A new model for climate system analysis: Outline of the model and application to palaeoclimate simulations

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We present a new reduced-form model for climate system analysis. This model, called CLIMBER-2 (for CLIMate and BiosphERe, level 2), fills the current gap between simple, highly parameterized climate models and computationally expensive coupled models of global atmospheric and oceanic circulation. We outline the basic assumptions implicit in CLIMBER-2 and we present examples of climate system analysis including a study of atmosphere–ocean interaction during the last glacial maximum, an analysis of synergism between various components of the climate system during the mid-Holocene around 6000 years ago, and a transient simulation of climate change during the last 8000 years. These studies demonstrate the feasibility of a computationally efficient analysis of climate system dynamics which is a prerequisite for future climate impact research and, more generally, Earth system analysis, i.e., the analysis of feedbacks between our environment and human activities.

Keywords: climate modelling, climate system, system analysis, climate system modelling, Earth system modelling

1. Introduction

Human interventions are currently altering the Earth's surface and the composition of the atmosphere at an increasing rate such that "the balance of evidence suggests a discernible human influence on global climate" [13]. During the last 10,000 years, the present interglacial period, the climate has been rather calm in comparison with the 100,000 years before [6]. Presumably, it is not a mere coincidence that agriculture has developed during the current phase of climatic stability. Generally, the Earth's climate exhibits calm or slowly varying conditions interspersed with episodes of rapid change on all time scales [4]. Therefore, an important and exciting question is on how the conditions of little variability are maintained and what are the causes of rapid change. Moreover, we ought to know whether the Earth system could return to a more restless mode if anthropogenically induced modifications of the Earth continue to increase. It seems plausible that changes in the North Atlantic thermohaline circulation could have caused drastic climate variability in the past [25] and that the same could happen in a warmer climate [26]. If so, then this could be a major threat to human society. Consequently, a major challenge for the scientific community today is to explore the dynamic behaviour of the climate system as well as its resilience to large-scale perturbation (such as the continuing release of fossil fuel combustion products into the atmosphere or the fragmentation of terrestrial vegetation cover).

To address the problem of stability of the climate system one has to analyse the dynamic processes between its subsystems, the geosphere, or the abiotic world, and the biosphere, the living world. For this sake, the geosphere itself can be subdivided into the atmosphere, the hydrosphere (mainly the oceans), the cryosphere (inland ice, sea ice, and snow cover), and the lithosphere (the upper solid earth). There is increasing evidence that the dynamics of the climate system cannot be determined by studying its subsystems alone. Due to the (nonlinear) synergism between subsystems the response of the entire system to external perturbation drastically differs from the sum of the responses of the individual subsystem or a combination of a few of them. As a consequence, an integrated analysis of the fully coupled climate system is required to approach a solution of the problem.

Marked progress has been achieved during the past decades in modelling the separate elements of the geosphere and the biosphere [13]. This stimulated attempts to put all separate pieces together, first in form of comprehensive coupled models of atmospheric and oceanic circulation, and eventually as climate system models which include also biological and geochemical processes [9]. At the Potsdam Institute for Climate Impact Research, a new approach in simulating the climate system has been developed. The philosophy of this model is outlined and examples of its application to the analysis of palaeoclimates are presented in the following sections.

2. The new approach

2.1. General structure

Currently, there are basically two classes of climate system models – comprehensive ones and simplified ones [14].

Comprehensive models of global atmospheric and oceanic circulation describe many details of the flow pattern, such as individual weather systems and regional currents in the ocean. Similarly, complex dynamic vegetation models explicitly determine the growth of plants and competition between different plant types. The major limitation in the application of comprehensive models arises from their high computational cost. The troposphere, the lowest 15 km of the atmosphere in which weather occurs, reacts within a few days to changes in boundary conditions, for example, insolation. However, it takes several hundred years for the deep ocean to respond and a few thousand years to reach equilibrium. The response time will increase enormously if more "slow" elements of the climate system, like glaciers or the upper Earth's mantle, are involved. Even using the most powerful computers, only a very limited number of experiments can be performed with such models.

Another problem is the necessity of ad hoc flux adjustments to obtain a realistic present climate state (see, e.g., [5]). Flux adjustments are artificial corrections of simulated heat and freshwater fluxes at the interface between atmosphere and ocean models. The use of flux adjustments prevent the coupled atmosphere–ocean models from drifting into unrealistic climate states; however, they impose strong limitations on the applicability of the models to climate states which are substantially different from the present one.

