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# Amount of CO<sub>2</sub> emissions irreversibly leading to the total melting of Greenland

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[1] The long-term response of Greenland to anthropogenic warming is of critical interest for the magnitude of the sea-level rise and for climate-related concerns. To explore its evolution over several millennia we use a climate-ice sheet model forced by a range of CO<sub>2</sub> emission scenarios, accounting for the natural removal of anthropogenic CO<sub>2</sub> from the atmosphere. Above 3000 GtC, the melting appears irreversible, while below 2500 GtC, Greenland only experiences a partial melting followed by a re-growth phase. Delaying emissions through sequestration slows significantly the melting, but has only a limited impact on the ultimate fate of Greenland. Its behavior is therefore mostly dependent on the cumulative CO<sub>2</sub> emissions. This study demonstrates that the fossil fuel emissions of the next century will have dramatic consequences on sea-level rise for several millennia. **Citation:** Charbit, S., D. Paillard, and G. Ramstein (2008), Amount of CO<sub>2</sub> emissions irreversibly leading to the total melting of Greenland, *Geophys. Res. Lett.*, 35, L12503, doi:10.1029/2008GL033472.

## 1. Introduction

[2] The global temperature rise expected to occur by the end of the 21<sup>st</sup> century ranges between 1.1°C and 6.4°C [Meehl *et al.*, 2007] depending on models, demographic evolution, and on projections of politic and economic choices. Among the range of available scenarios, some of them assume a reduction of the carbon emissions after 2050 [Meehl *et al.*, 2007]. However, owing to the residence time of CO<sub>2</sub> in the atmosphere, the human activities will affect the climate for many centuries and millennia. One of the main consequences would be a rise of sea-level [Alley *et al.*, 2005; Gregory and Huybrechts, 2006] that will greatly exceed that projected for the next hundred years [Meehl *et al.*, 2007] due to steric changes but also to the melting of glaciers and ice sheets that dominates the uncertainties in sea-level rise estimates. Today, increased accumulation over East Antarctica [Davis *et al.*, 2005] roughly compensates the mass loss from the western part [Rignot and Thomas, 2002; Velicogna and Wahr, 2006] of the ice sheet. If this tendency persists over several centuries, the melting of Greenland will represent the dominant contribution to sea-level rise. Greenland also interacts with the atmosphere [Lunt *et al.*, 2004; Mikolajewicz *et al.*, 2007] and ocean dynamics [Fichefet *et al.*, 2003; Swingedouw *et al.*, 2006], and therefore, its long-term evolution may have huge consequences on the amplitude of climatic changes.

Depending on the temperature rise, the Greenland ice sheet (GIS) may be partially or entirely melted [Greve, 2000]. This raises the question as to whether a complete melting of GIS is an irreversible process. Namely, will Greenland remain ice-free once the atmospheric CO<sub>2</sub> concentration will return to its present-day level? Because of the time scales involved in the absorption of CO<sub>2</sub> by the Earth system [Falkowski *et al.*, 2000], several centuries/millennia must be explored to investigate this issue.

