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Modelling the Physical and Biogeochemical Impacts of a Freshwater Discharge in the North Atlantic with a Model of Intermediate Complexity

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ABSTRACT. An ocean-atmosphere climate model was coupled to a biogeochemical model of the ocean carbon cycle to study the physical and biogeochemical effects of a massive freshwater discharge in the North Atlantic Ocean. The experiment consists in discharging a total freshwater amount of 6×10^6 *km*^{3} *between 45 and 70°N over 1000 years. The discharge induces a complete shutdown of the thermohaline circulation and a substantial cooling of the North Atlantic while Atlantic intermediate waters become warmer and saltier. These physical consequences modify the biological activity. For instance, Net Primary Production (NPP) in the North Atlantic drops by 50%. Besides, the vertical gradient of dissolved inorganic carbon (DIC) and nutrient concentration is strengthened as a response to the reduction of vertical mixing in that area and enhanced advection of Antarctic Bottom Water. The recovering of thermohaline circulation after the discharge is characterized by an overshoot accompanied by a maximum in Net Primary Production.*

KEY WORDS: climate model, carbon cycle, thermohaline circulation, Heinrich event.

Introduction

Paleoclimate data analysis have shown that over the last 60,000 years the Earth's climate experienced a series of abrupt events which were characterized by changes in ocean circulation, sea surface and air temperature as well as atmospheric CO_2 concentration. It appears also that most of these events (and in particular the Heinrich events) are associated with massive iceberg discharges in the North Atlantic. However, the chronology of the various climatic processes implied in abrupt events remains a difficult question and climate modeling could provide interesting insight. In this study, the MoBidiC climate model from Louvain-la-Neuve is used to explore the impacts of a massive freshwater discharge in the North Atlantic on the ocean circulation, temperature, salinity as physical impacts but also on biological tracers distribution in the ocean.

The climate model

In order to study the transient behaviour of the interactions between the major climatic component at the millenium time scale it was necessary to develop a model requiring reasonable computing cost. The physical model used in this study (Gallée et al., 1991; Tulkens, 1998; Crucifix et al., 2000) includes a latitude-altitude grid and a sectorial representation of the Earth Surface: each zonal band is divided in sectors associated to continents, ice sheets and ocean basins. This model includes a zonally averaged, two levels quasi-geostrophic atmosphere, a continental surface model that also calculates the snow cover and vegetation distribution, a zonally averaged, primitive equation model of the ocean circulation in the three major basins and, finally, a thermodynamic-dynamic sea ice model.

The biological component represents the cycling of dissolved organic carbon (DOC), particulate organic carbon (POC), carbonates ($CaCO_3$), phosphates (PO_4, taken as the biolimiting nutrient), oxygen and alkalinity. In the euphotic zone, a Michaelis-Menten kinetics formulation parameterized as in Maier-Reimer (1993) controls the Net Primary Production (NPP) of organic matter. Half of the organic matter is produced as POC remineralizing instantaneously in the water column as in Martin et al. (1987). The other half is produced as DOC. Remineralization of DOC follows a first order kinetic-law calibrated such that global DOC inventory is constant. Production of carbonates in the euphotic zone and their complete redissolution in the water column follow Marchal et al. (1998a). Carbonate storage in the sediment is not taken into account. A chemical model based on the dissolution constants for carbonates and borates of Millero (1979) is used to compute the amount of aqueous CO_2 at the surface. At last, the wind-dependent formulation of Wanninkhov (1992) is used to compute oxygen and CO_2 exchanges between the ocean and the atmosphere. Wind velocity and sea surface temperature introduced in that formulation are calculated by the physical model.

Experimental setup

The experiment starts from the pre-industrial climate, i.e. the equilibrium response to a 280 ppmv CO_2 concentration and modern insolation.

