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Deglacial Changes in Ocean Dynamics and Atmospheric CO_2

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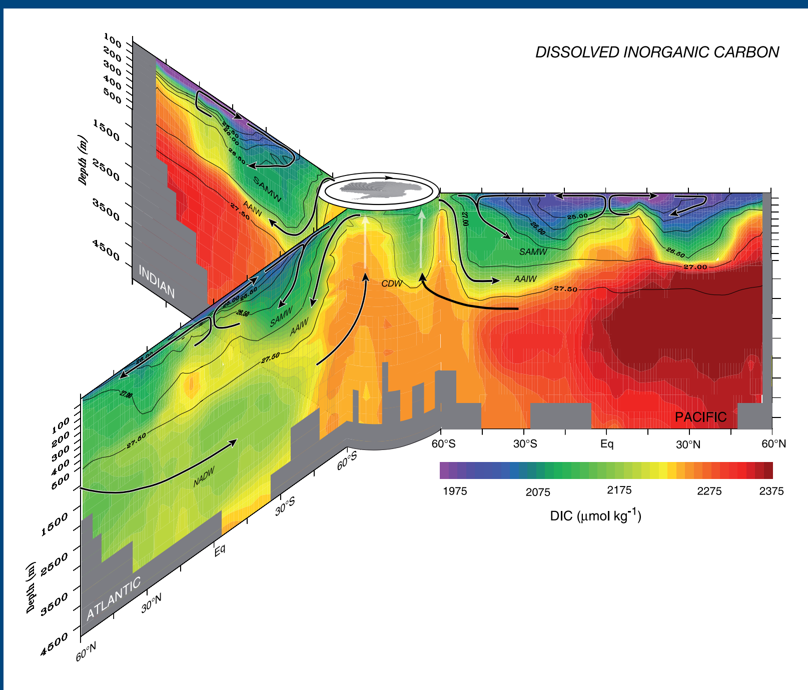

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The Last Four Glacial CO_2 Cycles Simulated with the CLIMBER-2 Model

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With 2 Figures

Antarctic ice cores reveal that atmospheric CO_2 concentrations, at least during the past 800 ka, varied synchronously with global ice volume and the magnitude of glacial-interglacial CO_2 concentration variations reached 100 ppm. It has been shown in a number of studies with climate-ice sheet models (e.g. Ganopolski and Calov 2011) that glacial cycles represent a strongly nonlinear response of the climate-cryosphere system to the astronomical forcing, primarily, through the variations of summer insolation in boreal latitudes of the Northern Hemisphere. At the same time, atmospheric CO_2 concentration represents an important internal positive feedback which strongly amplifies the longest (100 ka) component of glacial climate variability and translates globally regional climate signal from waning and waxing ice sheets. Explanation of full magnitude of glacial-interglacial variations of atmospheric CO_2 concentrations and the link between ice sheets evolution and CO_2 concentration still remain major scientific challenges. Most of previous studies addressed possible mechanisms of glacial CO_2 drawdown, and only few (e.g. Brovkin et al. 2012) attempted to explain CO_2 dynamics during entire glacial cycle, including glacial termination. Proposed mechanisms of the glacial-interglacial CO_2 variability include: change in the ocean temperature and volume, redistribution of different waters masses, change in ventilation of the deep and intermediate ocean, change in ocean alkalinity, biological productivity and several other mechanisms. Although paleoclimate records provide some useful constraints, the relative role of different mechanisms is still debated.

1. The Model and Experimental Setup

For our analysis we use the Earth system model of intermediate complexity CLIMBER-2 (Petoukhov et al. 2000). CLIMBER-2 includes a 2.5-dimensional statistical-dynamical atmosphere model, a 3-basin zonally averaged ocean model coupled to a thermodynamic sea ice model, the 3-dimensional thermomechanical ice sheet model SICOPOLIS, the dynamic model of the terrestrial vegetation VECODE and the global carbon cycle model. The carbon cycle model includes land carbon, oceanic geochemistry, a model for marine biota, and a sediment model (Brovkin et al. 2007, 2012). Weathering rates scale to runoff from the land surface, the coral reef growth depends on the sea level rise. The scale of nutrients utilization in sub-Antarctic ocean is proportional to the dust deposition over the Southern Ocean. Volcanic outgassing has been assumed to be constant through the glacial cycles. The model