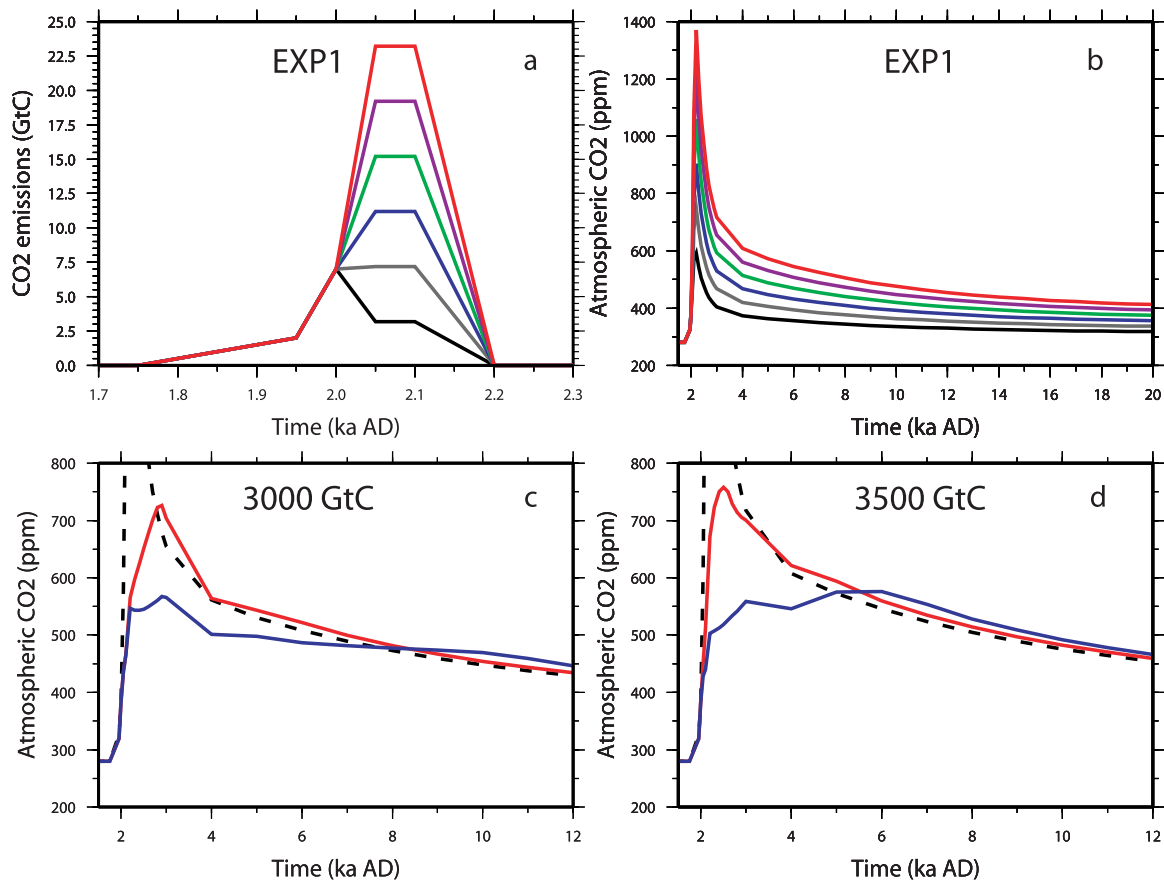
[3] The concept of “irreversibility” is often misleading in current literature. Some studies have investigated which CO<sub>2</sub> scenarios stabilized at different levels after 2100 could lead to the irreversible melting of Greenland [Gregory *et al.*, 2004; Greve, 2000; Huybrechts and de Wolde, 1999; Huybrechts *et al.*, 1991; Ridley *et al.*, 2005], but these scenarios did not account for the actual absorption of CO<sub>2</sub> by the Earth [Falkowski *et al.*, 2000]. A few studies carefully examined the potential irreversibility of the melting [Loutre, 1995; Lunt *et al.*, 2004; Toniazzo *et al.*, 2004]. However, none of them used both a realistic long-term scenario of CO<sub>2</sub> evolution and a model able to capture the climate-ice sheet interactions, so as to explore by a set of simulations the future behavior of GIS.

[4] Therefore, the aim of the present study is to assess with appropriate tools which amount of CO<sub>2</sub> emissions could lead to an irreversible melting of GIS and to investigate, for the first time, whether the rate at which CO<sub>2</sub> is released to the atmosphere during centuries has a huge impact on the behavior of Greenland at the centennial to millennial time scale.

## 2. Experimental Design

[5] In this study, we use an atmosphere-ocean-vegetation model of intermediate complexity, CLIMBER [Petoukhov *et al.*, 2000] coupled to a comprehensive ice-sheet component [Ritz *et al.*, 1997, 2001]. A brief description of the models and their coupling procedure, which accounts for the difference of resolution between climate and ice-sheet models, is provided in the auxiliary materials<sup>1</sup>. Here, we just remind that the ablation rate is computed using the widely-used Positive-Degree-Day (PDD) method, based upon an empirical relation between surface air temperatures and ablation rates of snow and ice [Reeh, 1991]. This method has been calibrated against observations performed for present-day Greenland, but has satisfactorily been tested for climates very different from the present-day one [e.g., Charbit *et al.*, 2005]. The coupled model has a fast computational time that allows for long-term processes to

