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Greenhouse Gases during the Last Glacial and the Deglaciation

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With 5 Figures

Abstract

Carbon dioxide is, after water vapor, the most important greenhouse gas. Its atmospheric concentration has naturally varied between 190 and 290 ppmv over the last half million years following glacial-interglacial cycles. Also methane has varied significantly during this time. This natural variability which gives important indications as to the mechanisms operating in the climate system. Particular attention is focused on the end of the last glacial when CO_2 and CH_4 exhibit centennial changes. Simulations using a simplified climate model suggest that the CO_2 changes are due to oceanic reorganisations.

1. Introduction

Estimating reliably future climate change crucially depends on our knowledge of past climate variability and our ability to simulate such changes using numerical climate models. Observational records of climate variables cover only the last 150 years. These records exhibit strong natural variability on the decade-to-century time scale on which any climate perturbation by man is superimposed. From this perspective, observational records cannot provide an objective view of natural climate variability. In order to obtain climate information further back in time, reliable and consistent climate recorders, so called paleoclimate archives, are needed. Climate and environmental information is most often indirectly stored in these archives. Such data is therefore referred to as "proxy data". One of the most important tasks of paleoclimatic research is the determination of the transfer functions which allow the translation of the stored information into physical climate variables (Bradley 1999).

Almost all paleoclimatic data are proxy, and therefore they are associated with various degrees of uncertainty. These derive from uncertain transfer functions, time-dependent transfer functions, and even "post-recording" processes. The best, and most reliable paleoclimatic archive are ice cores from polar regions. This is because a small number of climate relevant variables are directly stored and preserved in this archive. The ice of polar ice sheets is formed under the pressure of the overlying firn which is a porous material. The density of the firn increases with depth at the expense of the air volume. At the depth of 80 to 100 m, the air bubbles are closed and isolated from the air which was in diffusive contact with the atmosphere (Schwander et al. 1997). The bubble then encloses air from the time of close off, 100 to several 1000 years younger than the enclosing ice. Apart from the uncertainty regarding the exact age of the bubble (ice age-gas age difference), the bubble contains a direct, yet minute sample of the past atmosphere. In principle, it is therefore possible to reconstruct the entire gas content of the atmosphere over many 1000 of years in the past.

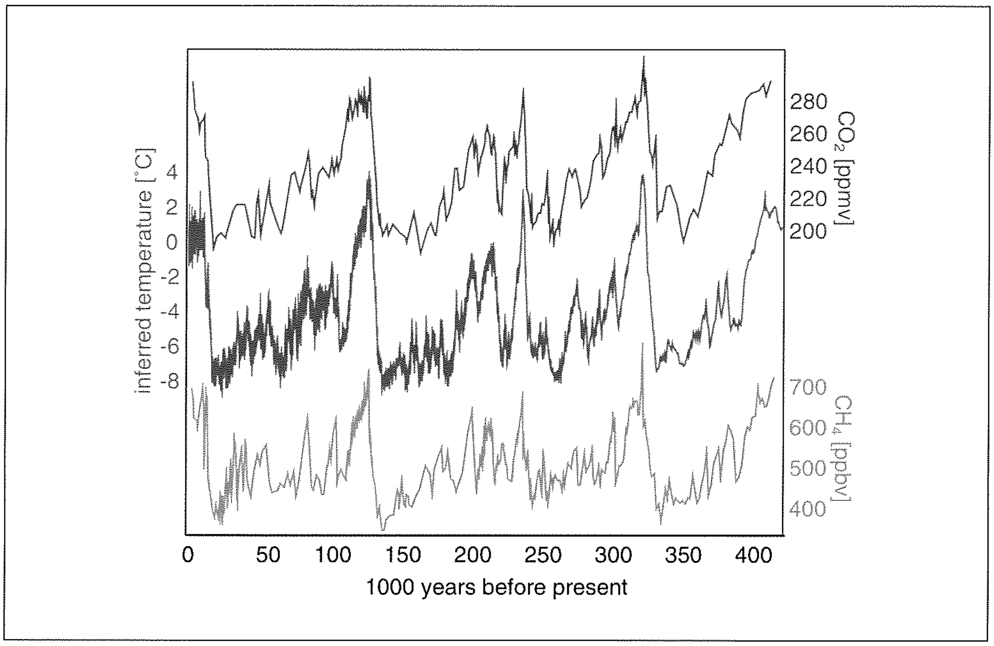

Fig. 1 Temperature, inferred from stable isotopes (*center*), CO_2 (top) and CH_4 (*bottom*) records over the last 420,000 years including 4 glacial cycles from detailed ice core measurements from Vostok Station. (From Petit et al. 1999)

