Earth System Models

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Earth system models: General remark

Earth system analysis - this term is often associated with the study of the “solid” Earth with its surrounding spheres, the atmosphere, cryosphere, and hydrosphere. However, within IGBP (the International Geosphere - Biosphere Programme) - at least - a more general definition, which has been proposed by Schellnhuber (1998, 1999) and Claussen (1998), for example, seems to be generally accepted. According to the latter, *Earth system analysis* addresses the feedbacks and synergisms between the ecosphere and the anthroposphere. The ecosphere or, the natural Earth system, encompasses the abiotic world, the geosphere, and the living world, the biosphere, whereas the anthroposphere includes all cultural and socio-economic activities of humankind which can be subdivided into subcomponents such as the psycho-social sphere etc.

Schellnhuber (1998, 1999) provides a general *symbolic formalism of Earth system analysis* in the following way: The state of the natural Earth system N is given by the vector $\boldsymbol{N}$, which varies with time t. The evolution equation is F_o. The anthroposphere, which is represented by some vector $\boldsymbol{A}$, can be regarded as some time-dependent boundary conditions to the natural Earth system just as any other exogenous force $\boldsymbol{E}$. Hence a model of the natural Earth system is schematically given by

$$\dot{\boldsymbol{N}}(t) \equiv \frac{d}{dt}\boldsymbol{N}(t) = F_o(\boldsymbol{N};t;(\boldsymbol{A}(t), \boldsymbol{E}(t)))$$

A similar equation the state of the anthroposphere reads

$$\dot{\boldsymbol{A}}(t) \equiv \frac{d}{dt}\boldsymbol{A}(t) = G_o(\boldsymbol{N}, \boldsymbol{A})$$

which could be considered a climate impact model, or, if G_o would not depend on $\boldsymbol{N}$, a scenario model, i.e., a model of population growth or increase of CO_2 emissions, for example.

Schellnhuber (1998, 1999, see also this book) extends the above equations to set up a scheme of a fully coupled Earth system model. He uses this system not to aim at a forecast of the Earth’s future, but to explore the system’s behaviour in a rather general way. For example, he designs a “theatre world” to demonstrate the feasibility of measures and strategies of Earth system management.

How the equation, or system of equations, G_o, can be formulated explicitly, is not yet clear. The conventional, thermodynamic approach might not be the appropriate tool to model the anthroposphere. Presumably, anthropogenic activities are hardly assessable in term of thermodynamic quantities, i.e., they can hardly be cast into a mathematical form of state variables, state equations and evolution equations with the exception of, perhaps, economic aspects (e.g. Hasselmann et al., 1997, and Klepper, this book, for a detailed discussion of economic theories and coupling of climate and economic models). New methods of qualitative modelling have do be developed.

But even if these methods were developed, I wonder whether the Earth system will be - even to a limited degree - predictable at all. Generally, people react to perceptions of global change rather than to the actual state of the Earth system. Hence any scientist, who tries to model the Earth system, readily interferes with the system by creating perceptions. Therefore, I assume that

Earth system analysis will face the problem of a *global-scale uncertainty relation* (Zurek, 1998). Just as at the micro scale, the interference of an observer with the system affects the system and, hence, the observation.

On the other hand, there are systems in physics and nature which are not predictable in principle, but manageable. For example, the dynamics of a coupled pedulum is not predictable, but reveals a deterministic chaos. Nonetheless, a child on a swing set - the “daily-life realisation” of a chaotic coupled pendulum - is able to manage the system. Hence one of the major problems to be tackled by Earth system analysis is the proof that humankind can, or cannot, manage the system. This proof should not be considered as prerequisite for designing a new, better world. History suggests that, when trying to “improve” our Earth, we most likely will face the same fate as Johann Wolfgang von Goethe’s “Zauberlehrling”. Instead, we ought to know whether we are able to curb the ongoing global-scale experiment or whether we have to adapt to our own “mis-”management.