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**Figure 1.** CO<sub>2</sub> emission scenarios and atmospheric CO<sub>2</sub> concentration. Emission CO<sub>2</sub> scenarios used in (a) the EXP1 experiments and (b) the corresponding atmospheric CO<sub>2</sub> concentration accounting for the natural absorption of CO<sub>2</sub>. The cumulative emissions are 1000 GtC (black), 1500 GtC (grey), 2000 GtC (blue), 2500 GtC (green), 3000 GtC (purple) and 3500 GtC (red). These values are reached in 2200. At that time the maximum CO<sub>2</sub> contents in the atmosphere are 592, 748, 904, 1060, 1215 and 1371 ppm respectively. Note that for clarity of the figure the scales of the time axis are not the same for emissions and atmospheric CO<sub>2</sub>. The atmospheric CO<sub>2</sub> concentrations displayed for EXP2 scenarios are for (c) 3000 GtC and (d) 3500 GtC. The EXP1 scenario corresponding to the same amount of CO<sub>2</sub> emission is also superimposed (black dashed line). For 3000 GtC, the CO<sub>2</sub> emissions continue until 6000 yr AD (red) and 11000 yr AD (blue), and until 5000 yr AD (red) and 7000 yr AD (blue) for 3500 GtC.

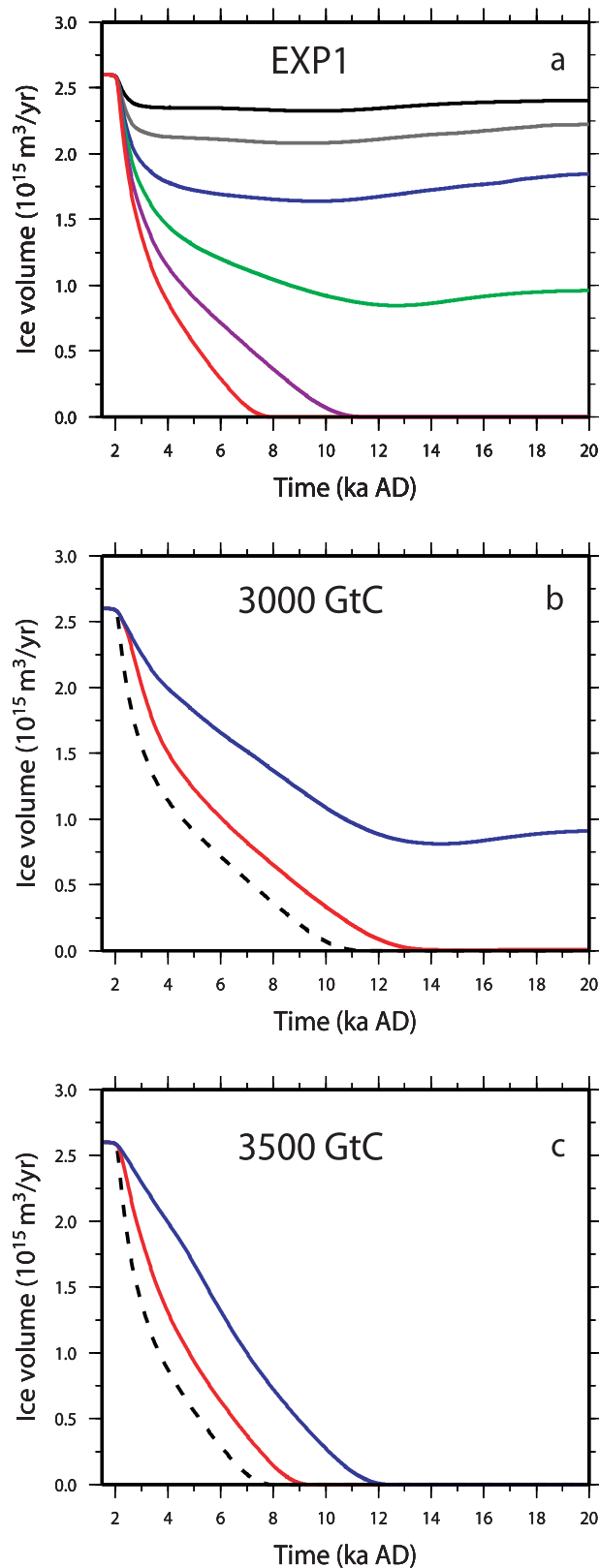
be investigated under several possible scenarios. Accounting for the natural sink of atmospheric CO<sub>2</sub>, we examine the response of GIS over the next 18,000 years to both insolation changes and anthropogenic CO<sub>2</sub> emissions increase.

