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Deglacial Changes in Ocean Dynamics and Atmospheric CO_2

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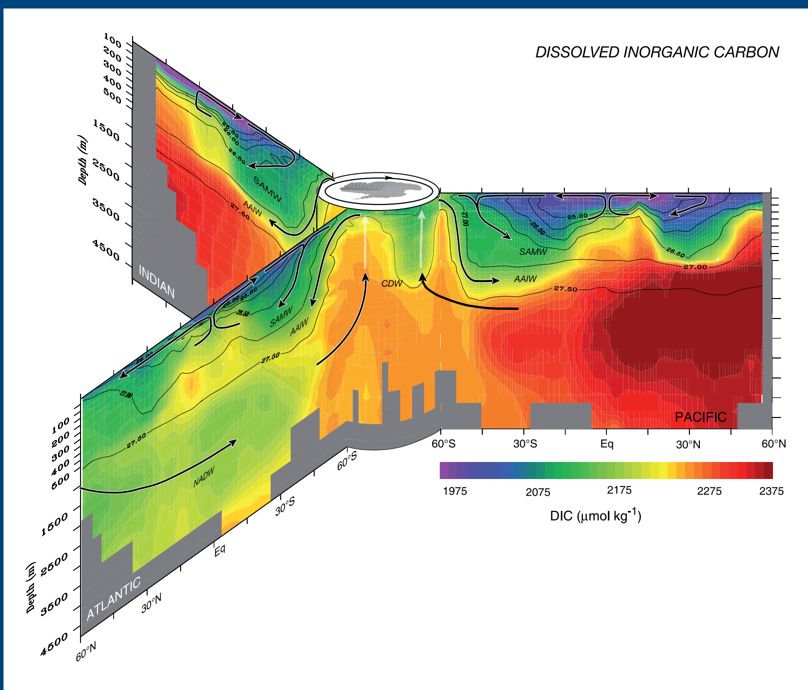

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The Role of the Terrestrial Biosphere in CLIMBER-2 Simulations of the Last 4 Glacial CO_2 Cycles

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With 3 Figures

Terrestrial ecosystems strongly affect fluxes of heat, water, and greenhouse gases between land and atmosphere. In pre-industrial climate, vegetation biomass and mineral soils contained about 2,000 Gt of carbon, about 4 – 5 times more than the atmosphere at that time. During Last Glacial Maximum (LGM), a decrease in atmospheric CO_2 from 280 to 200 ppmv should have caused about 30 % decrease in plant productivity mainly due to physiological effect of CO_2 (reduction in water use efficiency). In addition, expansion of ice sheets and climate change led to extreme reduction of boreal and temperate forests and an increase in savannah in subtropical regions. This view is strongly supported by pollen-based reconstructions of vegetation cover. A decrease in tropical forests due to less moisture and lower CO_2 level was compensated by a growth of forests on exposed tropical shelves. In total, effects of climate and CO_2 on terrestrial vegetation should have led to a strong reduction in terrestrial carbon storage. Model-based studies suggest a decrease in land carbon in the range from 300 to 800 GtC, with a largest uncertainty coming from the changes in distribution in vegetation cover. Estimates based on marine ^{13}C changes are close to 500 GtC, falling in the middle of the range of the model estimates. The later do not account for the boreal peat growth during the Holocene, estimated into about 400 GtC. In total, following previous model simulations, it could about 1,000 GtC of interglacial-to-glacial difference in terrestrial carbon storage (biomass and mineral soils).

Such strong variability in land carbon does not help to explain changes in atmospheric CO_2 during glacial cycles as changes in land carbon counteract the atmospheric CO_2 drawdown during glaciation inception and CO_2 increase during deglaciation. Translated into atmosphere CO_2 changes, this would mean not very much – 20 to 30 ppm depending on the strength of the ocean carbonate compensation and weathering effect on alkalinity – but it should be added at the top of 80 to 100 ppm changes needed to be explained by the ocean carbon cycle. On a long term, it is possible for the ocean to absorb extra 1,000 GtC in addition to its huge reservoir capacity of about 40,000 GtC, but during periods of fast climate changes the ocean is too slow to explain observed fast changes in atmospheric CO_2. Without an extra pool capable to release 400 – 500 GtC relatively quickly, the models are unable to explain the periods of fast CO_2 changes.