Modelling the Natural Earth System

Even if we ignore the interaction of anthroposphere with the natural Earth system, modelling the natural Earth system still remains a challenge to which I will restrict myself in the following. During the last 10,000 years, the present interglacial period, the climate has been rather calm in comparison with the 100,000 years before (e.g., Dansgaard et al., 1993). 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 (e.g., Crowley and North, 1991). 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 natural 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 (e.g., Bond et al., 1992) and that the same could happen in a warmer climate (Rahmstorf and Ganopolski, 1999). Consequently, a major challenge for the scientific community today is to explore the dynamic behaviour of the natural Earth 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 natural Earth system one has to analyse the dynamic processes between its subsystems, the geosphere and the biosphere (e.g., Peixoto and Oort, 1992). For this sake, the geosphere itself can be subdivided (see Figure 1) into the atmosphere, the hydrosphere (mainly the oceans), the cryosphere (inland ice, sea ice, and snow cover), the pedosphere (the soils), and the lithosphere (the Earth’s crust and the more flexible upper Earth’s mantle).

There is increasing evidence that the dynamics of the natural Earth 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 - which will be demonstrated below.

Marked progress has been achieved during the past decades in modelling the separate elements of the geosphere and the biosphere (Houghton et al., 1996). 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 (Foley et al., 1998).

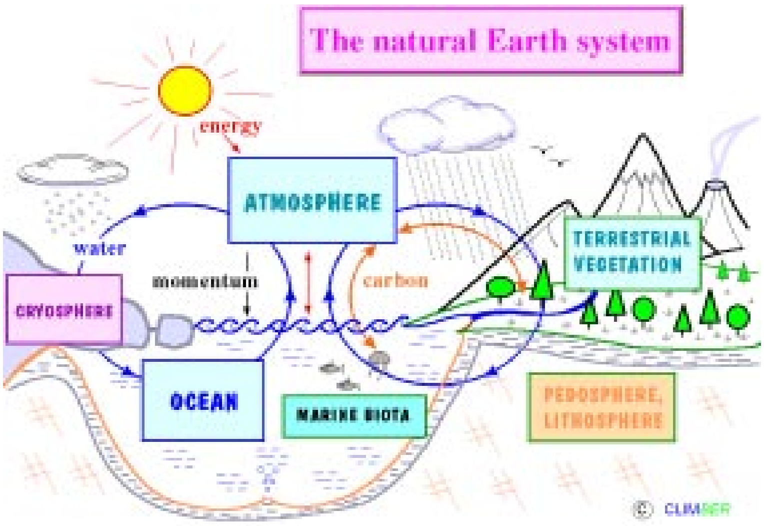

Fig.1: Sketch of the natural Earth's system. This sketch was designed by Andrey Ganopolski (Potsdam Institute for Climate Impact Research).

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., Cubasch et al., 1995). 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.

At the other end of the spectrum of complexity of natural Earth-system models, we find ***conceptual or tutorial models***. These models are simple mechanistic models which are designed to demonstrate the plausibility of processes. Watson and Lovelock's (1983) "Daisyworld" model is just such an example. It provides a simple description of global-scale homoeostasis to show that biota could influence environment to form a self-regulating system in which conditions remain favourable for life. Watson and Lovelock (1983) do not claim that the biogeophysical process described in their conceptual model is realistic - it is just a caricature of the real world. Indeed, we have reasons to believe that the biogeophysical feedback, a positive temperature-albedo feedback, operating in the Daisyworld tends to destabilize the real-world natural Earth system. To cite a second example: Paillard (1998) describes the long-term climate variations during the last 1 million years, i.e., the variations between rather short interglacial and longer glacials, by assuming that there are multiple states in the natural Earth system. The system switches to the one or the other state, if changes in insolation exceed some *ad hoc* defined thresholds. Paillard does not make use of any physical constraints, he merely demonstrates in the most simple way the concept of thresholds in the natural Earth system.