[6] Two series of experiments are conducted with the coupled CLIMBER-ice sheet model. In the first one (EXP1), the CO<sub>2</sub> scenarios are constructed assuming a linear variation of the emission rate from 2000 (7 GtC/yr) to 2050. The flux is then stabilized until 2100, and after 2200, no further CO<sub>2</sub> emission is released (Figure 1a). Since the model does not represent the global carbon cycle, the response function for atmospheric CO<sub>2</sub> to a given amount of CO<sub>2</sub> emission instantaneously introduced in the atmosphere is expressed as a sum of four exponentially time-dependent terms which account for dissolution in the ocean, chemical neutralization by carbonates on the sea floor and land and consumption by silicates weathering [Archer *et al.*, 1997] (see also auxiliary materials).

[7] To limit the effect of global warming, alternative solutions such as the sequestration of CO<sub>2</sub> are seriously

examined [Lal, 2004]. This sequestration is likely to be efficient only on a few centuries (ocean sequestration) or millennia (geological sequestration), with carbon released afterwards. To test the impact of such effects the second series of CO<sub>2</sub> scenarios (EXP2) has been constructed (Figure 1c and 1d). Keeping the total CO<sub>2</sub> emissions constant from one series to the other, EXP1 and EXP2 experiments differ by the period over which CO<sub>2</sub> is released to the atmosphere; the time scales of the different processes acting to remove CO<sub>2</sub> from the atmosphere are the same in all experiments. This implies that for EXP2, the maximum CO<sub>2</sub> content in the atmosphere is lower than that obtained in EXP1 and reached several centuries later, but the duration of high-level of atmospheric CO<sub>2</sub> is longer.

[8] We performed several EXP1 simulations differing by the total carbon emission ranging from 1000 GtC to 3500 GtC from pre-industrial times to 2200. In 2100, the amounts of total CO<sub>2</sub> emission range between 840 and 2340 GtC (Figure 1a) and are slightly below the lower and upper bounds respectively provided by the B1 (1340 GtC) and the A1FI (2480 GtC) IPCC scenarios [Meehl *et al.*,



**Figure 2.** Simulated ice volumes obtained with (a) the six EXP1 scenarios, (b) the 3000 GtC-scenarios and (c) the 3500 GtC-scenarios. The black dashed line in Figures 2b and 2c corresponds to the EXP1 scenario.

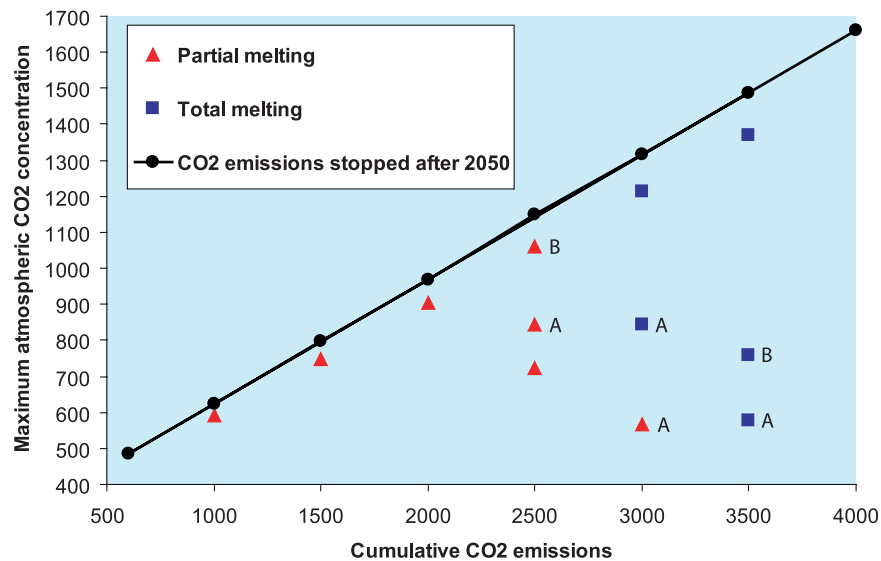
2007]. The EXP2 experiments have been run for a total amount of emitted  $\text{CO}_2$  fixed to 2500, 3000 and 3500 GtC. We present herein the results from 0 kyr to 20 kyr AD.