Polar ice cores permit the reconstruction of past CO_2 and CH_4 concentrations over at least 4 glacial cycles (Petit et al. 1999). These unique records are shown in Figure 1. Both greenhouse gases are remarkably confined within their range of variability. The atmospheric inventory of carbon varies by about 30 %, the methane inventory in the atmosphere almost doubles from the ice age to the interglacial. On the time scale of several 1000 years, the records are synchronous with the estimate of Antarctic temperature change derived from the stable isotopes of water. In spite of over 20 years of research, a universally accepted, and quantitative explanation of the glacial-interglacial changes of CO_2 and CH_4 has not yet been achieved (Sigman and Boyle 2000).

There have been a number of hypotheses explaining both the timing and the amplitude of the 80 ppmv changes but none of them is consistent with all available paleoclimatic evidence. A recent overview is given by Broecker and Henderson (1998). None of the physical mechanisms such as changes in deep water circulation, cooler sea surface temperatures, or longer residence time of the waters in high northern latitudes can explain individually the amplitude of the CO_2 drop during the glacial (Siegenthaler and Wenk 1984). Furthermore, none of the scenarios using sea level rise as a driver (shelf inundation and shallow-water carbonate, coral-reef hypotheses) are consistent because sea level rise occurs after the CO_2-increase. Finally, there is no clear paleoceanographic evidence for a significant increase in marine productivity drawing down atmospheric CO_2; some of the stable isotope data, $\delta^{13}C$ in marine sediments, actually point to the contrary.

Iron fertilization is another hypothesis. In some areas of the ocean, iron is a limiting nutrient and stronger dust input into the ocean by winds in a dustier atmosphere may enhance marine productivity resulting in lower atmospheric CO_2 (MARTIN 1990). As ice cores from Greenland and Antarctica indicate, the dust deposition drops significantly during the end of the glacial. However, the time scales of the changes in the dust supply are on the order of decades whereas those of CO_2 changes are millennia. At present, the most promising mechanisms appear to be linked to nutrient (through iron fertilization) and temperature changes in the Southern Ocean, with the nitrogen cycle playing an important role in explaining the relatively long time scales of CO_2 change (BROECKER and HENDERSON 1998).

Recently, Antarctic sea ice cover was proposed as a mechanism to reduce atmospheric CO_2 (STEPHENS and KEELING 2000). A perennial sea ice cover during the ice age would significantly reduce gas exchange in the Southern Ocean; a box model yields about 80 % of the glacial-interglacial change. However, the analysis is based on a simple model which does not constrain the dynamics of ocean currents and the formation of sea ice. Even if further additional mechanisms such as increased stratification and summer nutrient consumption are invoked (KEELING and VISBECK 2001), the hypothesis conflicts with evidence for lower productivity in the lower glacial Antarctic (SIGMAN and BOYLE 2001). Presently, the major uncertainties concern the role of the terrestrial and marine biospheres, and the importance of the nitrogen reservoir influencing the carbon balance between ocean and atmosphere.

2. Greenhouse Gas Changes during the Last Glacial

Methane is, after water vapor, the third most important greenhouse gas in the atmosphere. Similar to CO_2, methane exhibits regular changes during glacial/interglacial cycles. In contrast to CO_2, there is no ocean buffering for methane, and since the ocean reservoir of methane is very small compared to that of the atmosphere, fluctuations are large and rapid. The paleoclimatic records demonstrate that CH_4 traces all the abrupt climate events during the last glacial. Stadials tend to have methane concentrations that are about 50 % higher than during the coldest phases. Changes are very rapid and evolve within a few decades. Because of the short life time of CH_4 in the atmosphere (order 10 years), interhemispheric differences can develop and they provide important clues about the source areas of methane (DÄLLENBACH et al. 2000). Methane records have an important practical significance because they provide time markers for ice cores. This permits the synchronisation of these records and places climatic changes in one polar region into a global context (BLUNIER et al. 1998, BLUNIER and BROOK 2001).