Quite generally, conceptual models could be characterized as ***inductive deterministic*** models according to Saltzman (1985, 1988). They contrast with the comprehensive, ***quasi-deductive*** models which are, with respect to their main components, derived from first principles of hydrodynamics. Inductive deterministic models are formulated based on a gross understanding of the feedbacks that are likely to be involved. The system of equations - generally restricted to a very few - are designed to be capable of generating the known climatic variations, or as many lines of observational evidence as possible. The inductive approach is, to cite Saltzman (1985), "bound to be looked upon as nothing more that curve fitting - a charge that is fundamentally difficult to refute". Essentially, the predictive value of conceptual models is rather limited.

EMICs

To bridge the gap between conceptual and comprehensive models, ***Earth System Models of Intermediate Complexity*** (EMICs) have been proposed which can be characterize in the following way. EMICs describe most of the processes implicit in comprehensive models, albeit in a more reduced, i.e. a more parameterized form. They explicitly simulate the interactions among several components of the natural Earth system including biogeochemical cycles. On the other hand, EMICs are simple enough to allow for long-term climate simulations over several 10.000 years or even glacial cycles. Similar to comprehensive models, but in contrast to conceptual models, the degrees of freedom of an EMIC exceed the number of adjustable parameters by several orders of magnitude. EMICs are more quasi-deductive models, not inductive deterministic models, although some of the components of an EMIC could belong the this class. Indeed, most dynamic vegetation models are more or less empirically derived, inductive models. And also comprehensive models rely on inductive components to parameterize small scale processes.

Tentatively, we may define an EMIC in terms of a three-dimensional vector: Integration, i.e. number of components of the Earth system explicitly described in the model, number of processes explicitly described, and detail of description of processes (See Figure 2).

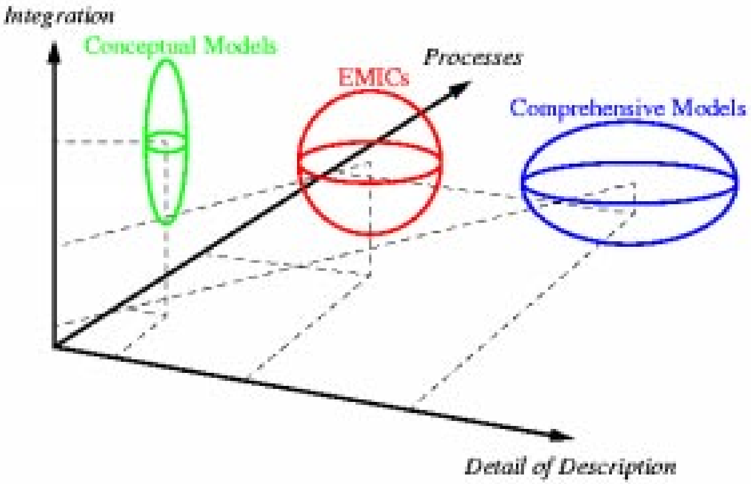

Fig.2: Tentative definition of EMIC

Currently, there are several EMICs in operation such as 2-dimensional, zonally averaged models (e.g. Gallée et al., 1991), 2.5-dimensional models with a simple energy balance (e.g. Marchal et. al, 1998; Stocker et al., 1992), or with a statistical-dynamical atmospheric module (e.g. Petoukhov et al., 2000), and reduced-form comprehensive models (e.g. Opsteegh et al., 1998). Thus, there exists a variety of EMICs of various degrees of complexity, and, obviously, there is no real gap between conceptual models, EMICs, and comprehensive models as suggested in Figure 2.

The common denominator of all EMICs is their scope: all EMICs are designed as models describing the "most important" processes governing the natural Earth system in order to facilitate long-term simulations or large-number ensemble simulations. A currently open question is which processes are "most important" to properly simulate Earth system dynamics. Certainly, EMICs should more or less completely describe all components of the natural Earth system. Figure 3 depicts an example of the modular structure of an EMIC.

