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Physical mechanisms behind biogeochemical glacial-interglacial CO_2 variations

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Abstract. The atmospheric concentration of CO_2 has undergone significant and fairly regular changes on a time scale of 100 kyr during the at least last four glacial-interglacial cycles. Here we present a novel coupled physical-biogeochemical mechanism for these variations. Previous studies had to arbitrarily specify the behavior of the physical climate system in order to invoke a biogeochemical mechanism for the glacial CO_2 changes, be it an arbitrarily specified change in the vertical ocean mixing [*Toggweiler*, 1999], or arbitrarily specified sea ice cover changes [*Stephens and Keeling*, 2000]. Instead, we present here a new, self-consistent, qualitative physical mechanism for both the vertical mixing and sea ice cover changes. In this mechanism, the cooling of North Atlantic Deep Water due to northern hemisphere glaciation is transported southward by the thermohaline circulation, and cools the deep water upwelling in the Southern Ocean. This, in turn, affects the Southern Ocean stratification, reduces the rate of vertical mixing of the surface water with the deep water and increases the sea ice cover. We also explain the continuous time evolution between glacial and interglacial states rather than treat them as two steady states, and are able to model explicitly for the first time the amplification of the glacial-interglacial variability of the physical climate system by the ocean biogeochemistry.

Introduction

The past years have seen a long series of attempts [*Sarmiento and Toggweiler*, 1984; *Knox and McElroy*, 1984; *Siegenthaler and Wenk*, 1984] to explain why the atmospheric concentration of CO_2 during glacial periods has been about 80 ppm less than during warmer interglacial periods [*Petit et al.*, 1999]. Two recent works seemed finally able to explain the variations in a way that does not contradict the available proxy record [*Toggweiler*, 1999; *Stephens and Keeling*, 2000]. However, both proposed explanations relied on unexplained and arbitrarily specified behavior of the physical climate system in the Southern Ocean, be it a specified change in the vertical ocean mixing [*Toggweiler*, 1999], or specified sea ice cover changes[*Stephens and Keeling*, 2000]. In this work we present a new, self-consistent, qualitative physical mechanism for both the vertical mixing and sea ice cover changes, and therefore are able to present a fuller self consistent picture of the glacial-inter-glacial CO_2 changes.

Dealing with the glacial-interglacial transition mechanism and explaining changes in Southern Ocean vertical mixing and sea ice cover clearly requires a physical model of the glacial-interglacial cycle that is more detailed than the highly idealized ones used previously [*Källén et al.*, 1979; *Saltzman and Verbitsky*, 1994; *Paillard*, 1998]. A sufficiently detailed physical climate model, including simplified yet explicit model components for the oceanic meridional circulation, sea ice, land glaciers, and atmosphere, and a corresponding new mechanism for the 100 kyr glacial oscillations were recently presented in *Gildor and Tziperman* [2000a,b,c]. Here we add to this model an ocean biochemistry model, to create what we believe is the first explicit coupled physical-biogeochemical model of the glacial-interglacial cycles, and investigate the two-way interaction between the ocean biogeochemistry and the climate system.

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The model

Our global meridional box model, shown in Figure 1 and based on that of *Gildor and Tziperman* [2000a,b,c], is composed of ocean, atmosphere, sea ice and land ice sub-models, including an active ocean biogeochemistry and a variable atmospheric CO_2 which may change due to exchanges with the ocean. The main modifications implemented for the present study are as follows. The upwelling water in the Southern Ocean plays an important role in the biochemical mechanisms of *Toggweiler* [1999] and *Stephens and Keeling* [2000]. This upwelling is the result of the westerly winds there, driving a northward Ekman drift and thus an upwelling in the Southern Ocean [*Toggweiler and Samuels*, 1993a; *Gnanadesikan*, 1999], and is specified to be at a constant rate of 16 Sv. The northern hemisphere meridional circulation is calculated in the usual way in such models [*Stommel*, 1961]. The vertical mixing between the surface and deep boxes in the Southern Ocean also plays an important role in this work and is formulated based on the internal wave parameterization of *Gargett* [1984], to be inversely proportional to the vertical density gradient between the surface and deep waters, $K_v = K_0(\partial\rho/\partial z)^{-1}$.