Due to these problems, simplified and computationally efficient models of the climate system are used for a variety of applications, in particular palaeostudies as well as climate change and climate impact projections [14]. These models are spatially highly aggregated, for example, they represent atmosphere and ocean as two boxes, and they describe only a very limited number of processes and variables. The applicability of this class of model is limited not by computational cost, but by the lack of many important processes and feedbacks operating in the real world. Moreover, the sensitivity of these models to external forcing is often prescribed rather than computed independently.

There is an obvious gap between simple and comprehensive models which has been filled by CLIMBER (for CLIMate and BiosphERe) developed at the Potsdam Institute for Climate Impact Research (PIK). CLIMBER is a climate system model of intermediate complexity. CLIMBER computes many processes and feedbacks in the climate system like comprehensive models, but it has a fast turnaround time. Currently, some 4000 simulated years take roughly one day on a workstation of the latest generation and half an hour on a super computer.

The fast turn-around time of CLIMBER (in its current version labelled level 2) is partly a result of its low resolution. CLIMBER-2 resolves individual continents, subcontinents and ocean basins (see figure 1). Latitudinal resolution is 10°. In the longitudinal direction the Earth is represented by seven equal sectors in the atmosphere and land modules (for convenience, hereafter called "atmosphere grid"). The ocean model is a zonally averaged multibasin model, which in longitudinal direction resolves only three ocean basins (Atlantic, Indian, Pacific). Each ocean grid cell communicates with either one, two or three atmosphere grid cells, depending on the width of the ocean basin. The geography of the Earth surface in CLIMBER-2 represents a compromise between attempts to minimise the number of atmosphere grid cells covering both ocean and land areas and to keep realistic ocean areas for the globe, individual ocean basins, and each latitudinal belt. Very schematic orography and bathymetry are prescribed in the model, to represent the Tibetan plateau, the high Antarctic elevation and the presence of the Greenland–Scotland sill in the Atlantic ocean.

CLIMBER-2 encompasses six modules, an atmospheric module, an ocean and sea-ice module, a vegetation module, an inland ice module, and modules of marine biota and oceanic biogeochemistry. The last three components have been implemented into the CLIMBER-2 framework, but not yet fully tested. Therefore we will, in the following, present model simulations in which the ice sheets and the atmospheric CO_2 are prescribed from data rather than

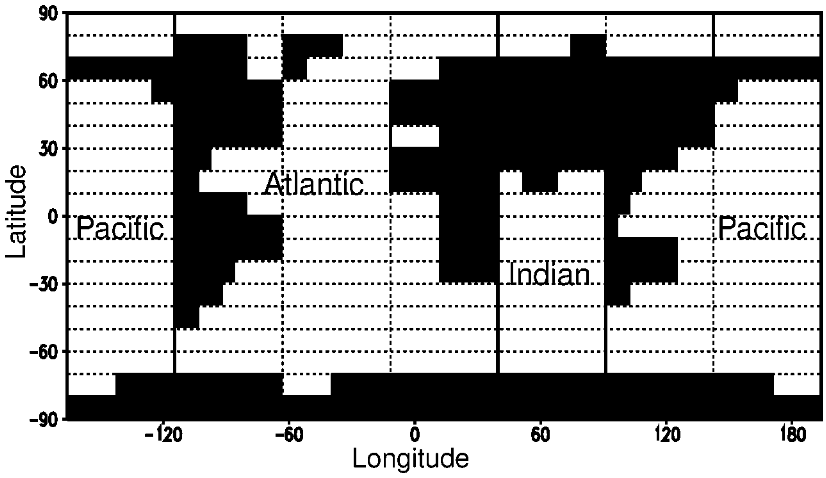

Figure 1. Schematic representation of the Earth's topography in the CLIMBER-2 model. Dashed lines show the atmospheric grid, solid lines separate ocean basins.

computed internally. Implicit in the vegetation module is a simple carbon model, and the oceanic module is able to take up and dissolve inorganic CO_2 and transport it into deep layers by diffusion and advection; however, to close the carbon cycle, we have to wait for the oceanic biogeochemistry to properly work. The modules communicate via fluxes of energy, momentum, moisture, and carbon. Insolation and anthropogenic activities, such as land use and increase of greenhouse gases, are given as external boundary conditions. A detailed description of this model as well as its validation can be found in Petoukhov et al. [24]; here, only a brief outline is given.