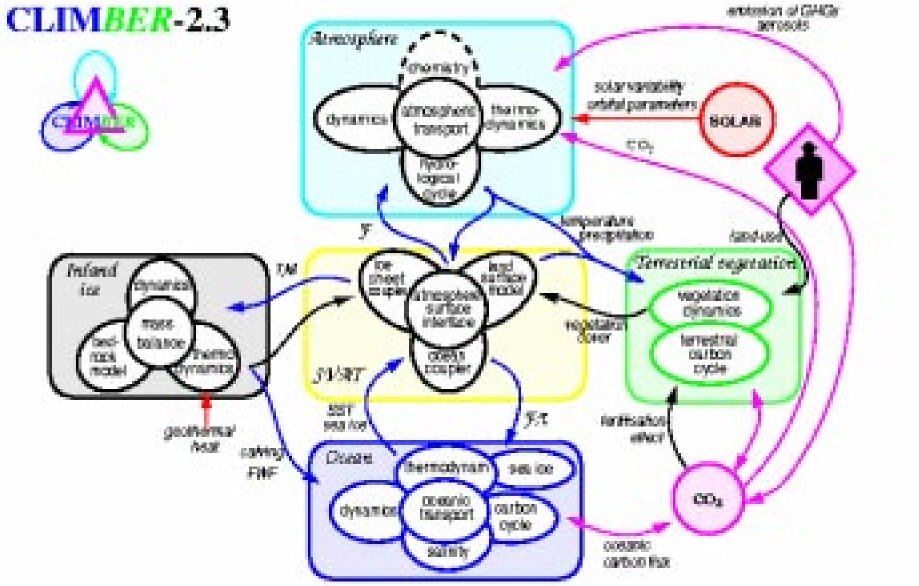

Fig. 3: Structure of CLIMBER-2, an EMIC developed at the Potsdam Institute for Climate Impact Research (Petoukhov et al., 2000; Claussen et al., 1999).

Moreover, all EMICs have to be global, geographically explicit models, because fluxes within the system are global (e.g., the hydrological cycle, the carbon cycle, and energy cycle) and changes in one region my well be caused by changes in a distant region. However, how much spatial resolution is required to appropriately capture processes with global significance?

In some cases, regional processes can be described in an aggregated form, as, for example, in so-called statistical-dynamical models of the atmosphere (Saltzmann, 1978; Petoukhov et al., 2000). 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, one parameterizes the average transport effects of the rapidly varying weather systems on the large-scale, long-term atmospheric motion, rather than simulating them explicitly. This approach seems to be applicable to meridional heat and moisture transports from the subtropics to the high latitudes; however, it would lead to cumbersome hydrological pattern, if applied to low latitudes. There, moisture is advected from the arid subtropics towards the humid tropics - certainly not a diffusive process. In this case, an alternative model has to be found. For example, Petoukhov et al. (2000) 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 inter tropical convergence zone.

At the end, only extensive comparison with result from comprehensive models and validation against data and palaeo reconstructions will yield an answer on which processes are important to be included into an EMIC explicitly and which processes can be parameterized, i.e., described in an more aggregated, implicit way.

Examples using EMICs

EMICs have been used for a number of palaeostudies, because they provide the unique opportunity of transient, long-term ensemble simulations (e.g. Claussen et al., 1999) - in contrast to so-called time slice simulations in which the climate system is implicitly assumed to be in equilibrium with external forcings - which rarely is a realistic assumption. Also the behaviour of the natural Earth system under various scenarios of greenhouse gas emissions has been investigated exploring the potential of abrupt changes in the system (e.g. Stocker and Schmittner, 1997; Rahmstorf and Ganopolski, 1999). Here I will briefly summarize three examples of Earth system analysis using EMICs.