The biochemistry model is similar to those used in 3D biochemical general circulation models [*Maier-Reimer*, 1993]. The model includes total CO_2, alkalinity, and PO_4 (taken to be the limiting nutrient) as prognostic variables that are used to calculate the oceanic pCO_2 and therefore also the exchange of CO_2 with the atmosphere [*Siegenthaler and Sarmiento*, 1993]. The biochemistry prognostic equations are similar to the advection-diffusion equations used for the temperature and salinity, except for an added source/sink term due to export production and remineralization. Redfield ratio is assumed constant and rain ratio is treated as in *Maier-Reimer* [1993]. The rate of export production depends on the latitude via the light factor, the amount of nutrients, and the ocean area not covered by sea ice. The sinking particles from each surface box are assumed to completely remineralize in the deep box below.

A physical mechanism for glacial-interglacial changes in Southern Ocean vertical mixing and sea ice cover

Consider our box model results for one full glacial cycle (Figure 2a-f). The stratification in the Southern Ocean is composed of cold fresh upper water above salty and warmer water whose source is the North Atlantic Deep Water (NADW) water mass. We propose, following our model results, that during the build-up stage of Northern Hemisphere ice sheets (Figure 2a, at time 100 kyr to 30 kyr), the deep water formed in the North Atlantic becomes gradually colder (Figure 2b) as a result of the general Northern Hemisphere cooling due to the increased albedo of the growing land glaciers. Similarly, the mixing of the NADW on its way south with cooler glacial-period surface water in mid-latitudes results in the NADW arriving to the Southern Ocean colder and denser. This is in agreement with both proxy records [*Schrag et al.*, 1996] and general circulation model studies [*Weaver et al.*, 1998] which indicate colder deep water in the Atlantic ocean during the last glacial maximum (LGM) and a colder outflow to the Southern Ocean. Because Antarctica is covered by ice even during interglacial periods, the temperature of the adjacent surface water in the southern box stays close to the freezing point in our model. The Southern Ocean deep water cooling makes our model stratification in the Southern Ocean gradually more stable during glaciation (Figure 2c), consis-

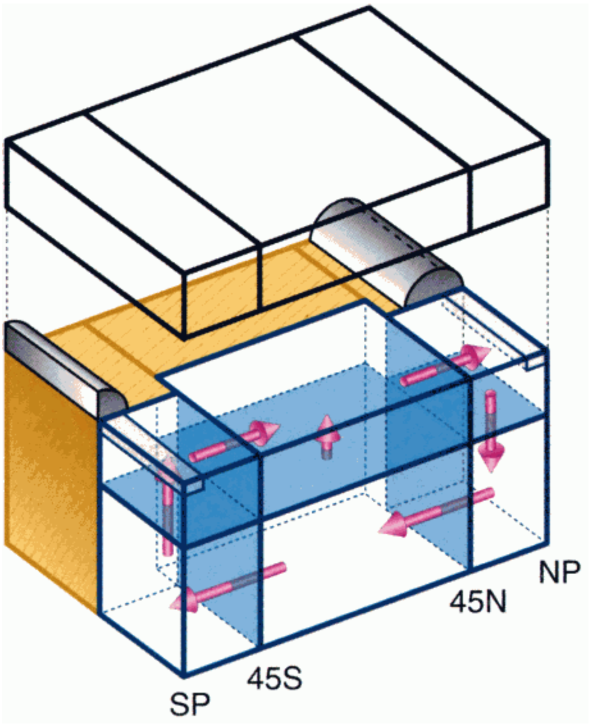

Figure 1. The coupled box model used in this study, showing the atmospheric boxes (upper slab), the thermohaline circulation (arrows), the land ice sheets over land and a partial sea ice cover in the polar ocean boxes. The ocean biogeochemistry and the atmospheric CO_2 fully interact with the physical climate components.