In Figure 2, the longest synchronisation of Greenland and Antarctic ice cores currently available is shown. Taking into account the gas age-ice age differences from these two cores, the temperature reconstructions based on the isotope measurements are placed on a common time scale. It is remarkable that some of the Dansgaard/Oeschger events (D/O events) identified in the Greenland ice cores (numbers 1 to 21) have counterparts in the Antarctic core (events A1 to A7). The temporal characteristic of the southern events is notably different from that of the D/O events. The warming in the north is always abrupt, while in Antarctica the warming evolves on a millennial time scale. The cooling in the north, on the other hand, is slowly evolving initially and is abrupt only before the coldest phase in the event. The synchronisation further reveals that the cooling in the south starts at the time of the warming in the north. This has been referred to as an "antiphase" behaviour between north and south and appears as one of the clearest expressions of the "bipolar seesaw" (Stocker 1998). The particular phasing suggested by the ice core synchronisation can be qualitatively and quantitatively explained by abrupt changes of the Atlantic thermohaline circulation, short THC (Stocker 2000, Stocker and Marchal 2000). Models of reduced complexity have attempted to simulate these events (Stocker and Wright 1998, Ganopolski and Rahmstorf 2001), but both models exhibit these abrupt changes only in response to a specific perturbation. A self-consistent simulation that is free of *a priori* assumptions regarding a possible forcing has not yet been achieved. It is evident that the greenhouse gas records, and the synchronisation both provide important constraints on the model simulations and help verify or falsify hypotheses.

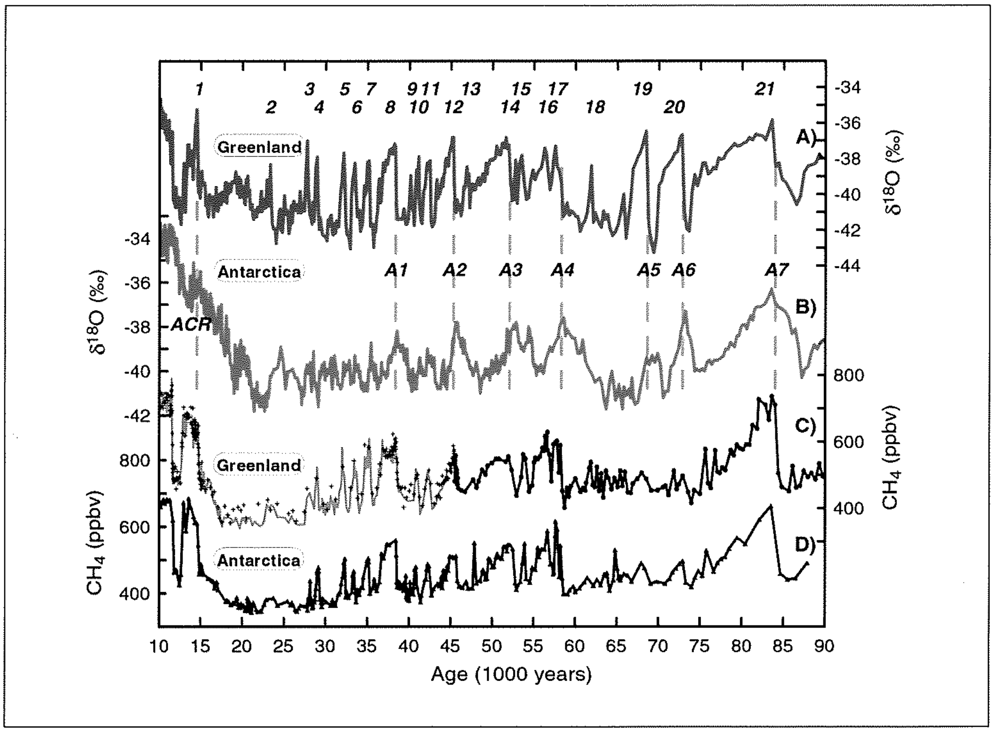

Fig. 2 Synchronisation of ice cores from Greenland and Antarctica based on high-resolution measurements of methane (lower black curves) on both cores. Methane in the atmosphere varies with each of the Dansgaard/Oeschger events (events 1 to 21), which provides time markers on which the synchronisation is based. (From Blunier and Brook 2001)

