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Millennial-scale oscillations in the Southern Ocean in response to atmospheric CO_2 increase

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ABSTRACT

A coupled climate-ice-sheet model is used to investigate the response of climate at the millennial time scale under several global warming long-term scenarios, stabilized at different levels ranging from 2 to 7 times the pre-industrial CO_2 level. The climate response is mainly analyzed in terms of changes in temperature, oceanic circulation, and ice-sheet behaviour. For the $4 \times CO_2$ scenario, the climate response appears to be highly non-linear: abrupt transitions occur in the Southern Ocean deep water formation strength with a period of about 1200 yr. These millennial oscillations do not occur for both lower and larger CO_2 levels. We show that these transitions are associated with internal oscillations of the Southern Ocean, triggered by the Antarctic freshwater budget. We first analyse the oscillatory mechanism. Secondly, through a series of 420 sensitivity experiments we also explore the range of temperature and freshwater flux for which such oscillations can be triggered.

1. Introduction

Ice core data as well as marine and continental records reveal the existence of pronounced millennial time-scale variability in the Quaternary climate system (Broecker et al., 1985; Bond et al., 1992, 1993; Sachs and Lehman, 1999; Elliot et al., 2002; Sanchez-Goni et al., 2002; Wang and Mysak, 2006; Wainer et al., 2009). As an example, the Dansgaard-Oeschger events (Dansgaard et al., 1989, 1993) are characterized by abrupt transitions occurring in a few decades, and by a period of a few thousand years. Such rapid climate variability appears to be stronger in glacial periods than during interglacials, but there is not yet a full consensus about its origin. Two types of explanation have been suggested: periodic external forcing (Keeling and Whorf, 2000; Braun et al., 2005), and internal oscillations in the climate system, for which ocean circulation is a likely candidate (Broecker et al., 1990; Clark et al., 2002; Broecker, 2006; Alvarez-Solas et al., 2010).

The main reason for the non-linear behaviour of the ocean circulation is the existence of positive feedback mechanisms. The large-scale thermohaline circulation is affected by two major positive feedbacks relying either on an advective or a convective mixing. The advective feedback is characterized by the northward advection of salty water in the Atlantic that enhances water density in the North, causing in turn a stronger thermohaline circulation (Stommel, 1961; Bryan, 1986). The convective feedback is associated with a vertical mixing which removes freshwater coming from precipitation, ice melting or calving. This process prevents the formation of a fresh light surface layer which further inhibits convection (Welander, 1982; Lenderink and Haarsma, 1994). These two mechanisms allow the existence of multiple equilibrium states of the oceanic circulation. Oceanic millennial-scale variability has been analyzed since several years by a large range of models of different complexity. The first one indicating the existence of multiple equilibria in the thermohaline circulation and illustrating the importance of the advective feedback mechanism was the Stommel's horizontal two-box model (Stommel, 1961). The existence of self-sustained thermohaline oscillations in a vertical water column was demonstrated by Welander (1982) with a vertical two-box model. In addition to box models representing convective and advective feedbacks, Earth Models of Intermediate Complexity (EMICs) and General Circulation Models (GCMs), with more detailed dynamics, have then been used to explore the oscillatory behaviour of the ocean (Mikolajewicz and Maier-Reimer, 1990; Timmermann et al., 2003; Abshagen and Timmermann, 2004). On the other hand, it has also been suggested that an oceanic oscillatory behaviour could be excited through white-noise forcing even when the deterministic solution is completely stable (Mikolajewicz and Maier-Reimer, 1990; Ganopolski and Rahmstorf, 2002). Most of these studies were designed to elaborate plausible spontaneous mechanisms for the origin of Dansgaard-Oeschger (D-O) events.

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In the present climate, the deep water formation has been observed through two main processes: open-ocean deep convection and sinking of dense high salinity shelf waters. The open-ocean deep convection occurs in some regions of the Atlantic Ocean: the Labrador, Greenland, and Mediterranean Seas as well as in the Weddell Sea (Marshall and Schott, 1999). On the other hand, the rejection of salt by sea ice formation plays an important role in the formation of AABW (Nicholls et al., 2009). In this case the convection occurs in very narrow water columns, or plumes, with spatial scales <1 km (Marshall and Schott, 1999).

Usual convective schemes on EMICs and GCMS are based either on the application of very high mixing coefficients when the water column becomes unstably stratified (as in CLIMBER-2) or on actual mixing of the water column. This results in a mixing of the whole grid-cell area, and therefore on larger spatial scales than observed. In spite of these limitations, deep water formation occurs under these conditions, the large-scale oceanic circulations are reproduced in CLIMBER-2 and a reasonable Atlantic overturning circulation can be attained for present-day conditions (Rahmstorf and Ganopolski, 1999; Petoukhov et al., 2000), but also for the Last Glacial Maximum (LGM) (Ganopolski and Rahmstorf, 2001) and for the last interglacial period (Khodri et al., 2003).

Nevertheless, the more stable present-day interglacial period is being currently perturbed by anthropogenic emissions of greenhouse gases. Theoretical considerations about ocean dynamics and glacial variability of the thermohaline circulation lead several authors to argue that the climatic stability of the Northern hemisphere high latitudes could change in response to the increase of greenhouse gases in the atmosphere, due to the warming of oceanic surface layer and freshwater input from Greenland melting (Broecker, 1997; Rahmstorf and Ganopolski, 1999; Rahmstorf, 2003; Swingedouw et al., 2007; Charbit et al., 2008). However, this context does not favour the occurrence of millennial oscillations in North Atlantic Ocean. As noted by Ramhstorf (2003): "D-O events are not present in the Holocene possibly because the North Atlantic Ocean circulation is not close to a threshold in a warm climate". Therefore, the question arises as to whether anthropogenic warming may drastically impact the climate stability of the Southern hemisphere: Could this warming trigger an oscillatory behaviour of the Southern Ocean? Could this warming destabilize the Antarctic ice sheet leading to periodic ice discharges into the Southern Ocean, similarly to Heinrich events in the Northern hemisphere?

