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Effect of land-ice melting and associated changes in the AMOC result in little overall impact on oceanic CO_2 uptake

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[1] The impact of Greenland Ice Sheet (GIS) melting and associated weakening in the Atlantic Meridional Overturning Circulation (AMOC) on carbon uptake is quantitatively evaluated using coupled climate and biogeochemistry models. We compare two 140-yr global warming scenarios, forced by the same increase in atmospheric CO_2, but with different GIS melting rates. The AMOC weakening in our 2 scenarios is −47% and −21% at 4 × CO_2 when the melting of GIS is or is not considered, respectively. We find that GIS melting and AMOC-induced weakening have little influence on the CO_2 uptake. By isolating the specific effects of salinity and temperature changes on carbon uptake, we find that opposing processes tend to limit the effect of GIS melting. Indeed, in the GIS melting scenario, less saline and cooler waters in high latitudes northern seas tend to increase CO_2 uptake and counter-balance the decreasing CO_2 uptake that follows from circulation changes alone.

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1. Introduction

[2] Anthropogenic CO_2 emissions will result in substantial climate change in the coming century. Many feedbacks will respond to the CO_2 perturbation and, if they are positive (negative), will tend to enhance (dampen) global warming. The most important feedbacks in the climate system are associated with water vapor and albedo [*Hansen et al.*, 1984]. Another possible feedback, which has been recently identified [*Klepper and de Haan*, 1995] and confirmed in General Circulation Models [*Cox et al.*, 2000; *Friedlingstein et al.*, 2001], is related to the carbon cycle response to global warming. It has been shown that anthropogenic climate change could reduce both ocean and land carbon uptake, thereby further increasing atmospheric CO_2 concentrations. The strength of this feedback can be estimated as the increased amount of carbon in the atmosphere due to the response of the carbon cycle to climate change. Despite the fact that, thus far, all models simulate a positive feedback, there is still a large uncertainty on the magnitude of this feedback, between +20 ppm and +200 ppm in 2100 according to the models participating in C^{4}MIP [*Friedlingstein et al.*, 2006]. This large uncertainty is due to the uncertain responses of the land and ocean carbon cycles.

[3] For the ocean, the integrated CO_2 uptake reduction due to global warming (IPCC SRES emission scenario A2) from 1860 to 2100 varies from 64 to 222 PgC for the models participating in C^{4}MIP [*Friedlingstein et al.*, 2006]. Several effects contribute to this reduction. CO_2 uptake is directly affected by an increase in temperature via a decrease in solubility. Indirectly, an increase in surface temperature stratifies the surface ocean, which in turn decreases the Mixed Layer Depth (MLD), ocean mixing and the potential to take up anthropogenic carbon. The changes in the hydrological cycle also impact CO_2 uptake through the influence of salinity on solubility and MLD. In addition, it has been argued that the weakening of the Atlantic Meridional Overturning Circulation (AMOC) in response to global warming could have a large impact on carbon uptake. Using a carbon model forced with ocean dynamics from a simulation wherein the AMOC had collapsed, *Sarmiento and Le Quéré* [1996] showed that ocean circulation changes explain 85% of the total reduction in CO_2 uptake. However, in this experiment, temperature was fixed at the initial seasonally varying steady-state ocean values. This experimental design therefore only captures the dynamic impact of AMOC changes and not the associated impact on temperature. More recently, other studies have confirmed a reduction in the oceanic uptake of CO_2 due to global warming conditions and quantified the effect of SST warming, reduced ocean circulation and marine biology changes on these reduction [*Sarmiento et al.*, 1998; *Matear and Hirst*, 1999; *Joos et al.*, 1999; *Plattner et al.*, 2001]. None of these studies has evaluated the potential impact of Greenland Ice Sheet (GIS) melting and associated changes in AMOC on the CO_2 uptake. Moreover the role of AMOC changes in terms of circulation changes and related modifications of temperature and salinity has been investigated in the context of present day and paleoclimate conditions [*Marchal et al.*, 1998; *Schmittner et al.*, 2007] but never for future climate change.