If such massive reorganizations of the atmosphere-ocean system are responsible for the millennial changes during the last ice age, the question arises what their effect on the global carbon cycle might be. High-resolution CO_2 measurements by Stauffer et al. (1998) and Indermühle et al. (2000) on two Antarctic ice cores reveal a clearer picture of the dynamics of the global carbon cycle on time scales of less than a few 1000 years (Fig. 3). The variability of atmospheric CO_2 during the glacial does not exceed 20 ppmv, which implies that these changes have a negligible feedback on the radiative balance of the atmosphere.

The CO_2 variations are surprisingly small, although a series of abrupt climate changes is evident in many paleoclimatic records (Stocker 2000). Indeed, earlier suggestions that CO_2, much like CH_4, would change during each D/O event could not be confirmed. But the CO_2 changes appear correlated with (at least some) Heinrich events and/or the longest and most prominent of the D/O events (Fig. 3). Some of these (the major Heinrich events and, associated with them, the longest of D/O events) are thought to be due to large atmosphere-ocean reorganizations in the form of complete collapses of the Atlantic THC. In order to test such hypotheses with physical-biogeochemical climate models, the measured amplitude and timing of the CO_2 changes serve as crucial constraints.

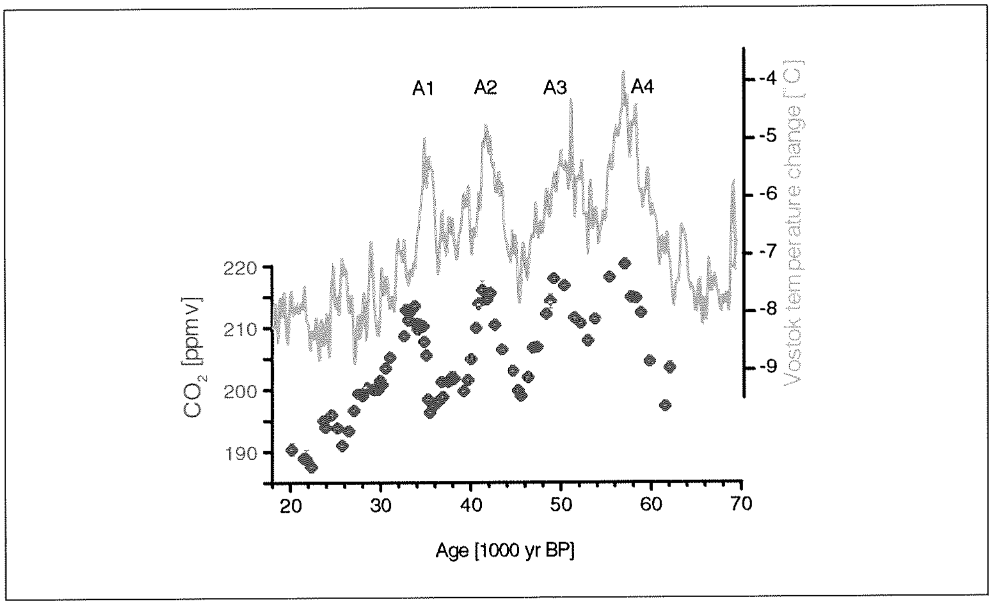

Fig. 3 Millennial changes in CO_2 reconstructed from Taylor Dome ice core and synchronised to the Vostok temperature estimates. Each stadial event in Antarctica is associated with an increase of CO_2 by about 20 ppm. The exact phasing of the warming and the CO_2 changes is uncertain. (From Indermühle et al. 2000.)