The next ice age

The current ice age, which the Earth entered 2 to 3 million years ago, is characterized by multiple switches of the global climate between glacials (with extensive ice sheets in the Northern Hemisphere) and interglacials (with climate similar to or warmer than today). The interglacials - at least during the last half million years of the so-called late Quaternary - were rather short in comparison with the glacials. The interglacial last some 10 ky (ky = 1000 years), the glacials, some 100 ky. Our current interglacial, the Holocene, which peaked around 6 ky BP (before present), is already 11,5 ky old. Hence we face the question: when will we enter the next glacial? Currently, there are two competing theories: Statistical extrapolation of palaeorecords (e.g. Thiede and Tiedemann, 1998) suggest that the next ice age is just “around the corner” and will start within the next thousand years. This argument is based on comparing the interglacials, in particular the last interglacial, the Eemian, which centred around 125 ky BP. Indeed, there is a striking similarity between the temperature curve of the Eemian and the Holocene. In particular, there seems to be a slight, but significant global long-term cooling trend from the mid-Holocene to today which could be interpreted as indication of the next ice age.
Following the astronomical theory of ice ages, however, the next glacial will not occur within the next 50 ky (e.g. Berger and Loutre, 1997a, b). According to the astronomical theory, ice ages are triggered by changes in insolation at high northern latitudes, say at 65^{o}N, during the summer solstice. These changes are caused by variations in the eccentricity of the Earth’s orbit which has varied from near circularity to slight ellipticity at periods at about 100 ky and 400 ky over the last 3 million years. The tilt of the Earth’s axis varied between 22^{o} and 25^{o} over a period of almost 41 ky. The wobble, i.e., the precession of the equinoxes, which is arises from the precession of the spinning Earth and the precession of the Earth’s orbit, changes with a double period of 19 ky and 23 ky. In the past, large amplitude and high frequency variations in the summer insolation at 65^{o} N have been observed. Starting some 60 ky BP, however, the precession cycle

almost disappeared and between now and 50 ky AP (after present), the amplitude of variations in insolation is small owing to the very low value of eccentricity (Berger, 1978; see Figure 4a).