### 3. Results

[9] In all EXP1 experiments, the  $\text{CO}_2$  perturbation induces an abrupt increase of the global surface air temperature until 2200, followed by a slow decline until 4000 AD, and then, by even slower decreasing phases, each governed by the time scales of the different sinks of atmospheric  $\text{CO}_2$  (auxiliary materials, Figure S1). At 2200, the global temperature rise ranges from 1.6 to 4.0°C (3.1 to 6.2°C over Greenland), and from 1.3 to 2.9°C by the end of 2100 (2.6 to 5.1°C over Greenland), depending on which scenario is considered. This latter interval is slightly below the best estimates provided in the last IPCC summary report (i.e. 1.8–4.0°C), but falls within the lower and upper limits of the likely range (1.1–6.4°C) of the temperature changes given for 2090–2099 relative to 1980–1999 and projected with the six SRES scenarios [Meehl *et al.*, 2007]. More precisely the simulated interval of temperature is fully similar to that provided by the B1 scenario, denoting a low climate sensitivity of our model.

[10] The simulated EXP1 ice volumes highlight two different behaviors (Figure 2a). A first one is observed for the lowest scenarios (1000 to 2500 GtC) where a fast depletion rate between 2000 and 4000 AD is followed by a slower decline. After several millennia, a slight growing phase takes place, mainly due to the increase of the ice thickness (auxiliary materials, Figure S2). Nevertheless, at the end of the simulations Greenland has lost between 10 and 63% of its initial ice volume. In these simulations, the deglaciation is limited to the 60–70°N latitudinal belt, which appears to be the most sensitive to climate change (auxiliary materials, Figure S3). This contradicts the studies from Huybrechts and de Wolde [1999] and Greve [2000] who suggest that GIS first retreats to the eastern mountain ranges under warming conditions, but is in agreement with the results of Cuffey and Marshall [2000] obtained for the Eemian period which was warmer than today. Melting of the ice in the southern region greatly lowers the surface albedo, thus reducing the reflected solar energy and amplifying the net radiative heating. As a consequence, Greenland does not recover appropriate climatic conditions to induce a new glaciation process in ice-free areas, and the re-growth of the ice volume is limited to ice-covered regions even if the atmospheric  $\text{CO}_2$  concentration returns to its present-day level.

[11] The Greenland behavior obtained with the largest scenarios (3000 and 3500 GtC) is quite different (Figure 2a). The rapid phase of ice-sheet shrinkage continues until complete melting (i.e. around 11,500 and 8000 AD respectively). These two simulations have been run until the atmospheric  $\text{CO}_2$  contents recover values similar to the present-day ones, namely until 40,000 and 70,000 AD respectively. During this period, no ice-cap has been nucleated over Greenland area because the temperature increase is amplified by the reduced surface albedo. This suggests that beyond 3000 GtC, the melting of GIS is irreversible for EXP1-type scenarios.



**Figure 3.** Maximum CO<sub>2</sub> content displayed as a function of CO<sub>2</sub> emissions for EXP1 and EXP2 scenarios. The red triangles correspond to experiments leading only to a partial melting of the Greenland ice sheet. Blue squares are for situations where irreversible melting is obtained. Some blue squares are at the same atmospheric CO<sub>2</sub> level than some red triangles (points A). On the other hand, a partial melting can be obtained with a larger atmospheric CO<sub>2</sub> level than that leading to the complete retreat of the ice sheet (points B). Black dots correspond to the maximum CO<sub>2</sub> concentration that could be reached in the atmosphere for a given amount of CO<sub>2</sub> emission, if the emissions were stopped in 2050.