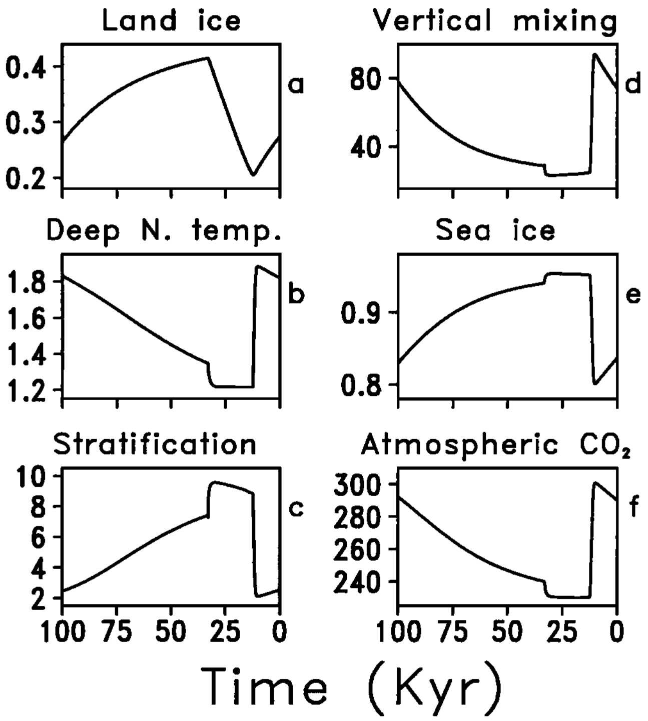

Figure 2. Model results for a complete glacial-interglacial cycle. (a) land ice in the Northern Hemisphere (fraction of northern land box area covered by glaciers), (b) temperature of the NADW flowing into the Southern Ocean (°C), (c) the stratification in the Southern Ocean (density difference between upper and deep water, $10^2 \times kg\,m^{-3}$), (d) vertical mixing in the Southern Ocean (Sv), (e) sea ice extent in the Southern Ocean (fraction of the Southern Ocean area), (f) atmospheric CO_2 in ppm.

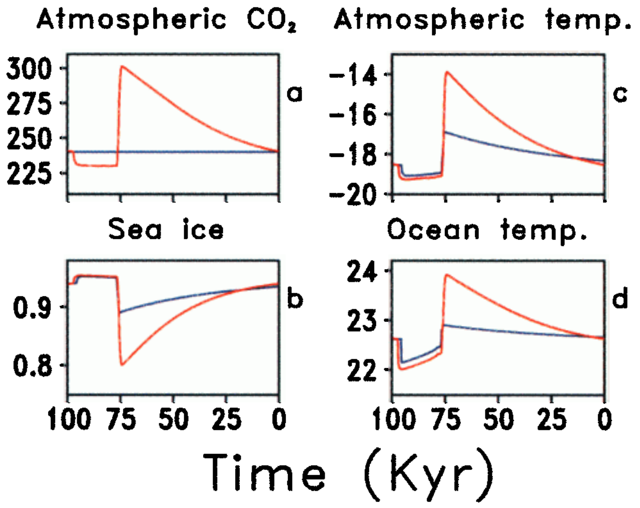

Figure 3. The amplification of the glacial-interglacial signal of the physical climate system by the atmospheric CO_2 variations. Shown are results from a physics only model using a fixed atmospheric CO_2 concentration (blue) and results from a full coupled model with an active ocean biochemistry model (red). (a) atmospheric CO_2 (ppm), (b) Southern Ocean sea ice extent (fraction of the Southern Ocean area), (c) atmospheric temperature above the Southern Ocean (°C), (d) mid latitude upper ocean temperature.

tent with proxy observations [*Francois et al.*, 1997]. Based on the above mentioned vertical mixing parameterization [*Gargett*, 1984], such a more stable stratification reduces the mixing between the CO_2 rich deep water and the surface water in our model (Figure 2d). This is precisely the change of mixing deduced from proxy records [*Sikes et al.*, 2000] and also the one needed to be arbitrarily specified by *Toggweiler* [1999], without the physical mechanism which we provide here. Note that a symmetrically opposite effect happens during deglaciation: the NADW warms, stratification in the Southern Ocean weakens, and the vertical mixing there strengthens.

While Southern Ocean sea ice exists throughout the model glacial cycle, its meridional extension varies between glacial and inter-glacial states (Figure 2e), as well as with the seasonal cycle. During all phases of the glacial cycle, the NADW upwelling in the Southern Ocean is warmer than the surface water and acts to limit the sea ice extent there [*Gordon*, 1981]. During the glaciation phase, the cooling of the NADW (Figure 2b) cools the water upwelling in the Southern Ocean (which is still warmer than the surface water). This cooling of the upwelling water, as well as the reduced vertical mixing of the surface water with the warm deep water (Figure 2d) both contribute to the growth of the Southern Ocean sea ice in our model (Figure 2e) during glaciation. The change in sea ice cover during the glacial-interglacial oscillation which is predicted by our proposed physical mechanism and model, is similar to that arbitrarily specified by *Stephens and Keeling* [2000], and explains part of the atmospheric CO_2 variations via the insulating effect of sea ice cover on gas air-sea exchange.

The variations in the vertical mixing and in the sea ice extent in the Southern Ocean induce together, via the ocean biochemistry, a difference of about 75 ppm in our atmospheric model CO_2 between glacial and interglacial periods (Figure 2f).