3. Changes during the Last Termination

The highest resolution of changes of greenhouse gases during phases of massive climate change has been achieved recently by Monnin et al. (2001). The measurements were done on the new deep core from Dome Concordia, Antarctica, and cover the last deglaciation (Fig. 4). The warming starts around 18 kyr BP (18,000 years before present) and proceeds until about 14 kyr when the Antarctic Cold Reversal (ACR) starts. At 18 kyr BP, i. e. about 2 kyr before the rapid warming appears in Greenland ice cores, CO_2 starts to rise. This rise coincides with the rise in temperature as indicated by the stable isotopes measured on Antarctic ice cores, although there is still some uncertainty in the ice-age/gas-age difference. Glacial-interglacial changes of CO_2 that occur over many millennia therefore seem to be more closely linked with the climate changes in the south, than with those in the north.

The change in warming trend at around 14.5 kyr BP is marked by a step increase of CO_2 and stable values thereafter until the end of the ACR. In contrast, methane exhibits an abrupt increase to near Holocene values which persist during the ACR. The end of the ACR is characterised by the strongest warming phase in Antarctica and coincides with the Younger Dryas (YD), clearly marked by the reduction in CH_4. On the other hand, CO_2 increases linearly during the YD. The most remarkable observation, however, is the fact that the CO_2 changes fall into four clearly distinguishable time phases I to IV (see Fig. 4) which appear more closely related to the CH_4 record than to that of the inferred temperature from the isotopes. This strongly suggests that processes in the tropics and the northern latitudes have a direct, or at least indirect influence through ocean circulation and possible reorganisations, on the centennial changes in the atmospheric concentration of CO_2.

The unique sequence of events and characteristic rates of change of the major greenhouse gases is not quantitatively understood, with the exception, perhaps, of the steady increase of CO_2 during the cold event of the YD (Marchal et al. 1999). No model simulation is currently available that simulates even the gross features of the paleoclimatic data shown in Figure 4.

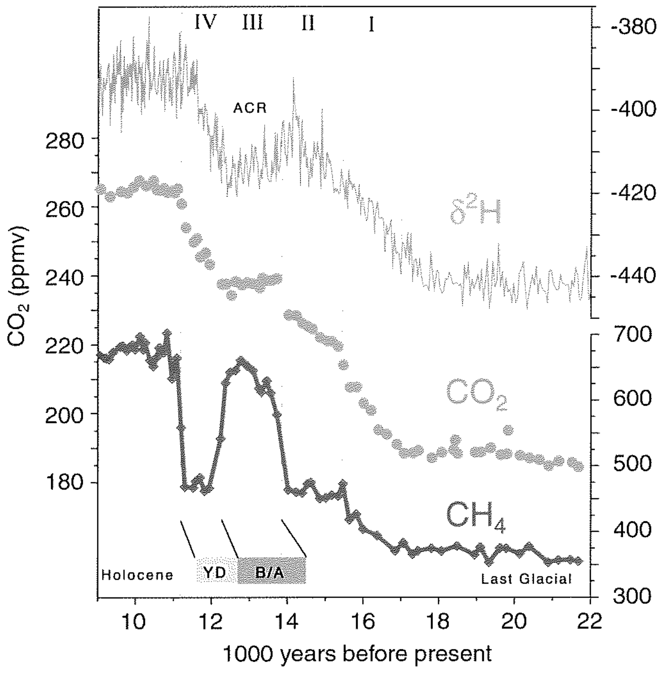

Fig. 4 High-resolution records of temperature, inferred from stable isotopes, and the two major greenhouse gases CO_2 and CH_4 during the deglaciation. The transition is characterised by step changes and changes in the rate of increase of CO_2 which are occurring in four distinct phases (I to IV) for which also CH_4 exhibits important changes. Measurements are done on ice from Dome Concordia, Antarctica (from Monnin et al. 2001).

Nevertheless, the data are telling us that there must be a close link between events unfolding in the northern hemisphere (the sequence of the abrupt Bolling/Allerod warming and the subsequent cooling of the Younger Dryas) and Antarctica. The deep ocean circulation is one mechanism that could explain the remarkable absence of rapid (i.e., decadal) temperature changes in Antarctica, as well as the opposite thermal evolution of north and south, superimposed on the general trend of warming during the transition from the ice age to the Holocene.