2.2. The atmospheric module

The atmospheric module is based on the so-called statistical–dynamical approach [23,27]. Implicit in this approach is the assumption that the general structure of the atmosphere can be expressed in terms of large-scale, long-term fields of the main atmospheric variables, with characteristic spatial and temporal scales of $L > 1000$ km and $T > 10$ days, and ensembles of synoptic-scale eddies and waves, i.e., weather systems like depressions, areas of high pressure, storms, etc., represented by their (L^2, T) averaged statistical characteristics. In other words, we parameterize the average transport effects of the rapidly varying weather systems on the large-scale, long-term atmospheric motion, rather than simulating them explicitly. However, in contrast to earlier models (see, e.g., [20]), we do not generally parameterize atmospheric transport as a diffusive process. This would lead to cumbersome hydrological pattern as, for example, in nature, moisture is advected from the arid subtropics towards the humid tropics – certainly not a diffusive process. Instead, we prescribe the existence, but not amplitude and extent, of a Hadley cell regime, thereby allowing for counter-gradient meridional transports of moisture from the subtropics to the intertropical convergence zone. The phenomenological basis for this approach is:

- The existence of a pronounced stable minimum on a time scale of 10–15 days in power spectra of the main atmospheric variables in various geographic regions and in different periods of time [19,31].
- The existence of a characteristic horizontal spatial correlation radius of the order of 1000–3000 km for the synoptic component [18] which is the upper limit for the horizontal spatial correlation radii of the above mentioned fast processes.

The equations for (L^2, T) averaged values and their ensemble characteristics are derived from a set of primitive hydrothermodynamic equations. An important assumption made when deducing the governing equations is that the atmosphere at the (L^2, T) spatial/temporal scales has a universal vertical structure of temperature and humidity fields. This assumption is supported by the results of a large number of empirical studies in a variety of geographic regions and periods of time (see, e.g., [32]). The use of a universal vertical structure allows us to reduce the 3-dimensional description of the atmosphere to a set of 2-dimensional, vertically averaged prognostic equations for temperature and water vapour. For the simulation of processes in which the vertical structure of the atmosphere has to be known, we reconstruct the 3-dimensional structure from the 2-dimensional field using the (empirically derived) vertical structure functions. The large-scale zonal wind is diagnosed from the thermal wind relation, which seems to be a very reasonable assumption when comparing data and model results (for details, see [24]).

The concept of fixing the topological structures and letting the amplitudes of the atmospheric circulation change could limit the applicability of CLIMBER-2. Hence the existence of universal structures is taken as a hypothesis, derived from empirical evidence of present-day climate (see, e.g., [32]). Its extension to past climate has to be validated. As a first test, CLIMBER-2 has been carefully verified using data of present-day climate [24]. This is not a trivial task, because the degrees of freedom in CLIMBER-2 exceed the number of adjustable parameters by several orders of magnitude – in this respect, CLIMBER-2 resembles more a comprehensive model than a simple model. Therefore it is impossible to completely tune CLIMBER-2 to data. Moreover, without any re-tuning or calibration, CLIMBER-2 satisfactorily simulates climate states which are different from present-day climate. Examples will be given in section 3. Therefore it is believed – although it cannot be strictly proven – that the assumption of universal structures is sensible.

2.3. The ocean module

The ocean module describes the ocean hydro- and thermodynamics, sea ice and the ocean carbon cycle. It is based on the multibasin zonally averaged model of Stocker et al. [29]. In the longitudinal direction CLIMBER-2 resolves only three ocean basins (Atlantic, Indian, Pacific), but in the latitudinal direction the ocean boxes match the atmospheric boxes. The vertical structure of the ocean is represented in 11 uneven levels with an upper mixed layer of 50 m thickness. For each level and for each individual ocean basins, the module simulates the zonally averaged temperature, salinity, meridional and vertical velocity. For the latitudinal belts without any meridional boundaries (circumpolar oceans), the module also calculates the zonally averaged zonal component of velocity based on the meridional density gradients and assuming zero pressure gradient at the bottom. Ocean module and atmospheric module are coupled without flux correction – a technical task which can be achieved much easier than in comprehensive models, because it simply takes too much computing time to tune the details of the coupling in comprehensive models.