[12] In EXP2 simulations, the temperature signals (auxiliary materials, Figure S4) roughly follow the same trend than those observed for EXP1, although their variations are flattened, implying that the temperature maximum is lower than that reached in the EXP1 simulations. Therefore, the EXP2 simulations constitute appropriate sensitivity tests to investigate the response of GIS to the amplitude and the duration of warming. Simulated ice volumes obtained with EXP2 scenarios are displayed in Figures 2b and 2c. For EXP2-2500 GtC scenarios, the response of GIS is roughly the same than that obtained in the EXP1-2500 GtC run (auxiliary materials, Figure S5). On the contrary, all 3500 GtC scenarios (EXP2 and EXP1) lead to the complete deglaciation of GIS (Figure 2c), although the maximum values of the simulated temperatures are not greater than those obtained in the EXP2-2500 GtC case. The differences in the response of Greenland are related to the duration of the period over which the temperature is close to its maximum (auxiliary materials, Figure S4). On the other hand, the full disintegration of GIS in EXP2 experiments is delayed by 1500 and 4500 years compared to EXP1 because the EXP2 simulated temperatures are lower (Figure S4), which tends to slow down the deglaciation process. Complete deglaciation also occurs in one EXP2-3000 GtC scenario with a time-lag of about 2000 years, whereas the second one leads to only a partial melting of GIS. This is due to the temperature which remains lower throughout the simulation than those obtained with any of the 2500 GtC scenarios, although the duration of warming is quite long (~8 millennia). These results demonstrate that the behavior of Greenland depends both on the amplitude and the duration of warming. The combined effect of these both parameters is directly related to the total amount of emitted CO<sub>2</sub>. Therefore, another way of viewing these results is displayed in Figure 3. This diagram clearly shows

that the maximum atmospheric CO<sub>2</sub> content is not the primary factor responsible for the complete melting of Greenland and that the ultimate fate of GIS is mainly sensitive to the cumulative CO<sub>2</sub> released.

#### 4. Discussion and Concluding Remarks

[13] This set of simulations reveals that complete and irreversible melting of Greenland could be avoided if the total CO<sub>2</sub> emissions would not overcome 2500 GtC (Figure 3). Considering that the fossil fuel emissions that have been burnt up to now are around 350 GtC, policy and mitigation measures must be drastic enough so that the emissions during the next centuries are limited to ~2150 GtC. Owing to the low sensitivity of our model, this value represents an upper limit. Moreover, a number of factors are not represented, such as the radiative forcing of other greenhouse gases. Other processes, such as the evolution of permafrost that stocks large amount of carbon at depth [Nelson, 2003], could have a strong influence on the global emission. In case of partial or total melting of these areas, large quantities of CO<sub>2</sub> (and also of CH<sub>4</sub>) could be released to the atmosphere [Oesterkamp, 2005], thus lowering the critical threshold of fossil fuel emissions that leads to an irreversible melting of Greenland. Regarding the ice-sheet model, some fast processes such as the basal lubrication induced by the penetration of surface melt water, the fast flowing ice streams or the acceleration of outlet glaciers recently observed in South Greenland [Dowdeswell, 2006; Rignot and Kanagaratnam, 2006] are not represented. Accordingly, this study probably underestimates the impact of the rapid dynamics of the Greenland ice sheet. These phenomena mainly affect the southern part of Greenland which appears to be the most sensitive in our model. On the other hand, the lack of representation of these rapid pro-

cesses may be partly compensated by the use of the PDD method which may slightly overestimate the ablation [Van de Wal, 1996]. Accounting for the rapid dynamical processes and a more physically-based calculation of the Greenland surface mass balance would therefore certainly modify the timing of the simulated deglaciation but should not drastically change our conclusions concerning the influence of the rate at which CO<sub>2</sub> is released and the critical magnitude of CO<sub>2</sub> emissions beyond which complete melting of GIS would be irreversible. Therefore, this study clearly demonstrates that due to the long-term processes involved in the global carbon cycle or the evolution of the ice sheets, the climatic changes induced by anthropogenic activities operating on a few centuries will have large consequences for the surface of the Earth for ongoing millennia.

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