The freshwater discharge begins after 1 ka of integration (Fig. 1). Freshwater is uniformly discharged in the North Atlantic between 45° and 70°N. The freshwater input increases from 0 to 0.38 Sv (1 Sverdrup = 10^6 m^3/s) over 500 years and then decreases linearly to 0 during another 500 years. This corresponds to a total freshwater volume of 6 x 10^6 km^3. The model is integrated during 8000 years after the freshwater discharge in order to recover an equilibrium state.

Results

Consistently with previous model studies (e.g. Schiller et al., 1997), the freshwater discharge induces a shutdown of the thermohaline circulation (THC). The amount of heat released from the North Atlantic to the atmosphere drops from 550 MW to -150 TW. This negative value means that a net heat transfer from the atmosphere to the North Atlantic appears. Fig. 2 depicts the change in Atlantic potential temperature between inactive THC regime (t = 2ka) and active THC regime (t = 1ka), and Fig. 3 illustrates the corresponding change in salinity. Temperature and salinity of Atlantic Intermediate Water increase very substantially when THC shuts down because in these regions the diffusion of warm and salty water from the surface is no longer balanced by advection of cold and fresh deep waters. It appears also that temperature change resulting from the THC shutdown is asymmetric with respect to the equator, the warming being more intense in Atlantic Intermediate waters South of the equator than in the North. This result agrees qualitatively with the previous study by Stocker and Wright (1996), although the warming is greater here. Similarly, the simulated increase in Atlantic intermediate water salinity is large. In particular, sea surface salinity in equatorial Atlantic increases by 1.5 to 2.5 psu while the OAGCM study by Schiller et al. (1997) indicates only small changes in that region.

Finally, northward advection of fresh and cold Antarctic Bottom Water is enhanced and extended northward. This induces a cooling and a freshening of deep Atlantic waters.

The drastic reduction of NADW ventilation - leading to an increase in NADW residence time - combined with the advection intensification of nutrient-rich Antarctic Deep Water impacts also on the distribution of biogeochemical tracers, as illustrated on Fig. 4 and 5. In the Deep Atlantic, PO_4 concentration increases by more than 0.5 mmol/m^3 with respect to active THC regime. This is in quantitative agreement with the model estimate of Marchal et al. (1998b). For the same reasons, DIC concentration increases by 60 mmol/m^3 in the deep Atlantic. On the other hand, less nutrients are advected from the surface to the aphotic zone in inactive THC regime. This is responsible for a weakening of the biological activity in the North Atlantic by approximately 50%, as shown on Fig. 6.

After the freshwater discharge, the overturning rate increases abruptly. Approximately 170 years after the end of the discharge, NADW export into the Antarctic exceeds temporarily 27 Sv and then decreases progressively back to 21 Sv. This "over-

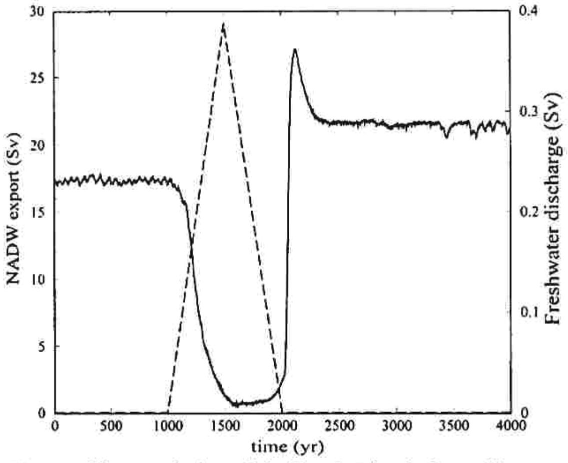

Fig. 1. Time evolution of the North Atlantic Deep Water export into the Antarctic basin (plain, LHS scale) and of the freshwater flux applied in the 45–70 N Atlantic (dashed, RHS scale). Units are Sverdrups (Sv = 10^6 m^3s^{-1}).