Because CLIMBER-2 resolves only three ocean basins, it is limited in its applicability to periods of the Earth's history in which the distribution of continents does not differ drastically from today's. Moreover, the zonally averaged ocean module is not able to describe the horizontal gyre structures or horizontally oscillating flow patterns like El Niño, which are an important part of the ocean circulation and interact with the thermohaline circulation. It is assumed that horizontal motion mainly affects climate variability at time scales of decades, but not climate change triggered by external forcing.

2.4. The vegetation module

Simulation of terrestrial vegetation is based on a continuous description of plant functional types [1]. Hence, for each continental grid cell, the vegetation module computes fractions of vegetation cover and desert. The vegetation module includes a simple carbon model in which allocation of carbon to four pools (short living matter such as leaves, long living matter such as stems and roots, humus, soil) is evaluated [16]. From the allocation of carbon to the living pools, the leaf area index (area of leaves per unit area) is estimated which serves to estimate albedo and resistance to transpiration. The latter are important parameters of the interface module which is designed to compute the energy and moisture fluxes at the interface between atmosphere and land, ocean or inland ice.

Vegetation structure is estimated by using a bioclimatic description of the two plant functional types, forest and grass. Vegetation adapts to climate on a time scale proportional to the turn-over time of carbon in the pool of slowly varying biomass, i.e., stems and roots. It has to be emphasised that vegetation dynamics is fitted to modern Earth. Hence any simulation of palaeoclimates in the distant past for which evolution might have changed vegetation characteristics should be interpreted with caution.

2.5. The interface

The climate system modules are coupled via an Atmosphere–Surface Interface (ASI). In ASI, fluxes of energy, moisture, momentum, and substances at the interface between the atmosphere and any surface are computed. ASI is based on the Biosphere–Atmosphere Transfer Scheme (BATS) [7] being simplified and modified for the level of spatial and temporal aggregation in CLIMBER-2. This mainly concerns the parameterization of soil moisture and water run off. ASI distinguishes six surface types: open water, sea ice, forest, grassland, desert and glaciers. Different types can coexist in one grid cell, and for each type, state variables, i.e., temperature and soil moisture, as well as surface fluxes are calculated separately.

3. Examples of climate system analysis

So far, CLIMBER-2 has been verified for present-day climate. Furthermore, it has been compared with other comprehensive models [10]. It has been shown that CLIMBER-2 not only recaptures the large-scale patterns of atmospheric and oceanic motions and vegetation structure. CLIMBER-2 also reveals quite the same sensitivity to external perturbation, such as a doubling of carbon dioxide in the atmosphere, changes in solar radiation, changes in Earth's orbital parameters, and changes in the North Atlantic current, as complex models do. For example, CLIMBER-2 computes a 3.1°C global, near-surface warming as an equilibrium response to a doubling of present-day atmospheric CO_2. Here we present results from analyses of palaeoclimates which were used as a validation of CLIMBER-2.

3.1. The last glacial maximum

The last ice age reached its peak around 21,000 years ago. Ice sheets up to three kilometres thick covered the northern parts of America and Europe. In Europe, tundra and steppe extended as far as modern France [4]. The reason for the periodically recurring ice ages is believed to be slight changes in the Earth's orbit which caused changes in the solar radiation reaching the Earth. But exactly how these gradual and subtle changes in the distribution of solar warmth led to such rapid and drastic glaciation is still one of Nature's unsolved puzzles.

Experiments with CLIMBER-2 suggest that changes in ocean currents were a crucial factor in the cooling of the climate during the ice age, particularly in Europe [12]. (See table 1 for boundary conditions used in the experiments.) These changes encompass the southward shift of North Atlantic Deep Water (NADW) formation by about 20° in latitude during the glacial maximum, a stronger penetration of Antarctic Bottom Water (AABW) into the northern Atlantic, and a substantially reduced heat transport into the high latitudes of the North Atlantic with a corresponding southward movement of the winter sea-ice margin to between 50 and 60°N. The overall rate of NADW formation is only slightly reduced, but because the northern North Atlantic current was less salty and hence less dense, NADW

Table 1
Boundary conditions used for the experiments described in sections 3.1–3.3. The perihelion is given in days of a 360-day model year.