A possible solution to this problem was recently suggested by an involvement of terrestrial carbon storage in cold environments (e.g. Ciais et al. 2012). Decomposition of organic matter is strongly temperature-dependent with an average Q_{10} factor of 2, i.e. it slows down by a factor of 2 in response to the temperature drop by 10 °C. In frozen soils, decomposition of soil carbon is negligible. A presence of ice in the soils, for example in the form of ice wedges in the permafrost soils, leads to a burial of carbon on a very long time scale until the permafrost is thawed and organic carbon is available for decomposition again. Because the glacial inception led to continuous decrease in temperature, decomposition of plant litter at the surface was slow, and most of organic was not decomposed but accumulated at the surface. The formation of permafrost led to continuous burial of carbon in the soils, which could reach tens and hundreds of kg C m^{-2}. Current stocks of carbon in permafrost environment are estimated in about 1,500 Gt of carbon, and these storages should be much higher during the glacial periods because significant part of permafrost was thawed during deglaciation. These processes of decomposition of frozen carbon in response to deglacial changes continue today because of thermokarst and thermal erosion which occur irregularly after surface disturbances due to surface fires or water erosion during spring snow melt. In addition, substantial part of frozen organic carbon was trapped under the ice sheets. This organics was likely transported by the ice dynamics to the edges of the ice sheets boundaries, where it could decompose quickly during abrupt warming events.

1. Terrestrial Carbon Model Setup

The CLIMBER-2 model is the Earth System model of intermediate complexity (Petoukhov et al. 2000). It includes all necessary components to simulate dynamics of the Earth climate and carbon cycle on multi-millennial time scale. The physical model components include dynamic-statistical atmospheric model, 3-basin zonally averaged ocean model, thermodynamic sea ice model and ice-sheet model (Ganopolski and Calov 2011). The biogeochemistry model includes terrestrial vegetation and carbon cycle model VECODE, marine biogeochemistry model including models of marine biota and deep-sea carbonate sediments, as well as a model of carbon isotopes. For glacial cycle simulations, the biogeochemistry model is updated with models of coral reef growth and terrestrial weathering (Brovkin et al. 2012). The CLIMBER-2 model has been applied for simulating paleoclimates and biogeochemistry including LGM time slice and transient biogeochemistry dynamics during the Holocene and the last glacial cycle, as well as transient changes in climate-ice sheet system over the last eight glacial cycles (Ganopolski and Calov 2011).

To address the role of permafrost carbon in the glacial CO_2 cycles, we updated CLIMBER-2 model with a module for carbon in permafrost, peat, and carbon buried under ice sheet. Recently, Crichton et al. (2014) included permafrost component into CLIMBER-2 framework by accounting for the permafrost extent based on the frost index and by slowing down the timescale of decomposition of the slow carbon pool. Here, we follow another approach. Instead of modifying the timescale of already existing slow carbon pool in the soil model, we introduce three new carbon pools: boreal peat, permafrost, and carbon buried under ice sheet. A simplified model of the peat growth assumes that under favourable conditions for the peat growth, a small fraction of litter is accumulated in the peat pool. This is occurring during the warm periods such as interglacials. The permafrost area is calculated based on soil temperature, and organic content of the permafrost fraction of the grid cell is allocated into the permafrost carbon pool. During the ice sheet growth, the carbon under ice sheets is re-allocated into the buried carbon. During deglaciation, this buried carbon is transformed into unfrozen