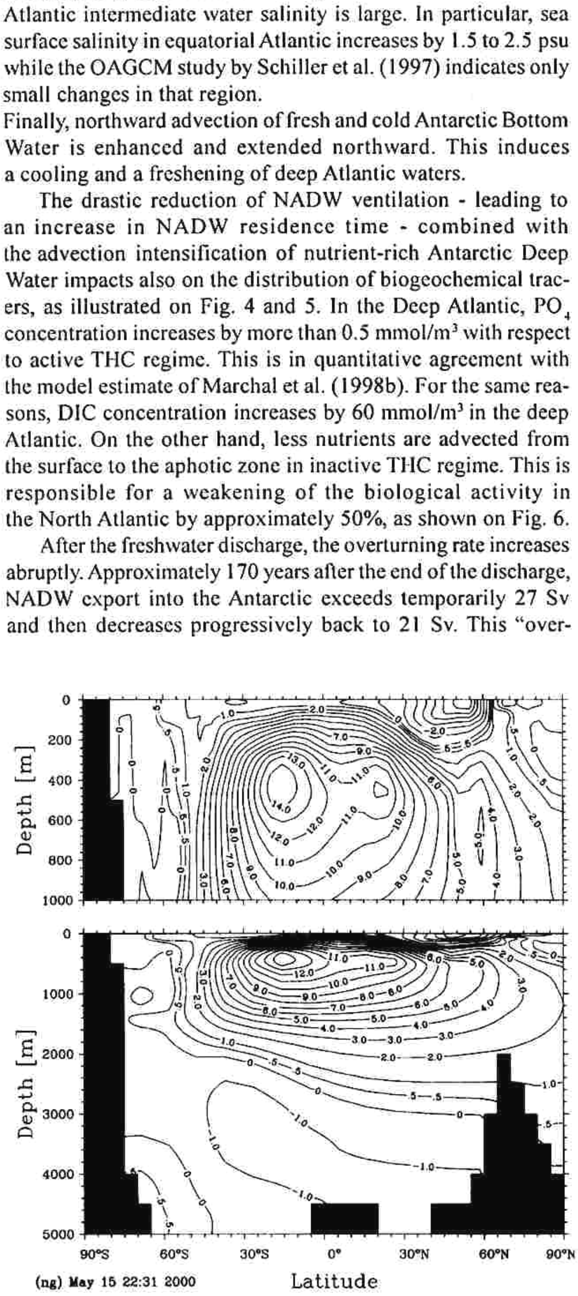

Fig. 2. Latitude-depth profile of the difference in zonally averaged potential temperature (°C) in the North Atlantic Ocean between inactive THC circulation state (t = 2 ka, at the end of the freshwater discharge) and active THC state (t = 1 ka, begin of the freshwater discharge).

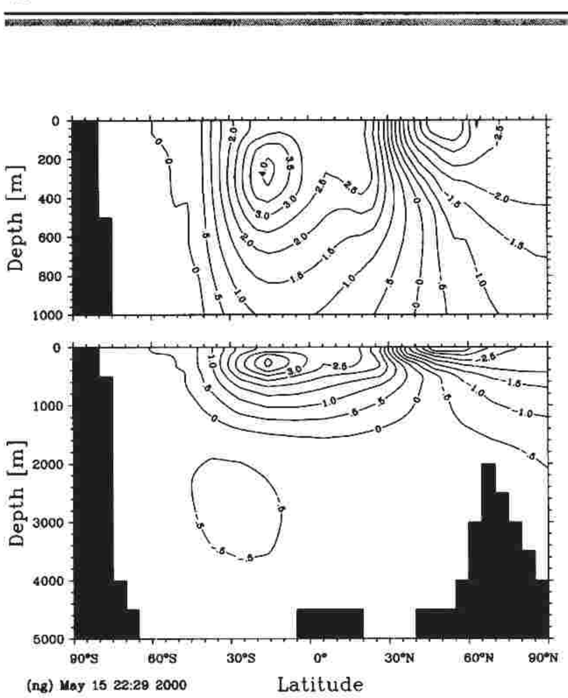

Fig. 3. Latitude-depth profile of the difference in zonally averaged salinity (in psu) in the North Atlantic Ocean between t = 2 ka and t = 1 ka.