	Inland ice	Sea level	CO_2 (ppm)	Orbital parameters		
				Excentricity	Obliquity	Perihelion
LGM	Peltier [22]	−105 m	200	0.01899	22.95°	16.9
Mid-Holocene	present-day	present-day	280	0.01868	24.105°	261.4
The last 8000 years	present-day	present-day	280	0.01908–0.01672	24.192–23.446°	227.2–4.4

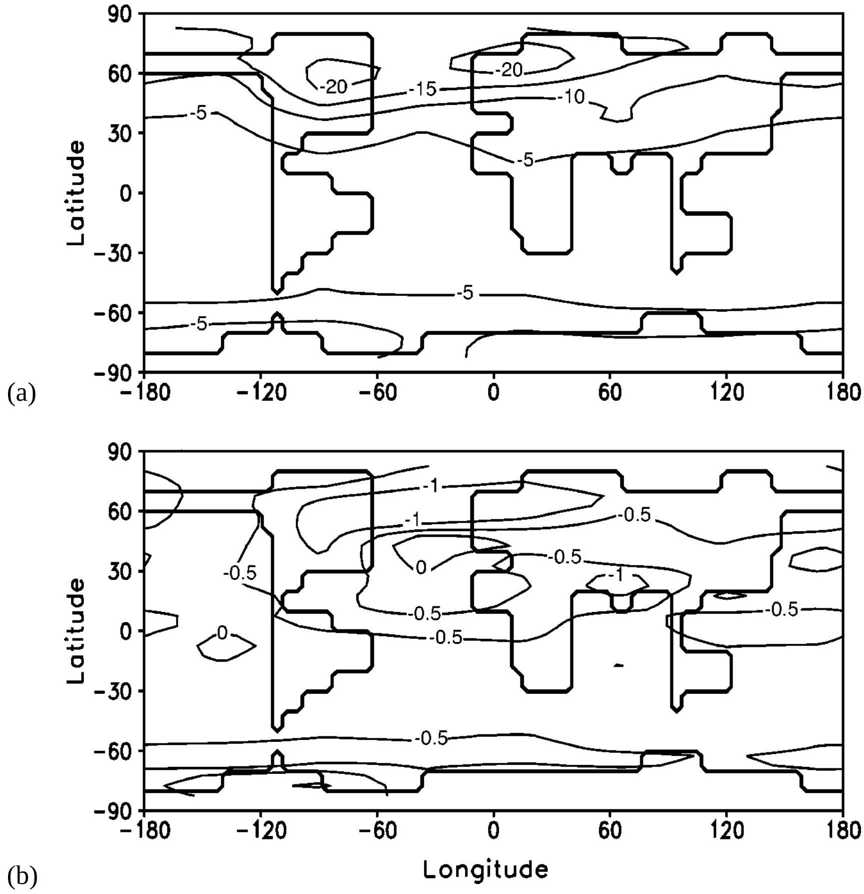

Figure 2. Change in annual air temperature (in °C) near the Earth's surface (a) and annual precipitation (in mm/day) (b) at the height of the last ice age, 21,000 years before present, compared to today. (Before plotting, the model output has been interpolated bi-linearly.)

flow was shallower than today. Compared to today's climate, CLIMBER-2 further obtained enhanced formation of intermediate water in the North Pacific. These results seen in CLIMBER-2 agree fairly well with recent reconstructions from ice-age sediment cores [28].

The entire Northern Hemisphere was on average almost nine degrees Celsius colder than it is today, according to the simulation results. When comparing the simulation of the fully coupled system with a similar simulation in which, however, the oceanic heat transport is fixed at present-day values, it can be concluded that three degrees of this cooling were caused by a shift of the North Atlantic ocean circulation. Some areas even cooled by more than 20 degrees as a result of the altered currents (see figure 2).

3.2. The middle Holocene

Remnants of the last glaciation had disappeared by about 7000 years ago and since then, the inland ice masses have changed little. Also the CO_2 concentration in the air was roughly the same as some 150 years ago, before the industrial revolution. Nevertheless, the climate some 6000 years ago, was quite different from today's climate. Generally, the summer in Northern Hemisphere mid- to high latitudes was warmer as palaeobotanic data indicate an expansion of boreal forests north of the modern treeline [8]. In North Africa, palaeoclimatological reconstructions using ancient lake sediments and archaeological evidence indicate a climate wetter than today [33]. Moreover, it has been found from fossil pollen that the vegetation limit between Sahara and Sahel reached at least as far north as 23°N [15].