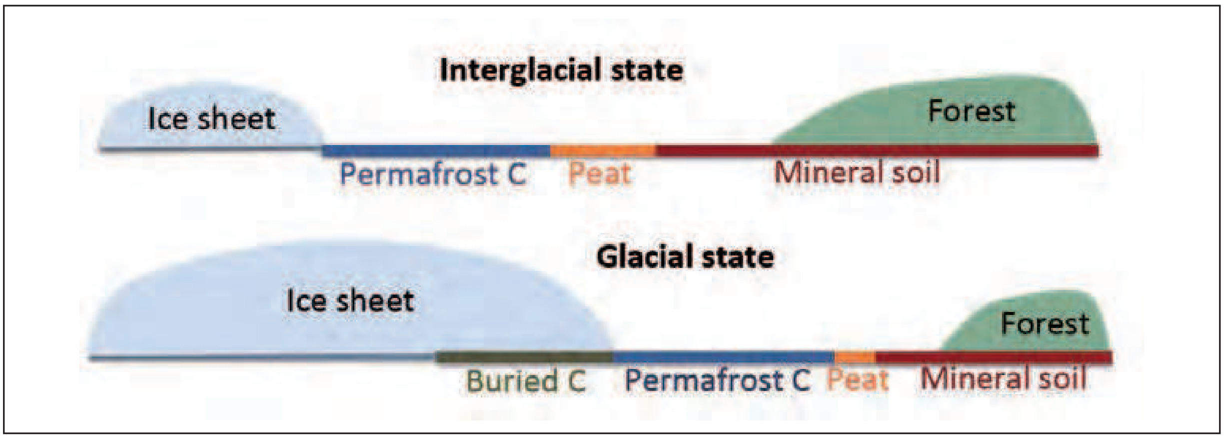

Fig. 1 A sketch of changes in soil carbon pools in regions affected by ice sheet dynamics.

soil pool from which it can relatively quickly be released to the atmosphere. The dynamics of the soil carbon pools during the glacial cycle is illustrated on Figure 1.

The physical model in glacial transient simulations is driven by changes in the orbital forcing and by reconstructed concentrations of greenhouse gases, while the carbon cycle model simulates atmospheric CO_2 interactively, but without feedback to the physical system. For more details of the setup of the physical model, the performance of the ocean carbon cycle model, and simulated atmospheric CO_2 concentration see the companion paper by Ganopolski and Brovkin in this issue.

2. Results

In the course of the four last glacial cycles, total terrestrial carbon storages are changing in the range of 2,700 to 3,100 GtC (Fig. 2). This variability is less than variations in particular components of the terrestrial carbon cycle. The biomass and mineral soil storages are at maximum of 1,800–2,100 GtC during interglacials, and they go down to 1,500–1,600 GtC during glacial maxima. The boreal peat storages grow up to 500 PgC at the end of interglacials or during warm interstadials, but decline to almost zero during glacial maxima. The buried carbon shows the strongest amplitude of changes of ca. 800 GtC with a rapid increase during glacial inception and a rapid decrease during deglaciation. The permafrost carbon in general follows the same dynamics as the buried carbon but shows less amplitude of changes while more abrupt reaction during periods of rapid climate changes.

During glacial inception, while biomass and mineral soil carbon decrease, terrestrial carbon storage increases due to an increase in buried and permafrost carbon (see comparison of 125 to 115 ka BP on Fig. 3). As a result, the land carbon change contributes to drawdown CO_2 during the period of large ice sheet initiation. This would help to start glacial inceptions in the model. At the Last Glacial Maximum, the land total storage is slightly less than at the-industrial. The fast decrease in permafrost and buried carbon during deglaciation contributes to the rapid CO_2 growth as the land carbon storages decrease by about 200 GtC between 20 and 10 ka BP despite of strong increase in the biomass and mineral soil carbon. At the end of the Holocene, the land carbon storage grows due to peat accumulation, and the permafrost carbon starts to increase in response to the cooling in the high northern latitudes.