[4] In this study, we quantify the role of GIS melting and associated AMOC changes on the oceanic uptake of CO_2 using a state-of-the-art coupled model. We analyze two transient experiments from *Swingedouw et al.* [2006] (hereinafter referred to as S2006) in which the atmospheric CO_2 concentration is increased by 1%/yr following the CMIP2 protocol [*Meehl et al.*, 2000]. In a first experiment, the melting of GIS is taken into account, which results in a 47% decrease of the AMOC at 4 × CO_2. In a second experiment,

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Table 1. Simulations Description and Cumulative CO_2 Uptake After 140 Years in PgC

Name	Description	CO_2 Uptake
CTL	Control simulation	638.4
GW1	Transient simulation with ice-sheet melting	567.9
GW2	Transient simulation with no ice-sheet melting	571.3
Exp1	Sensitivity experiment similar to GW2 but with GW1 temperature	580.7
Exp2	Sensitivity experiment similar to GW2 but with GW1 salinity	587.3
Exp3	Sensitivity experiment similar to GW2 but with GW1 sea-ice cover	572.4

the GIS melting is not considered and the decrease of the AMOC is only 21% at 4 × CO_2 (see S2006, for more details).

[5] In addition to changes in the ocean circulation, the two experiments differ substantially with respect to the changes in temperature, salinity and sea-ice cover that result. Land-ice melting causes a freshening of the North Atlantic. This effect is amplified by the weakening of the AMOC which imports less salinity to the North Atlantic. Sea surface temperature and sea-ice cover are also affected by the changes in the AMOC. Here, we will quantify the effect of all these GIS melting induced changes on CO_2 uptake.

2. Experimental Design

[6] Climate-induced changes in the ocean are calculated with version 4 of the Institut Pierre Simon Laplace ocean-atmosphere coupled model (IPSL-CM4 [*Marti et al.*, 2005; *Swingedouw et al.*, 2007]). We use the simulations of S2006 to investigate direct and indirect effects of land-ice melting and AMOC changes on oceanic CO_2 uptake. Monthly mean output of the climate simulations is used to force an ''off-line'' version of the global ocean carbon model PISCES [*Aumont and Bopp*, 2006]. PISCES uses the carbonate system formulation recommended by the Ocean Carbon-Cycle Model Intercomparison Project (OCMIP) and includes a simple marine ecosystem model, with 4 plankton functional groups (nanophytoplankton, diatoms, microzooplankton and mesoplankton). Nutrient co-limitation of phytoplankton growth is a function of N, P, Si and Fe. The iron cycle is explicitly modeled including input from atmospheric dust and coastal sediments. In the water column, sinking of particulate carbon is explicitly considered using a simple 2 size-classes model for the particulate organic carbon.

[7] PISCES has been forced by transient climatologies of 3 climate simulations from IPSL-CM4 (CTL, WIS and NIS simulations of S2006). 'CTL' is a control pre-industrial climate simulation and the two others are global warming scenarios forced by a 1%/yr increase in atmospheric CO_2 starting from pre-industrial conditions and in which GIS melting is taken into account (GW1) or not (GW2). The same atmospheric change in CO_2 concentration (+1%/yr) has been applied to the three biogeochemical simulations (CTL, GW1 and GW2, Table 1). The effects of global warming on the ocean carbon uptake, as well as the specific impact of land-ice melting are isolated using these 3 experiments. The reduction in AMOC is larger in GW1 than in GW2. In the North Atlantic, salinity and temperature are lower in GW1 than in GW2 and sea ice cover is higher in GW1 than in GW2.