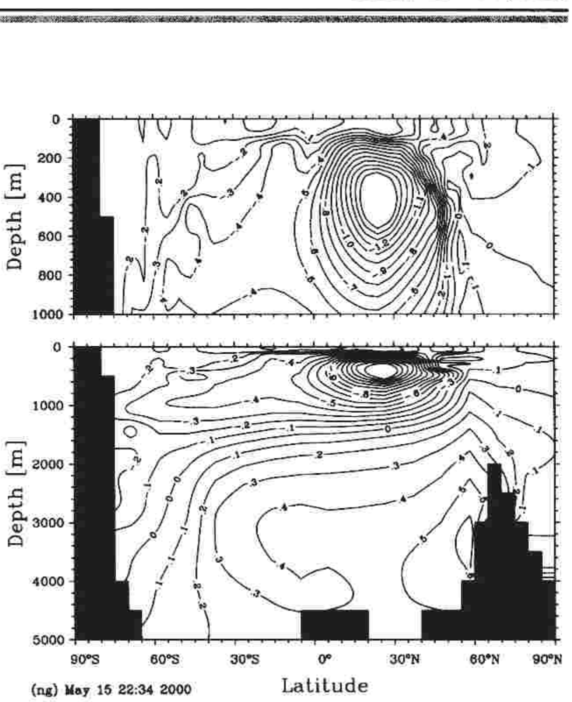

Fig. 4. Latitude-depth profile of the difference in zonally averaged phosphate concentration (in mmol/m^3) in the North Atlantic Ocean between t = 2 ka and t = 1 ka.

shoot" was earlier described by Mikolajewicz and Maier-Reimer (1994) and is a consequence of intense cooling and evaporation of warm intermediate water brought to the surface. Simultaneously, convection in the North Atlantic brings to the surface large amounts of PO_4 previously stored in deep waters. Net Primary Production reaches then a maximum in response to the increase in surface nutrient concentration and sea surface temperature in the North Atlantic and come back to its initial level approximately 4000 years after the discharge.

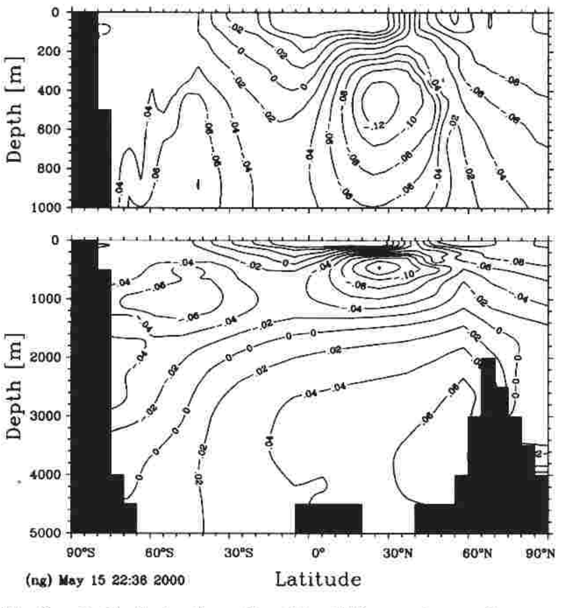

Fig. 5. Latitude-depth profile of the difference in zonally averaged dissolved inorganic carbon concentration (in mmol/m^3) in the North Atlantic Ocean between t = 2 ka and t = 1 ka.

Conclusion

The freshwater discharge induces a shutdown of the thermohaline circulation and enhances the northward advection of Antarctic Bottom Water. The simulated tracer distribution responses are in qualitative agreement with previous 2D and 3D model studies although the increase in salinity and temperature of Atlantic Intermediate waters is likely to be overestimated, while changes in nutrients and DIC in Deep Atlantic appear more realistic. The important impact of the freshwater on NPP through changes on nutrient concentration and sea surface temperature in the North Atlantic appears as the main result.