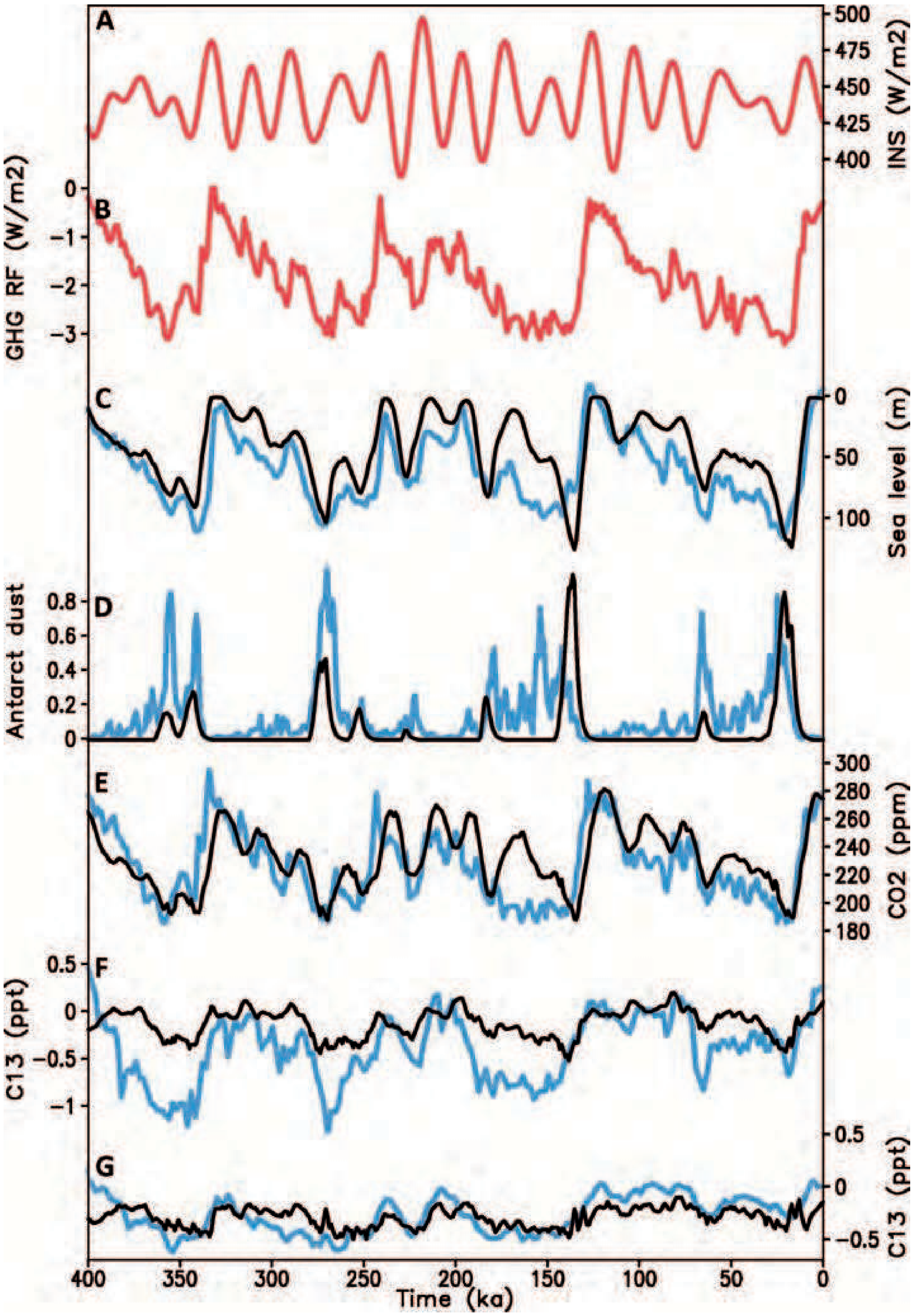

Fig. 1 Transient simulations of the last four glacial cycles forced by orbital variations and observed concentration of well-mixed GHGs. (*A*) Maximum summer insolation at 65°N; (*B*) radiative forcing (relative to preindustrial) of