[8] The effect of GIS melting on the ocean CO_2 uptake is isolated through the comparison of GW1 and GW2. We also consider complementary experiments to address the specific effects of land-ice melting and induced AMOC changes on ocean CO_2 uptake. The effect of temperature changes alone (Exp1) is isolated by forcing PISCES with GW2 fields, but with oceanic temperature taken from GW1. We employ an identical strategy to isolate the effect of salinity (Exp2) and sea-ice cover (Exp3). Note that in these experiments we isolate the direct effects of GIS melting induced changes in temperature, salinity and ice-cover on the carbon cycle (solubility, chemistry and biology), but not through changes in ocean dynamics (Table 1). The effect of circulation has not been separated from biology, since export production is intimately related to the nutrient fields in our model and hence to circulation. The ''circulation and biological'' effect is computed by subtracting the specific effects of temperature, salinity and ice-cover (from Exp1 to 3) from the difference GW1-GW2. As non-linear effects can affect the response, this is only an approximation of this effect. Mixed layer effects are also included in this ''circulation and biological'' effect.

[9] A historical simulation was also conducted with PISCES in order to validate the present model against observations for anthropogenic CO_2 uptake (HIS). It begins in 1860 and is forced until the year 1994 by observed atmospheric pCO_2 concentrations [*Etheridge et al.*, 1998; *Keeling and Whorf*, 2005] and the transient climatology of a historical run with the same coupled climate model.

3. Results

[10] The PISCES model succeeds in reproducing the main features of the observed anthropogenic carbon uptake. The total anthropogenic uptake amounts to 106 PgC in the model for year 1994 and compares well with observation-based estimates of 118 ± 19 PgC [*Sabine et al.*, 2004]. Figure 1 shows that the zonal mean anthropogenic carbon in the Atlantic basin for year 1994 of our HIS simulation is in good agreement with the estimate of Sabine et al. from observations and the use of the ΔC^* method. The penetration of anthropogenic carbon is maximal at high latitudes, particularly in the North Atlantic where its penetration to 3000 m depth is well captured by HIS. In the South Atlantic, the penetration is maximal at 40°S and reaches 1500 m depth in the simulation, as well as in the observations. We note however, that the penetration of anthropogenic carbon in northern high latitudes is underestimated (Figure 1). This is certainly due to the underestimation of the AMOC in the model (11 Sv), which results in a weak ventilation of the Atlantic water mass.

[11] In the CTL simulation, ocean CO_2 uptake increases to 5.8 PgC/yr at 4 × CO_2 (Figure 2c). When the climate change impact is included (in GW1 simulation), the ocean CO_2 uptake at 4 × CO_2 is reduced by 13.8% to 5.0 PgC/yr. When integrated over 140 years, this reduction amounts to 70.5 PgC (Figure 2d), corresponding to an additional 16 ppm of CO_2 in the atmosphere (assuming an airborne fraction of 50%).

