it into better agreement with the CALM data, with RMS error between the two reduced from 1.29m to 0.45m. However, inter-site variance is not well captured by either version of the model (linear r^2 =.11 and.08 for control and insulation, respectively), indicating a large component of unresolved local control of ALT. In addition, ALT is still overestimated along much of the arctic coastal region, as well as in peatland regions, where the organic stocks are underestimated.

4. Discussion

[14] The slowing of decomposition by both cryoturbation and organic insulation leads to soil passive carbon pool fractions that are not in equilibrium, even after 10,000 years. This is a climatically relevant timescale, and it implies that soils, even undisturbed by fire or other centennial-scale events, may not have fully equilibrated over the Holocene, with important implications for their carbon balance [*Wutzler and Reichstein*, 2007], in particular a sustained ability of the soil to act as a small carbon sink in the presence of a stable climate. Here, for the case including both cryoturbation and C insulation, total carbon accumulation at the end of the 10,000 yr run is 1 gC/m^2/yr. This agrees in general with observations that high-latitude soils generally act as carbon sinks under a steady climate, although the modelled magnitude is small compared to observations of 0–40 gC/m^2/yr [*Oechel and Billings*, 1992]. The magnitude of this effect is greater due to cryoturbation than to organic insulation.

[15] Data on the vertical profile of SOM, particularly below the top meter that is the standard control section for pedological surveys, is relatively scarce. However, estimates suggest that in highly cryoturbated permafrost soils (turbels), 38% of the carbon from the top 3 meters is in the top meter, 33% in the second meter, and 28% in the third meter; and that overall in permafrost soils, 496 Pg C exist in the top meter, and 1024 Pg C exist in the top 3 meters [*Tarnocai et al.*, 2009], of which 278 Pg are in histel or histosol (organic soils, e.g., peat deposits), so that 746 Pg C are in mineral soils. Here, considering only mineral soils, we calculate 320 Pg C in the top meter and 476 Pg C to 3 meters for the total

terrestrial region north of 60°N, as compared to a control case of 287 Pg with all carbon in the top meter. Thus our deeper carbon stocks here are likely still an underestimate of the actual permafrost carbon down to 3 meters. This is most likely due to our not including deposition processes in these calculations, as these lead to the substantial accumulation of deeper carbon in loess or Yedoma deposits [*Zimov et al.*, 2009], and in alluvial orthel soils [*Tarnocai et al.*, 2009].

[16] The inclusion of cryoturbation and insulation by SOM in ORCHIDEE leads to a positive feedback between soil temperature and carbon, which leads to a buildup of approximately 30% more SOM in the top meter of soil in permafrost regions after a 10,000 yr period. This is in better agreement with observations of soil carbon, especially in Eastern Siberia, where large carbon stocks exist, even in mineral soils. However, as the model does not simulate the processes that lead to peat buildup [e.g., *Ise et al.*, 2008], it still underestimates the carbon stocks in Western Siberia and the Canadian peatlands. Future work in ORCHIDEE will address this shortcoming. However, the suggestion from our results is that there are at least two main processes that lead to high carbon buildup in surface soils and below the active layer of arctic regions: the temperature limitation of respiration and deep mixing that we model here, which is especially effective in the coldest regions such as Eastern Siberia, and the anoxic limitation of decomposition that leads to peat buildup, which dominates Western Siberia and the Canadian peatlands.

5. Conclusions

[17] *Tarnocai et al.* [2007, 2009] show large quantities of SOM in permafrost layers of arctic soils; in order to model the response of the high-latitude carbon cycle to climate change, it is crucial to take this carbon into account. We have investigated the effect of two processes, the vertical mixing of SOM by cryoturbation and thermal insulation by SOM, on the buildup of SOM in arctic soils. Both processes together lead to significantly higher SOM content in soils, and better agreement with observations of SOM content, both geographically and vertically, although total carbon stocks are still underestimated.

[18] **Acknowledgments.** This research was supported by the project Impact-Boreal, funded by the Agence Nationale pour la Recherche (ANR). Computing support was provided by CEA.

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