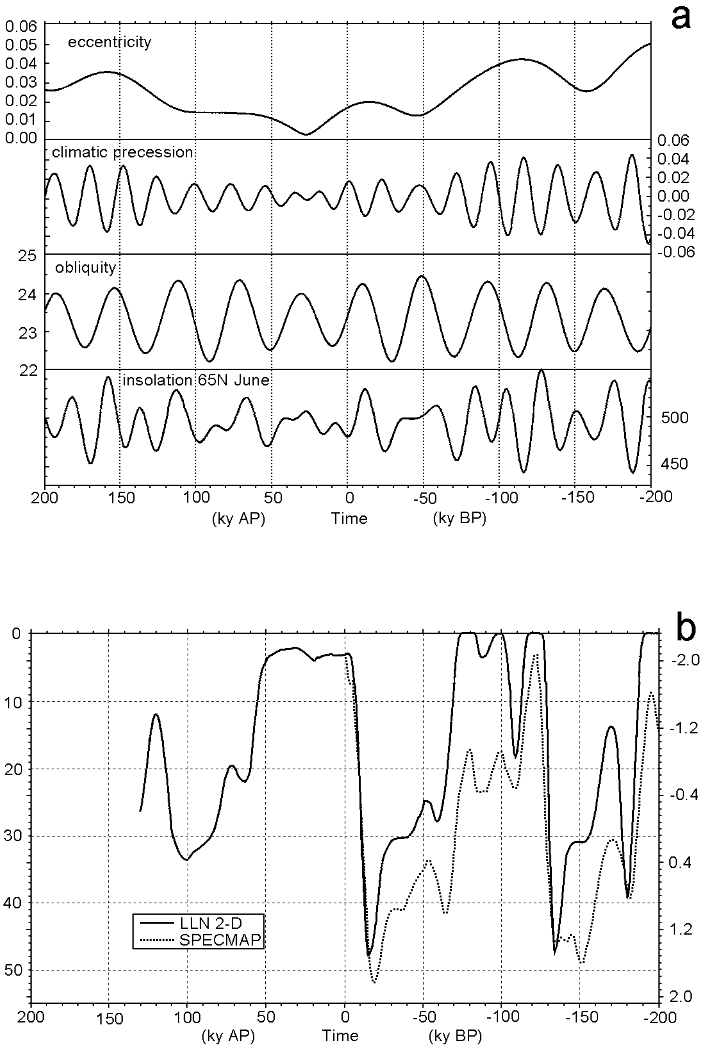

Fig. 4: (a) Long-term variations of the astronomical elements (eccentricity, precession, obliquity) and of the insolation at 65^{o}N at the summer solstice from 200 ky BP to 200 ky AP. This figure is taken - with modifications - from Berger (1978). **(b)** Full, thick line: Long-term variations of the northern hemisphere ice volume (in 10^6 km^3) simulated by Berger and Loutre (1997a). (Please note that ice volume increases downward, left hand scale.) Dashed, thin line: changes in the oxygen isotope ^{18}O, a proxy for ice volume change on global average. This figure is taken - with modifications - from Berger and Loutre (1997a)

The astronomical calculation suggests that the Eemian can not be an analogue of our present-day interglacial. Indeed, by using insolation changes as boundary conditions Berger and Loutre (1997a) predict that, in the absence of other forcings, such as anthropogenic greenhouse-gas emissions, the next glaciation in the northern hemisphere will occur about 55 ky AP (see Figure 4b). Hence Berger and Loutre (1997a) conclude that we are indeed going to the next ice age. However in contrast to the previous interglacials, the climate is likely to remain more or less stable and warm over the next 40 ky, then cools abruptly leading to the stadial of 55 ky AP, and finally to the next glacial maximum of 100 ky AP.

The current warm phase: the Holocene

Remnants of the last glaciation had disappeared by about 7000 years ago and since then, the inland ice masses have changed little. Nevertheless, the climate 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 Foley et al. (1994). In North Africa, palaeoclimatological reconstructions using ancient lake sediments and archaeological evidence indicate a climate wetter than today (Yu and Harrison, 1996). Moreover, it has been found from fossil pollen that the vegetation limit between Sahara and Sahel reached at least as far north as 23^0N (Jolly et al., 1998).

It is hypothesised that differences between modern and mid-Holocene climate were caused by changes in the Earth's orbit (Kutzbach and Guetter, 1986). 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 (e.g. Texier et al., 1997; Claussen and Gayler, 1997). 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.

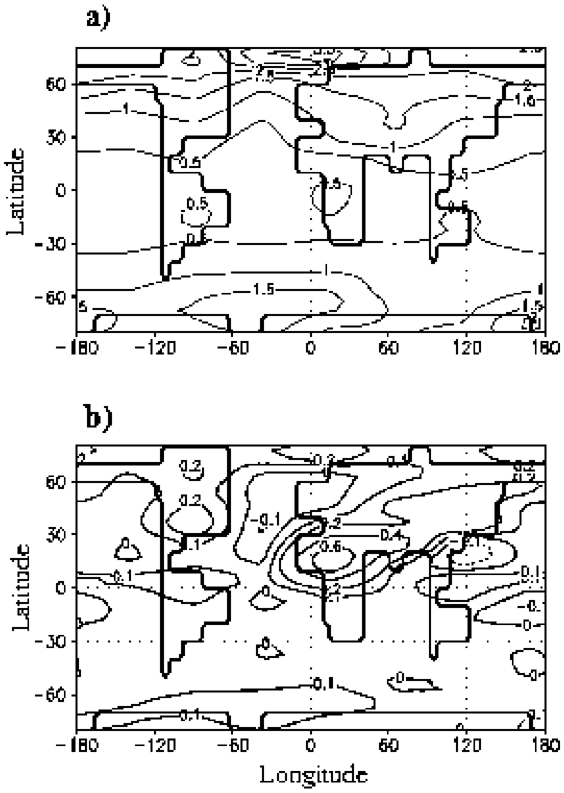

Fig.5: Changes in annual air temperature (in ^{0} C) near the Earth's suface (a) and annual precipitation (in mm/day) (b) during the mid-Holocene, 6000 years before present, compared to today. This figure is taken from Claussen et al. (1999b).