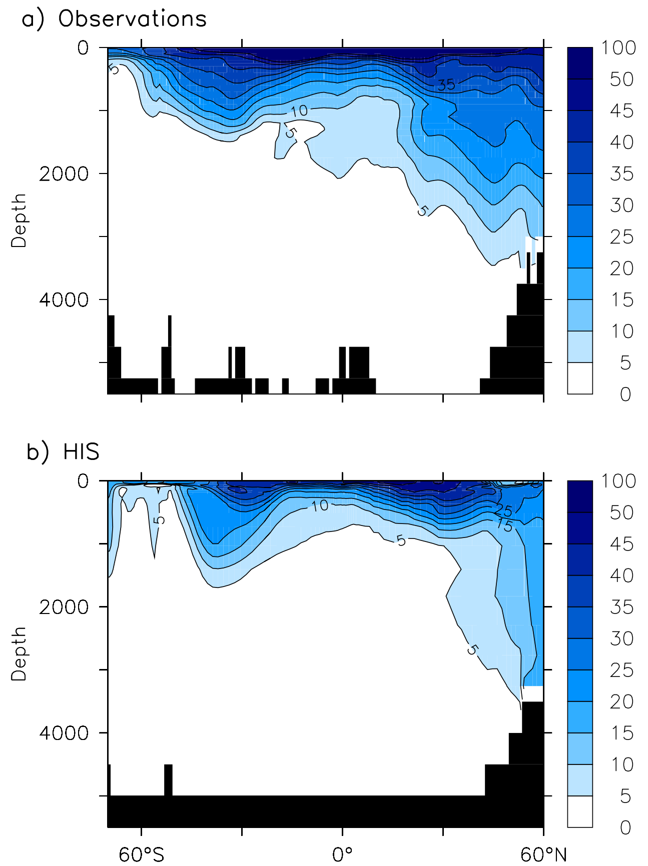

Figure 1. Zonal means of anthropogenic dissolved inorganic carbon (DIC) in the Atlantic basin (a) estimated from observations [*Sabine et al.*, 2004], and (b) modeled in the HIS simulation at year 1994. The contour interval is 5 μmol/L.

[12] Surprisingly, GW1 and GW2 show very similar oceanic carbon uptake (Figure 2c). Over the 140 years of model integration, the GW1-GW2 difference in cumulative carbon uptake is −3.4 PgC. This indicates that the marked reduction in the AMOC between GW1 and GW2 (Figure 2b) does not result in any significant change in the global ocean CO_2 uptake. Locally, a small, but significant, decrease in CO_2 uptake is simulated in the North Atlantic (Figure 3, between GW1 and GW2). This local difference explains the difference of 3.4 PgC between these experiments. That said, this difference remains small. This may be due to the significant decreases in temperature and salinity in this region, that both increase CO_2 solubility in GW1 relative to GW2, and both partly counteract the effect of circulation weakening only. We quantify this compensation using Exp 1-to-3.

[13] Sensitivity experiments show that the decrease in salinity (−2.2 PSU in the North Atlantic in GW1, relative to GW2) tends to increase the cumulative uptake of CO_2 by 16.0 PgC. The decrease in temperature (−1.4 K in the North Atlantic in GW1, relative to GW2) increases cumulative CO_2 uptake by 9.4 PgC. The increased sea-ice cover only has a small impact of +1.1 PgC. Under linear approximation (supported by *Joos et al.* [1999] and *Matear and Hirst* [1999] studies), we estimate that the effect of "circulation + biology" when the AMOC weakening is large (GW1) drives a 29.9 PgC decrease in CO_2 cumulative uptake (as compared to GW2), thereby explaining the negative impact of land-ice melting and associated AMOC reduction on ocean CO_2 uptake. Indirect effects counteract the direct dynamical effect by as much as 89%, such that the total GIS melting and induced AMOC weakening have a small impact on oceanic carbon uptake over century time-scales, but could be larger on longer time-scales (millennial), according to the studies from *Marchal et al.* [1998] and *Schmittner et al.* [2007]. Figure 4 illustrates the quantification of the different compensating effects. Salinity changes play an important damping role on ocean CO_2 uptake. The 2.2 PSU surface salinity decrease in the North Atlantic between GW1 and GW2 is due to both land-ice melting and AMOC weakening. A salinity budget north of 40°N in the North Atlantic shows that 30% of the changes are due to the direct freshening of GIS melting, the rest being due to AMOC changes affecting salinity transport. The large effect