It is hypothesised that differences between modern and mid-Holocene climate were caused by changes in the Earth's orbit [17]. Particularly, the tilt of the Earth's axis was stronger than today. This led to an increased solar radiation in the Northern Hemisphere during summer which amplified the African and Indian summer monsoon, thereby increasing the moisture transport into North Africa. However, the response of the atmosphere alone to orbital forcing is insufficient to explain the changes in climate. Sensitivity studies have suggested that positive feedbacks between climate and vegetation may have taken place at boreal latitudes as well as in the subtropics of North Africa [3,8,30]. These feedbacks tend to amplify climate change such that the boreal climate becomes warmer (than without vegetation–atmosphere feedback) and the North African climate becomes more humid.

Using CLIMBER-2, the response of the atmosphere to changes in the Earth's orbit was investigated, including various combinations of climate subsystems [11]. It appears that if only the atmospheric response to orbital forcing is taken into account, this would yield a summer warming and

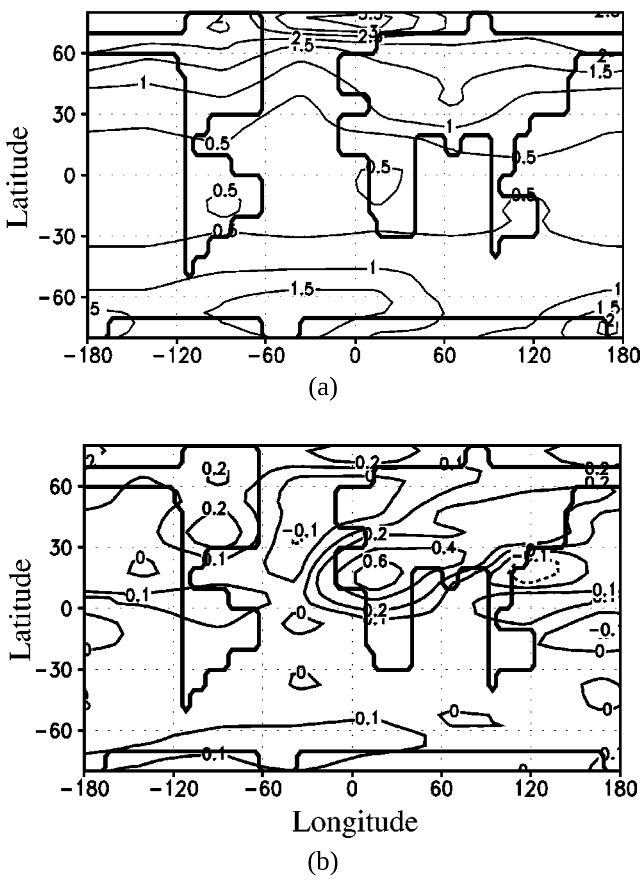

Figure 3. Changes in annual air temperature (in °C) near the Earth's surface (a) and annual precipitation (in mm/day) (b) during the mid-Holocene, 6000 years before present, compared to today.

a winter cooling above the Northern Hemisphere continents. If terrestrial vegetation interacts with the atmosphere, then we find a much stronger warming over the northern continents. This can be explained by a northward shift of forests which reduces the albedo in spring and early summer as snow-covered forests appear to be much darker than snow-covered grassland, thereby absorbing more solar radiation. If the atmosphere–vegetation system is coupled with the ocean, then we observe a further temperature increase in summer and a warming instead of a cooling in winter. On annual average, the warming over the Northern Hemisphere reaches up to 4°C (see figure 3(a)). The additional warming is caused by a stronger reduction of Arctic sea ice owing to the synergism between vegetation–snow-albedo feedback and sea-ice-albedo feedback. Precipitation is strongest over North Africa (see figure 3(b)), mainly owing to the atmosphere–vegetation interaction. Differences between simulated Holocene and present-day North Atlantic deep water formation are weak, less than 2 Sv (1 Sv $= 10^6$ m^3/s).

3.3. Climate change during the last 8000 years

During the last 8000 years, the climate has changed to a more arid state in which the present-day subtropical deserts developed. Hence one may ask whether this long-term climate change was a gradual one or whether it occurred in rather abrupt steps, perhaps even swinging back and forth like during the period of the last major deglaciation, 16000–10000 years ago. Forcing CLIMBER-2 with changes in the orbital parameters of the last 8000 years we obtain the following picture.