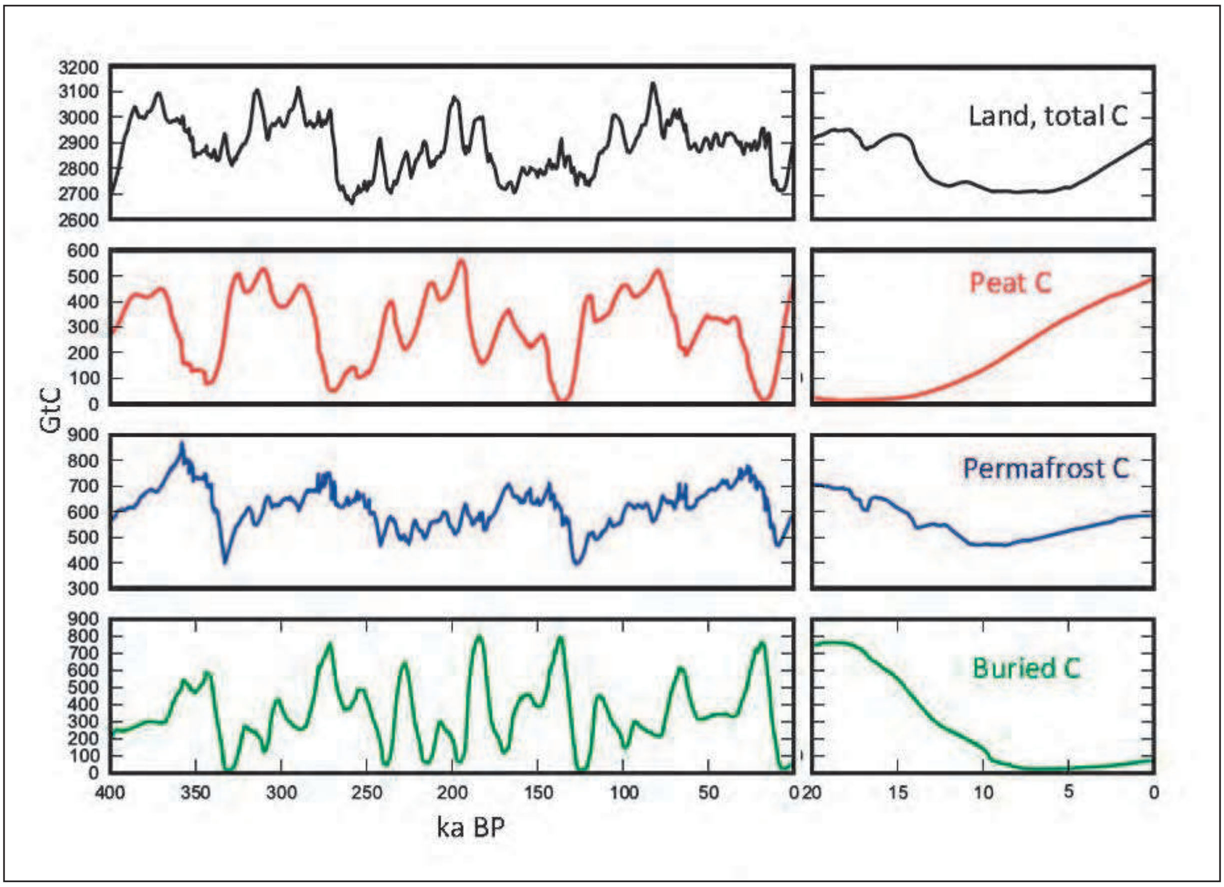

Fig. 2 Simulated changes in terrestrial carbon storages (GtC) during the last 400,000 years (*left*) and the last 20,000 years (*right*).