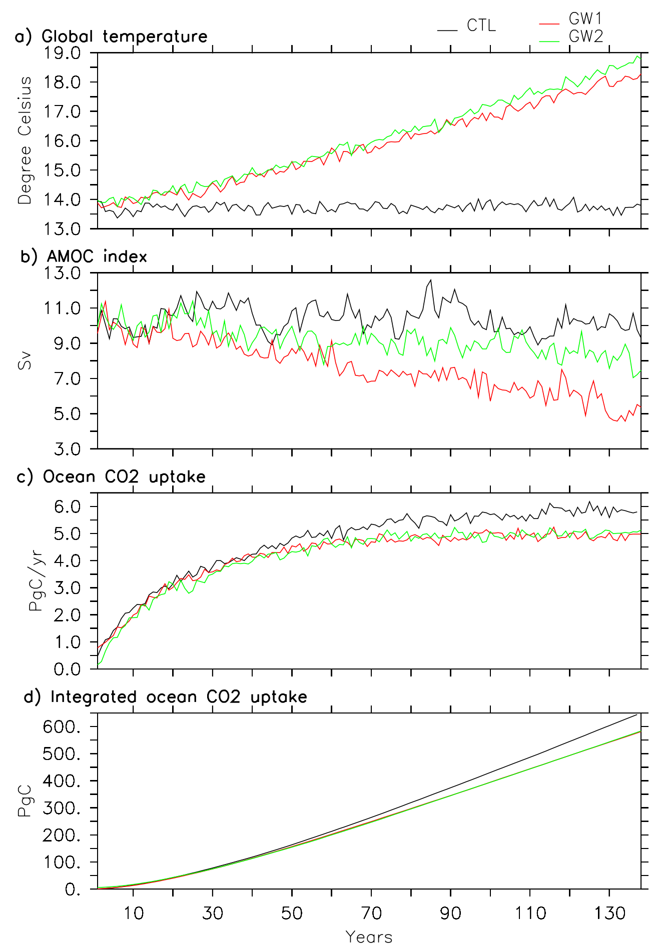

Figure 2. (a) Global mean evolution of atmospheric temperature at 2 m. (b) AMOC index evolution, defined as the maximum of the Atlantic meridional overturning circulation between 500 m and 5000 m depth. (c) Projected annual ocean CO_2 uptake as a function of time. (d) Same as in Figure 2c but for the cumulative ocean CO_2 uptake. In black is CTL simulation, in red GW1, and in green GW2. A 1%/yr increase of CO_2 emissions starting from 1860 conditions is applied.

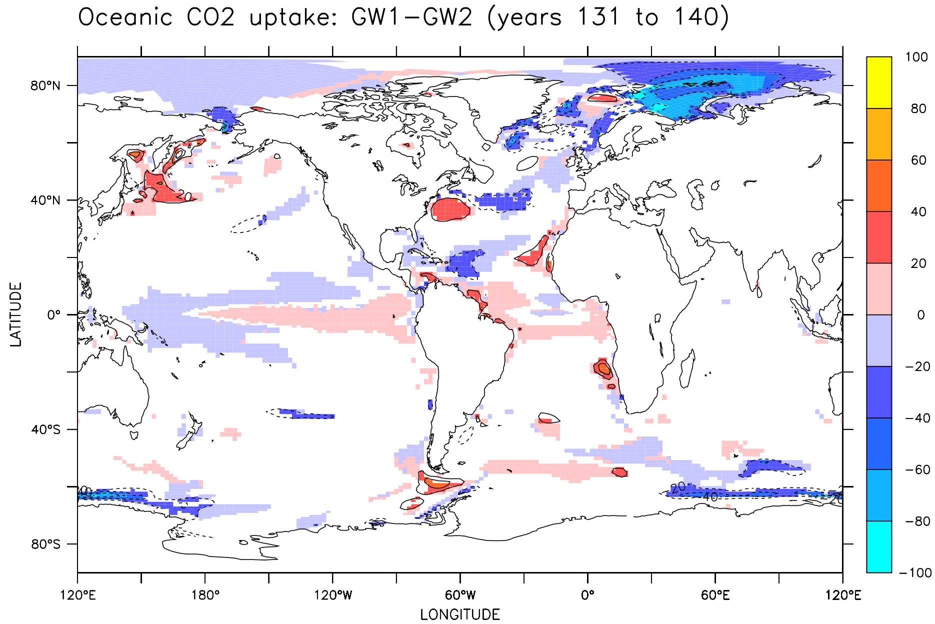

Figure 3. Difference between GW1 and GW2 in ocean CO_2 uptake at 4 × CO_2. The contour interval is 20 gC.m^{-2}.yr^{-1}. Colored zones correspond to the 99% student test significant differences.

of salinity on the CO_2 uptake is due to change in carbonate chemistry coefficients with salinity. Alkalinity concentrations are very similar in Exp 2 to GW2 and therefore cannot explain the difference in CO_2 uptake observed with GW2.