also includes the dust cycle model which simulates atmospheric dust loading and dust deposition rate. The later affects surface albedo of snow and iron fertilization effect in the South Ocean. Different components of the model have different spatial resolution. Atmosphere and ice sheets are coupled bi-directionally using a physically based energy balance approach (Ganopolski et al. 2010). Ice sheet model is only applied to the Northern Hemisphere. The contribution of the Antarctic ice sheet to global ice volume is assumed to be constant during glacial cycles and equal to 10 %. The CLIMBER-2 model in different configurations has been used for numerous studies of past and future climates, in particular, simulations of glacial cycles (Ganopolski et al. 2010, Ganopolski and Calov 2011) and carbon cycle operation during the last glacial cycle (Brovkin et al. 2007, 2012).

In our experiment, we prescribed temporal variations in astronomical parameters (eccentricity, precession and obliquity). Similarly to Brovkin et al. (2012) atmospheric CO_2 calculated by the carbon cycle module was not used as radiative forcing for the climate model component, which instead was forced by the prescribed equivalent CO_2 concentration, which accounts for the radiative forcing of three major greenhouse gases – carbon dioxide, methane and nitrous oxide. Their concentrations are taken from the Antarctic ice cores. Similarly, CO_2 fertilization effect on vegetation was computed using reconstructed CO_2 concentration. Therefore, there is no feedback of the simulated atmospheric CO_2 concentration to climate. Unlike our previous work (Brovkin et al. 2012), "Antarctic" dust deposition rate, which is used in the parameterization of the iron fertilization effect in the Southern Ocean, was not prescribed but simulated by the model. As the initial conditions we use the final state of the climate-cryosphere system which was obtained from our earlier simulation of the last glacial cycle. The model was run from 400 ka BP until the present.

2. Results

Simulations of the climate system response to orbital forcing and prescribed CO_2 concentration are described in detail in Ganopolski and Calov (2011). Simulated ice sheets volume, their spatial distribution and other climate characteristics are in reasonably good agreement with paleoclimate reconstructions (see Fig. 1). Simulated glacial cycles are characterized by global surface air temperature variations of about 5 ºC, maximum sea level drops by more than 100 m and tripling of the sea ice area in the Southern Ocean during the glacial maxima. Simulated CO_2 concentration closely follows global ice volume variations. The model correctly reproduces the magnitude of glacial-interglacial CO_2 variability of about 80 ppm. At the same time, the model underestimates the rate of CO_2 rise during glacial terminations and fails to simulate short CO_2 "overshoots" seen in the ice core records at the onset of MIS7 and MIS9 interglacials. Comparison of simulated deep ocean $\delta^{13}C$ with paleoclimate reconstructions show that the model correctly simulates larger $\delta^{13}C$ variability in the deep Atlantic compare to the deep Pacific but underestimates the magnitude of glacial-interglacial $\delta^{13}C$ variability, especially in the Atlantic. Under glacial condition the model simulates shoaling of

well-mixed GHGs; (*C*) global ice volume expressed in sea level equivalent; (*D*) Antarctic dust deposition rate in arbitrary units; (*E*) atmospheric CO_2 concentration; (*F*) deep South Atlantic $\delta^{13}C$; (*G*) deep North Pacific $\delta^{13}C$. Black line – modelling results, blue line – empirical data, red line – prescribed forcings.

the Atlantic meridional overturning circulation (Fig. 2*A*, *B*). As the result, the deep Atlantic under glacial conditions is filled with poorly ventilated water masses of southern origin (Fig. 2*C*). Because the dissolved inorganic carbon content of southern-source water is higher than that of North Atlantic deep water, carbon storage in the deep ocean increases significantly under glacial conditions (Fig. 2*D*).