The climate did not change gradually. In our simulation, the climate system smoothly reacted to the orbital forcing for some 2000 years, then it changed rather rapidly, within a few hundred years (see figure 4), followed by a further gradual drift. The abrupt change took place around 5500 years ago. According to the results of CLIMBER-2, it is associated with an increase in Arctic sea ice cover by almost 10^6 km^2, a small, but abrupt, increase of NADW formation by about 10^6 m^3/s, and a reduction of global precipitation by 0.05 mm/day with a subsequent increase in the extent of desert in North Africa. Close inspection of model results reveals that the slight, but steady summer cooling of the Northern Hemisphere leads to a gradual increase in Arctic sea-ice cover. This process enhances the meridional temperature gradient between equator and boreal latitudes which, subsequently, strengthens the mean meridional atmospheric circulation, i.e., the Hadley cell. The descending branch of the Hadley cell becomes stronger and thus the subtropics become drier. An increase in North Atlantic deep water formation leads to a stronger northward heat transport which, however, is not strong enough to compensate Northern Hemisphere cooling owing to orbital forcing and subsequent feedbacks triggered by orbital forcing. The abrupt change of vegetation in North Africa and associated increase in dryness precedes the abrupt change in NADW and Arctic sea ice by some 100–200 years in this experiment. Further experiments will be undertaken to show whether or not this time lag happens by chance. Moreover, sensitivity experiments are needed in which we will isolate feedbacks and synergisms – as explained for the mid-Holocene time-slice simulation – that could provide an answer to the questions on why North African desertification was rather rapid and why it happened some 6000–5000 years ago.

A rather abrupt decrease in North African vegetation cover and a change to a drier climate is indeed reported to have happened in the eastern Sahara some 4000 years ago [21] and in Morocco some 6000–5000 years ago [2]. Hence we have to look for a synopsis of North African palaeodata in order to relate the reconstructed changes in the eastern Sahara to the entire North African region. Moreover, we intend to perform ensemble simulations, i.e., a series of simulations starting with different initial conditions, all other conditions remaining unchanged. In this way it is possible to see whether the abrupt climate change is a persistent feature, or whether it is a random event, in other words, whether the precise date of this event is not predictable owing to the nonlinearity of feedbacks in the climate system.