3. Conclusions

The glacial CO_2 cycles are shaped by changes in marine biogeochemistry which exerts control on the atmospheric CO_2 on multi-millennial timescale. The response of terrestrial carbon to glacial boundary conditions is usually seen as an obstacle in explaining low glacial CO_2 levels. By introducing new carbon pools into terrestrial carbon model, we show that dynamics of soil carbon in the regions affected by the ice sheet growth could change the view on the role of terrestrial biosphere in glacial periods. Especially during the deglaciation period, the land could act as a source of several hundred GtC to atmosphere, contrary to the conventional terrestrial biosphere models that simulate carbon storages growth during deglaciation. While development of modelling approaches to simulate permafrost carbon and carbon stored under ice sheets are still in the initial phase and their calibration is a challenge, we think that these components are an important part of explanation of the glacial CO_2 cycles. More efforts need to be invested into understanding of frozen carbon dynamics.

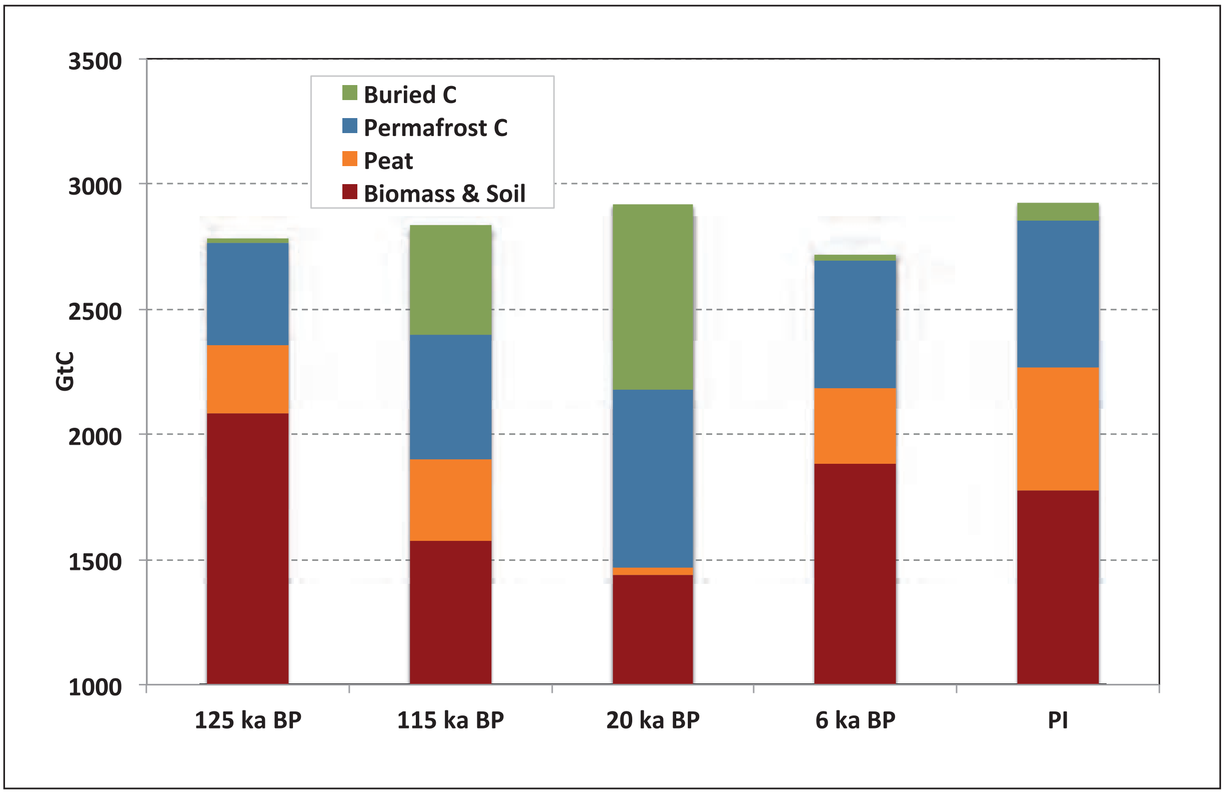

Fig. 3 Simulated land carbon storages at the last interglacial (125 ka BP), glacial inception (115 ka BP), Last Glacial Maximum (20 ka BP), mid-Holocene (6 ka BP), and pre-industrial.

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