4. Modeling Rapid Changes in Carbon Dioxide

Coupled climate models are necessary to provide a quantitative interpretation of the paleoclimatic data and to check hypotheses regarding possible mechanisms underlying the climatic changes. The data here require not only coupled physical models, but predictive components of biogeochemical processes, in particular the global carbon cycle, must be included. Three-dimensional models are not yet at a stage where they could be used for the interpretation of these paleoclimatic records, because their computational burden precludes integrations that cover the time scales of the data. Instead, models of reduced complexity must be used (STOCKER and MARCHAL 2001). These models are simplified with respect to their dynamics in the ocean and atmosphere and many processes are parameterised. Due to their efficiency they permit testing the robustness of results, e.g., through the method of Monte Carlo simulations (e. g., MARCHAL et al. 2001).

In the gas records presented above, we have noted the strong north-south coupling during the last glacial and the termination. This coupling is facilitated by the Atlantic THC which draws heat from the Southern Ocean when active. During a collapse of the Atlantic THC, heat is no longer exported from the Southern Ocean and a warming is simulated in those areas (STOCKER et al. 1992). While the physical behaviour appears to be broadly consistent with the particular phasing between Greenland and Antarctic ice cores during abrupt change (Fig. 2), the question arises, whether this model remains consistent with the paleoclimatic data if further components are coupled to it.

In order to test the hypothesis of a strong north-south coupling during a complete collapse of the Atlantic THC, a simplified physical-biogeochemical climate model was used (MARCHAL et al. 1998). The discharge of a defined amount of freshwater into the North Atlantic disrupts the THC and lead to a collapse of the circulation shown in Figure 5*A*. The goal is to simulate a cooling similar to that of the Younger Dryas (MARCHAL et al. 1999). It should be emphasized that the response of the THC is entirely dominated by the exact shape of the freshwater perturbation, and therefore it is tunable. This was done here to obtain a duration of the cold event that is similar to that observed. Furthermore, we only attempt to simulate the changes of CO_2 relative to a long-term glacial-interglacial increase from about 190 to 265 ppmv, because this model does not contain components that are thought to be important to address this problem (e. g., sediment chemistry).

The model shows that the strong cooling induced in the North Atlantic is compensated by a warming in the southern ocean through the effect of the "bipolar seesaw" (BROECKER 1998, STOCKER 1998). The cooling in the north would lead to an increased uptake of CO_2 through a stronger solubility pump, while the opposite is true for the southern ocean. While the global effect of changes in sea surface temperature remains less than about 5 ppmv with the warming in the south dominating the cooling in the North Atlantic, the combined effect of changes in DIC and alkalinity due to the discharge of the freshwater is an increase of atmospheric CO_2 a few 100 years after the full collapse of the THC in the North Atlantic (Fig. 5*B–C*). The net effect is thus an increase in atmospheric CO_2 between 7 and 30 ppmv on a timescale of 100 to 2000 years depending on the intensity of the THC change. At the time of abrupt warming in the north (resumption of the circulation), CO_2 is decreasing again. This is in qualitative agreement with the information from the ice cores (Fig. 4). Hence, the model supports the hypothesis that the millennial CO_2 changes are linked with ocean-atmosphere reorganizations triggered by freshwater pulses. It is important to note that the "chicken-and-egg" problem is not yet solved by these simulations: did changes in the south trigger collapses of the Atlantic THC, or did ice sheet disintegration in the north trigger changes in ocean circulation which then had an effect on the south? It is very likely that the sequence of H- and D/O events is a truly coupled ice-ocean-atmosphere phenomenon.