In order to answer these questions, we use in this paper the CLIMBER-2 (CLIMate-BiosphERe) Earth System Model (Petoukhov et al., 2000) coupled to Northern and Southern ice-sheet models (Ritz et al., 1997, 2001). Such a numerical tool allows the investigation of the long-term behaviour of Northern and Southern high latitudes in response to climate warming as well as the feedbacks between atmosphere, ocean and polar ice sheets. Due to massive freshwater discharges coming from the potential destabilization of the ice sheets and to the associated changes in oceanic circulation, the climate response to anthropogenic warming may be highly non linear. Therefore, in the present study, we explore the potential occurrence of rapid climate variability in the future within a large spectrum of perturbations (in terms of CO_2 and ice-sheets response) and we investigate the mechanisms that induce a new oscillatory behaviour.

2. Model description

The climate model used here is the CLIMBER-2 Earth system model of intermediate complexity (Petoukhov et al., 2000). This model is based on simplified representations of atmosphere, vegetation, ocean and sea-ice. The atmosphere component is based on a statistical-dynamical approach and has a coarse spatial resolution of 10° in latitude and approximately 51° in longitude. This module is designed to resolve large-scale processes (~1000 km), whereas statistical characteristics of the synoptic variability are parameterized as diffusion terms. The radiation scheme accounts for water vapour, CO_2 and the computed cloud cover (stratiform and cumulus). The ocean model is composed of three zonally averaged basins (Atlantic, Indian and Pacific) connected around Antarctica. The equations are solved on a 2.5° latitudinal grid with 20 vertical layers. The mean zonal effect of the horizontal wind-driven gyres is taken into account through imposed advective transport at key latitudes such as those covered by the Southern Ocean. The sea ice component predicts the ice fraction and thickness for each grid cell and includes a simple treatment of advection and diffusion of sea ice. In the model hierarchy, CLIMBER-2 is placed between energy balance models and General Circulation Models (GCMs) (Claussen et al., 2002). It describes a large set of processes and feedbacks in the climate system and favourably compares to GCMs for present-day and glacial climates (Petoukhov et al., 2000; Ganopolski et al., 2001), but has a much faster computational time due to its low spatial resolution and simplified governing equations. Moreover, this model has been revealed to be very useful to understand very important features of the glacial oceanic millennial variability (Ganopolski and Rahmstorf, 2001; Ganopolski et al., 2001; Ganopolski and Rahmstorf, 2002; Roche et al., 2004; Braun et al., 2005). The Antarctic ice sheet model, GRISLI (Ritz et al., 2001), is a 3-D ice-sheet model (40 × 40 km). It predicts the evolution of the geometry of the Antarctic Ice Sheet (AIS) and accounts for the thermomechanical coupling between temperature and velocity fields. It deals with both inland and floating ice and explicitly computes the migration of the grounding line. The Northern hemisphere ice sheet model, GREMLINS (45 km × 45 km) is developed in the same way than GRISLI, except that it only deals with inland ice (Ritz et al., 1997). These models, as the other ice-sheet models (Huybrechts, 1990; Greve et al., 1998; Huybrechts and de Wolde, 1999; Marshall et al., 2002) do not successfully reproduce small scale processes, such as the acceleration of the ice flow from outlet glaciers, which has recently been shown to be an important process for the acceleration of the Greenland melting (Rignot and Kanagaratnam, 2006). However, they include a representation of the main mechanisms responsible for slower and large-scale processes and can reasonably be used to simulate the behaviour of polar ice sheets over the next thousands years. The coupling method between GREMLINS and CLIMBER-2 is described in (Charbit et al., 2005) and (Kageyama et al., 2004): the mean annual and summer (June–July–August) surface air temperatures and annual snowfall computed by CLIMBER-2 are given to GREMLINS through downscaling techniques to compute the surface mass balance. In turn, the altitude and the nature (land ice, ice free land or ocean) of each ice-sheet model grid point are returned to CLIMBER-2. The freshwater fluxes resulting from ice-sheet melting is released into the ocean. The coupling method between CLIMBER-2 and GRISLI is based on the same procedure, but the oceanic temperatures at 500 m-depth are also used to compute the basal melting under the ice shelves (Philippon et al., 2006). This fully coupled climate-cryosphere model (referred to hereafter as CLIMBER-IS) has been used to reproduce the last glacial inception (Kageyama et al., 2004), the last deglaciation (Charbit et al., 2005), the future deglaciation of the Greenland ice sheet (Charbit et al., 2008) and the Antarctic contribution to the sea-level rise through last glacial termination (Philippon et al., 2006).

3. Experimental set-up

CLIMBER-2 is forced by insolation and a set of different anthropogenic atmospheric CO_2 scenarios starting from the pre-industrial value (i.e. 280 ppm, between 0 and 1860 AD) and stabilized at the following levels: 560, 840, 1120, 1400 and 1960 ppm, that is 2, 3, 4, 5 and 7 times the pre-industrial level. This highest value was estimated to approximately correspond to the total available fossil fuel supplies (Archer et al., 1997). Another experiment (control run)