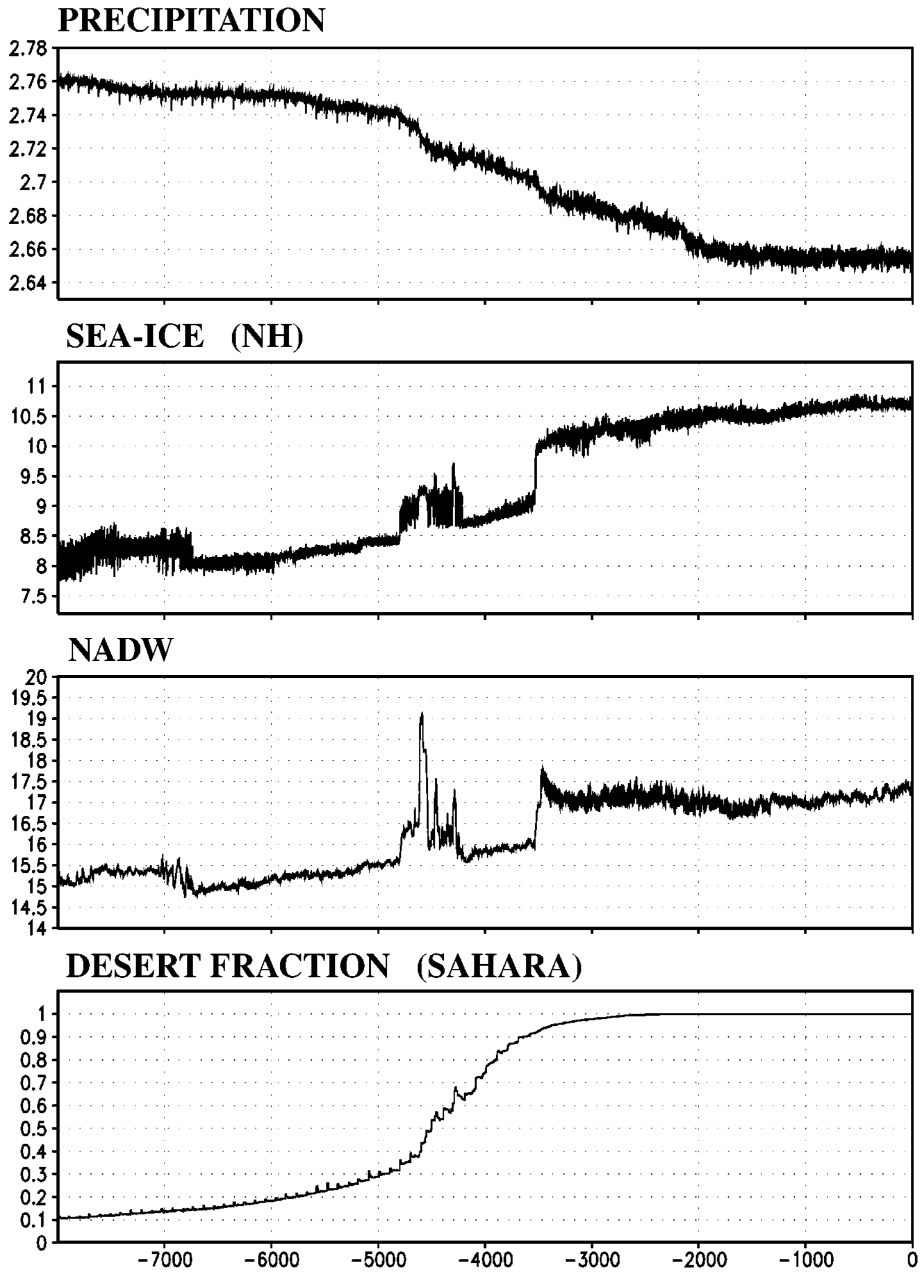

Figure 4. Changes in global mean precipitation (PRECIPITATION, in mm/day), area of Arctic sea ice (SEA-ICE (NH), in 10^6 km^2), formation of North Atlantic deep water (NADW, in 10^6 m^3/s), and fractional coverage of desert in North Africa (DESERT FRACTION (SAHARA), approximately 10°W–41°E, 10°N–30°N) as function of time (in years) before present. (Note that negative numbers on the abscissa indicate years before present; the time proceeds from the left to the right of the x-axis.)

4. Conclusion

Climate system analysis is a prerequisite for climate impact research at the global scale. It can be viewed, more generally, as a first step towards Earth system analysis which focuses on the (bi-directional) interaction between the climate system, i.e., the geophysical part of the Earth system, and the anthroposphere. Climate system analysis necessitates a climate system model which, on one hand, has to be computationally inexpensive and, on the other hand, must not be too simple. The important processes of atmospheric and oceanic circulation as well as the feedbacks between the subsystems of climate, i.e., atmosphere, ocean, vegetation, and, if long time scales are considered, ice masses and the upper Earth's mantle, have to be described realistically.

Here we have presented a new approach to bridge the gap between simple climate models and complex climate system models. We have developed a climate system model of intermediate complexity, CLIMBER-2. This model consists of several modules which simulate the large-scale, long-term patterns of atmospheric and oceanic characteristics as well as vegetation structure. The main reduction in required computer resources is gained by the atmospheric module as it resolves only the large-scale circulation and parameterizes the effects of heat and momentum transports by weather systems on the general circulation. CLIMBER-2 is not yet complete as the modules of dynamic inland ice, marine biota, and oceanic biogeochemistry are currently being implemented, but are not yet fully tested.

As an application to palaeoclimate system analysis, which also can be considered part of a validation of CLIMBER-2, we have explored three, partly preliminary simulations undertaken with CLIMBER-2: an analysis of the atmosphere–ocean interaction during the last glacial maximum, a study of the synergism between climate subsystems during the mild period of the mid-Holocene, and a study of transient climate change during the last 8000 years. The latter study, the transient simulation, is particularly interesting as it addresses problems of changing climate variability and potential "surprises", i.e., large excursions of the system. These examples demonstrate that CLIMBER-2 is able to simulate the global characteristics of a climate quite different from today, moreover, the occurrence of an abrupt climate change at the end of the mid-Holocene is captured.

In our analysis attention is focused on the coarse-scale pattern of climate and the question of synergism and stability in the climate system. Important questions are on how we can explain climate variability in the past and whether we are able to predict long-term climate variability in the future. As the first steps are quite promising, we believe that CLIMBER-2 could be coupled with models of anthropogenic activities, say socio-economic models, to build an Earth system model.

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