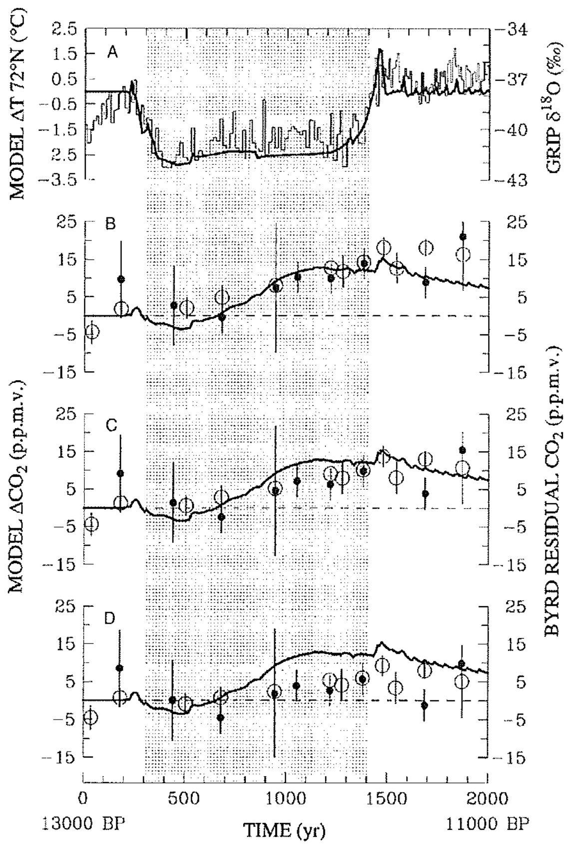

Fig. 5 Simulations of a typical cold event using a coupled physical-biogeochemical climate model. The cold event is induced by a freshwater release into the North Atlantic which collapses the thermohaline circulation. This leads to a strong and abrupt cooling (*A*). The atmospheric CO_2 changes are simulated (curves *B–D*) and compared to the residual CO_2 values from Antarctic ice cores (circles and dots). The residuals are calculated by subtracting constant rates of glacial-interglacial CO_2 change with increasing magnitudes. (From MARCHAL et al. 1999.)

5. Conclusions

The physical-biogeochemical state of the ocean is strongly influencing the atmospheric concentration of CO_2, the most important greenhouse gas after water vapor. CH_4 is mostly influenced by changes in the hydrological cycle and the availability and status of wetlands over the globe. The paleoclimatic record exhibits three different types of CO_2-changes, two of which are strongly associated with ocean circulation changes. By far the largest changes are the glacial-interglacial cycles of about 80 ppmv which still defy a complete and quantitative explanation. While the ocean plays a significant role through variations in the carbon pump strengths, most probably only a combination of different effects can explain the reconstructed changes. These include changes in the sea surface temperature, marine productivity, nitrogen fixation and in the interaction with carbonate sediments.

Two types of smaller CO_2-changes of the order of 20 ppmv have emerged from high-resolution measurements in Antarctic ice cores. The first appear to be correlated to the largest climate changes during the glacial, the H-events or the long D/O events of the Greenland ice cores. These climate changes are distinguished by the fact that changes in opposite phase are recorded in the Antarctic cores. This suggests an interhemispheric seesaw which is in operation during abrupt climate change. Simulations with coupled physical-biogeochemical climate models lend support to such a scenario. The driving force is afforded by meltwater discharges from the northern hemisphere ice sheets which disrupt the Atlantic THC. CO_2 changes of similar magnitude also occur during relatively stable climate periods such as the Holocene. Here, changes are most likely due to the terrestrial biosphere which is still responding to the recent glacial-interglacial transition and continues to be influenced by changes in the hydrological cycle, land surface conditions (retreating ice cover) and climate.

The paleoclimatic record teaches us two lessons. First, future changes can only be understood if the full range of natural climate variability is reconstructed. Such reconstructions are crucial for a sensible climate model building and development effort. It is the past changes, free of anthropogenic perturbations, which these models must be capable of simulating. Second, by correlating climate changes documented in various archives with the ice core based reconstructions of atmospheric CO_2, the link between the global carbon cycle and the atmosphere-ocean-biosphere system can be quantified. Model simulations suggest, that there is a potential in large non-linear changes in the physical climate system. These are shown to have an influence on the carbon cycle, on the uptake capacity of the world ocean and ultimately on the atmospheric concentration of CO_2.

Acknowledgement

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