We have so far ignored the mechanism of the glacial cycle in the Northern Hemisphere. This Northern Hemisphere cycle is responsible for the changes in the temperature of the NADW reaching the Southern Ocean and causing the vertical mixing and sea ice extent changes in our proposed mechanism. The glacial cycle "sea ice switch" mechanism of the physical climate system in our box model is described in details elsewhere [*Gildor and Tziperman*, 2000b, a]. We emphasize here that our physical mechanism for the changes in the Southern Ocean vertical mixing and sea ice extent is independent of the details of the mechanism of glacial cycles in the Northern Hemisphere. We do assume implicitly in our above discussion that the glaciation (and deglaciation) starts in the Northern Hemisphere (as it does in our physical model [*Gildor and Tziperman*, 2000b, a]) and affects the Southern Hemisphere after a few hundreds of years, once the NADW signal reaches the Southern Ocean.

The precise phasing between the two hemispheres, as well as between changes in atmospheric CO_2, land-ice volume and oceanic and atmospheric temperatures, is still being debated in the literature. Some recent proxies indicate that the Northern Hemisphere leads the Southern Hemisphere [*Clark et al.*, 1999; *Steig et al.*, 1998], while other studies based on $\delta^{18}O_{atm}$ proxy records indicate otherwise [*Bender et al.*, 1985; *Broecker and Henderson*, 1998]. However, obtaining precise timing information from this proxy is problematic, especially during rapid terminations, because the signal in oceanic $\delta^{18}O$ was recently shown to lag behind sea level changes and therefore not to reflect the actual timing of ice volume changes [*Clark and Mix*, 2000]. Yet additional proxy studies seemed to indicate that the deep water of the Southern Ocean lags behind the surface water [*Labeyrie et al.*, 1996], again in seeming contradiction to our mechanism. However, the comparison of the ages of surface and deep waters based on ^{14}C should also be reexamined based on the new finding of *Sikes et al.* [2000]. For the better-dated record of the last deglaciation, it seems that the increase of CO_2 concentration lags sea level rise as it should according to our mechanism by anywhere between zero and four thousand years [*Clark et al.*, 1999; *Yokoyama et al.*, 2000]. We conclude that presently available proxies do not contradict the assumption implied in our mechanism that the Northern Hemisphere leads the south. Another possible test of our proposed mechanism might be to examine the response of the climate system to ice discharges, e.g. Heinrich events, of sufficient magnitude to shut down NADW formation. One could then calculate from the proxy record the time it takes for CO_2 to respond to northern climate changes, and compare the results to the implications of our proposed mechanism.

In our proposed picture for the glacial CO_2 variations, the glacial oscillations exist due to a self-sustained internal variability of the physical climate system [*Saltzman and Verbitsky*, 1994; *Källén et al.*, 1979], with Milankovitch forcing providing the phase locking of the 100 kyr variability [*Saltzman and Verbitsky*, 1994; *Paillard*, 1998; *Gildor and Tziperman*, 2000a]. The CO_2 changes are therefore not the driving force of the glacial-interglacial oscillation [*Loutre and Berger*, 2000] but rather are induced by the physical changes to the Southern Ocean stratification and vertical mixing. There is, however, an interesting two-way feedback between the physical components of the climate system and the ocean biochemistry which our model allows to study for the first time. This feedback involves the amplification of the physical climate system glacial signal by the variations in the atmospheric CO_2. For example, the Southern Ocean mixing and sea ice changes induced by the glacial-interglacial cycle of the physical climate system cause variations in atmospheric CO_2 (Figure 3a) which, in turn, significantly amplify the glacial-interglacial cycle in the Southern Ocean sea ice variability (Figure 3b). This, through the sea ice albedo effect, amplifies the variability of the southern atmospheric temperature relative to a fixed CO_2 scenario (Figure 3c). Mid latitude atmospheric and ocean temperatures (Figure 3d) are also directly affected by the direct radiative forcing of the variable atmospheric CO_2. Such an amplifying role of the ocean biogeochemistry is consistent with recent model results [*Weaver et al.*, 1998] and may play a role in future climate change.

Our simple box model is clearly qualitative and leaves room for future improvements. Still, the detailed mechanism proposed here for the changes in the physical climate system that needed to be arbitrarily specified in previous studies of glacial-interglacial CO_2 changes, have the potential of closing an important gap in our understanding of glacial dynamics.

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