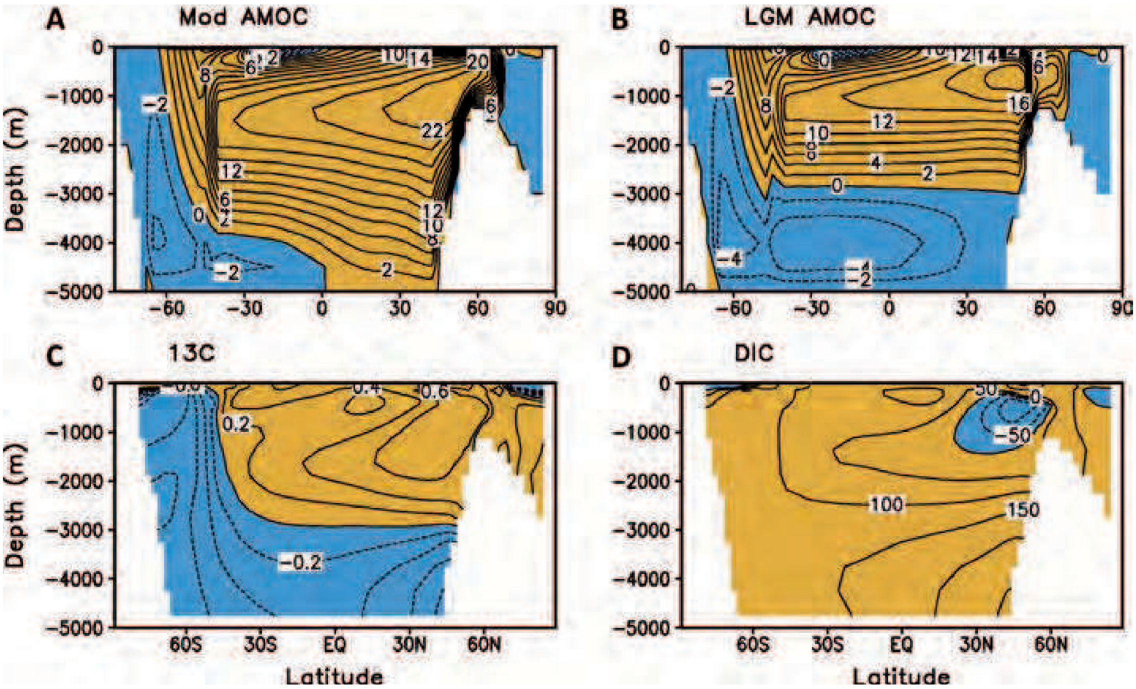

Fig. 2 Glacial-interglacial change in the Atlantic meridional overturning circulation (AMOC), dissolved inorganic carbon (DIC) and $\delta^{13}C$. (*A*) Modern AMOC (Sv); (*B*) glacial AMOC (Sv); (*C*) difference between glacial and interglacial Atlantic $\delta^{13}C$ (‰); (*D*) difference between glacial and interglacial Atlantic DIC (µmol/kg).

According to our modelling results, physical mechanisms – reduction in SSTs and changes in "standing volume" (i.e. redistribution between water masses of southern and northern origin, Brovkin et al. 2012) in response to the expansion of ice sheets and the resulting lowering of sea level – lead to the initial drop of CO_2 during each glacial inception. Enhanced stratification and more extensive glacial sea ice cover in the Southern Ocean also contribute to glacial CO_2 drawdown by reducing CO_2 outgassing in the Southern Ocean. This initial drop in CO_2 concentration is amplified by the $CaCO_3$ cycle and is followed by an increased build-up of ocean alkalinity during the rest of the glacial cycles, as exposed tropical shelves serve as a source of $CaCO_3$ to the ocean, and $CaCO_3$ burial is shifted from shallow waters to the deep sea. Increased nutrient utilization in the Southern Ocean plays an important role towards the end of each glacial cycle by contribution of up to 20 ppm to the CO_2 decline. The role of the land carbon is discussed in the companion paper by Brovkin and Ganopolski in this issue.

3. Conclusions

We present here the first simulations of the last four glacial cycles with interactive ice sheet and carbon cycle models. The model is able to reproduce the major aspects of glacial-interglacial variability, including temporal dynamics of atmospheric CO_2 concentration. At the same time, the model underestimates the rate of CO_2 rise during glacial termination and lacks CO_2 "overshoots" observed at the beginning of several interglacials. These problems may be related to the intrinsic limitations of zonally averaged ocean model or some missing processes. Our modelling results demonstrate that the carbon cycle remains out of equilibrium during glacial cycles which makes initialization of a carbon cycle model serious problem. In this study, we did not consider the feedback from simulated atmospheric CO_2 to the physical climate model because climate component of CLIMBER-2 was forced by prescribed equivalent CO_2 concentration. The next step will be simulation of glacial cycles driven solely by orbital forcing.

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