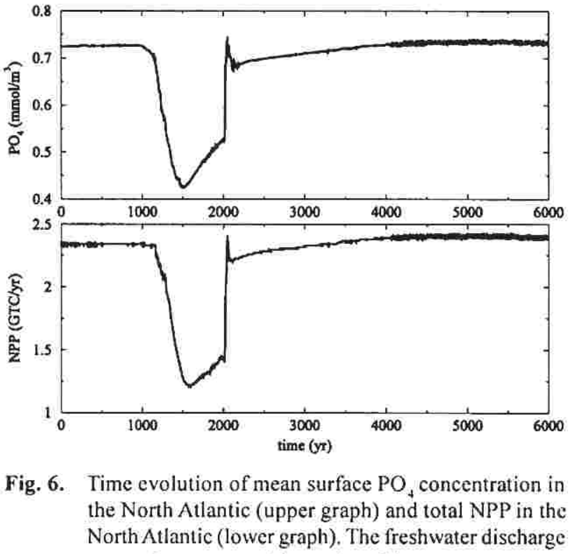

Fig. 6. Time evolution of mean surface PO_4 concentration in the North Atlantic (upper graph) and total NPP in the North Atlantic (lower graph). The freshwater discharge occurs between t = 1 ka and t = 2 ka.

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Geomagnetic Forcing on Climatic Variations

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ABSTRACT. The influence of geomagnetic forcing on variations of the global circulation including North Atlantic Oscillation (NAO) in the region between Europe and North America, variability of the rainfall in the Asian Monsoon region and the El Niño-Southern Oscillation (ENSO) in the Pacific region is studied. Statistically significant correlation coefficients were found between geomagnetic activity, the sea level atmospheric pressure (s.l.p.) and temperature. Enhanced geomagnetic forcing is shown to lead to the intensification of the westerly zonal flow across the Atlantic and to above-normal winter temperatures in Europe and northern Asia. Relatively high correlation coefficients that were found between changes in geomagnetic activity, the All India Rainfall Index (AIRI) and ENSO justify us to suggest that the increase of geomagnetic activity in April strengthens the zonal flow also on the southern hemisphere in the southern fall and winter. Strong southerly winds and the cross-equatorial flow extend across the entire Indian Ocean leading to the above-normal monsoon rainfall in India in June, July and August; La Niña (Cold event - CE) usually follows in the Pacific Ocean. At a time of the decreased geomagnetic activity in April the Australian high intensifies, the southerly cross-equatorial flow in the Indian Ocean is much weaker in the southern winter and the monsoon rainfall is deficient. El Niño (Warm event - WE) is usually observed in the Pacific.

KEY WORDS: geomagnetic activity, zonal flow, North Atlantic Oscillation, monsoon rainfall, El Niño.

Introduction

Climatically sensitive regions constitute a dominate source of yearly global climatic variations with great consequences for human society (Bradley, 1989). The NAO has strong effects on westerlies across the Atlantic and on temperatures in Eurasia. The variability of Asian monsoons affects a large portion of the world and three fifths of the world population depend on summer monsoon rainfall as given e.g. by the AIRI. The impact of the ENSO conditions is felt mainly in the Pacific even though its effect over an enormous region seems to influence the climatic variability on a global scale. Further study can help to answer the question whether the unusual NAO and ENSO behavior of the past two decades is due to global warming and anthropogenic changes or is consistent with natural variability of the climate system. Recent studies (Bucha,1976; or recently Bucha and Bucha, Jr., 1998; Pýcha et al., 1992 ; Bochníček et al., 1996 and Laštovička, 1996) have shown that geomagnetic activity may be regarded as an external forcing factor influencing fluctuations of climate and weather.