[14] As it impacts CO_2 exchange with the atmosphere over longer timescales, it is also important to consider oceanic storage of anthropogenic carbon. The amount of carbon stored at depth is smaller in GW1 than in GW2 by up to 66 μmol/L at 60°N due to differences in water masses ventilation. We show here that induced changes in AMOC impact anthropogenic carbon distribution in the ocean's interior and that this would influence oceanic carbon transport to lower latitudes. This therefore has the potential to impact outgassing on millennial time scale.

4. Discussions and Conclusions

[15] We have examined the hypothetical effect of GIS melting and associated AMOC changes on the ocean CO_2 uptake. To this end, we used a coupled climate model and an oceanic biogeochemical model to simulate the climate response to a 1%/yr atmospheric CO_2 increase (up to 4 × CO_2). Two parameterizations of GIS melting result in two different transient simulations that exhibit significant differences in the AMOC weakening. We show that the climate warming induced by the CO_2 increase leads to a 11% (70.5 PgC) reduction in the ocean CO_2 uptake. The GIS melting and associated weakening in the AMOC itself only result in a 3.4 PgC decrease in cumulative ocean CO_2 uptake after 140 years. This small impact is a result of compensating effects: (1) A decrease in salinity (+16 PgC) and temperature (+9.4 PgC), as well as an increase in sea-ice cover (+1.1 PgC) due to land-ice melting and AMOC weakening tend to increase CO_2 uptake. (2) Circulation and biological changes, determined by difference assuming linearity, result in a global decrease in CO_2 uptake by as much as 29.9 PgC.

[16] These small differences in CO_2 uptake due to GIS melting are however stored at depth. This storage is therefore effective for long time scales as the differences in surface CO_2 uptake in the North Atlantic due to Greenland melting will accumulate over time. This would lead to potentially significant differences in atmospheric CO_2 over longer timescales.

[17] Finally, we argue that the AMOC impact on CO_2 uptake, here induced by GIS melting, cannot be captured by only integrating an oceanic carbon model with velocity

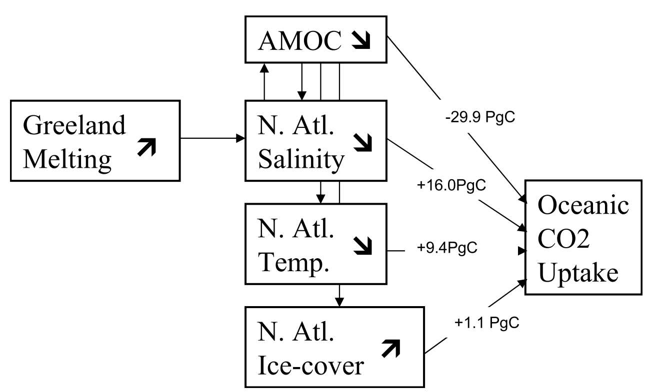

Figure 4. Scheme of the mechanisms at play in this study. The GIS melting implied a change in salinity in the North Atlantic (N. Atl.) that affects the AMOC and thus the temperature (Temp.) and sea-ice cover. We quantify the effect of temperature by the difference between Exp1 and GW2, the effect of salinity by Exp2-GW2, and sea-ice by Exp3-GW2. The direct circulation (velocity and biology) impact of the AMOC changes is evaluated under linear assumption by the difference between GW1−GW2 and the sum of Exp1−3 minus GW2. All these figures appear in the different arrows.

fields from a pre-industrial simulation and thermodynamics from a scenario [*Sarmiento and Le Quéré*, 1996], because both fields influence each other. Salinity and temperature changes associated with circulation changes can actually counteract direct circulation changes effect on oceanic CO_2 uptake.

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