Using EMICs, the response of the atmosphere to changes in the Earth's orbit and the amplification of the initial response owing to feedbacks between various components of the natural Earth system can be investigated. According to Ganopolski et al. (1998), it appears that the atmospheric response to orbital forcing alone yields a summer warming and a winter cooling above the Northern Hemisphere continents. If terrestrial vegetation interacts with the atmosphere, then a much stronger warming is found over the northern continents. This can be explained by a northward shift of forests and associated so-called taiga-tundra feedback. The biogeophysical feedback 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 a further temperature increase in summer and a warming instead of a cooling in winter is observed. On annual average, the warming over the Northern Hemisphere reaches up to 4^{o}C (see Figure 5a). The additional warming is caused by a stronger reduction of Arctic sea ice owing to the synergism between taiga-tundra feedback and sea-ice-albedo feedback which often, but not quite correctly is referred to as the “biome paradox”. Precipitation differences are strongest over North Africa see Figure 5b), mainly owing to the atmosphere-vegetation interaction.

During the last several thousand years, the climate has changed to a cooler and more arid state in which the present-day subtropical deserts fully developed. How did this long-term climate change happen, was it gradual or did it occur in steps? By using an EMIC, one finds that changes in high northern latitudes, i.e., changes in the abundance of taiga and tundra, occurred rather gradual. However, in the subtropics of North Africa, climate developed more abrupt - in comparison with the external forcing, the change in the Earth’s orbit around the sun. According to Claussen et al. (1999a), climate and vegetation reacted smoothly to the external forcing until some 5.500 years ago. Then it changed rapidly, followed by a further gradual drift (see Figure 6).

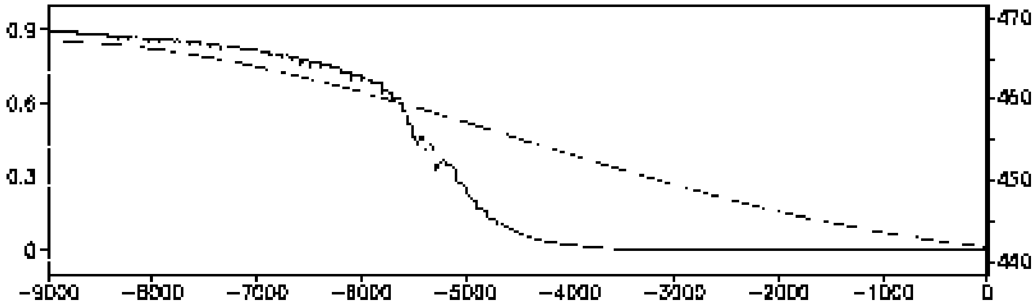

Fig. 6: Development of vegetation fraction in the Sahara (full line, non-dimensional units, left ordinate) as response to changes in insolation of the northern hemisphere during boreal summer (dashed line, in W/m^2, right ordinate). The abscissa indicates the number of years before present. This figure is taken from Claussen (2000).

A rather rapid decrease of Saharan vegetation, even more rapid than indicated in Figure 6, has recently been reconstructed from aeolian dust transport from the Western Sahara into the subtropical North Atlantic (deMenocal et al., 2000). In the more continental position of the Eastern Sahara, the desertification was presumably not as fast as in the western part, where the North African wet phase ended around 5000 to 4500 years (e.g., Pachur and Wünnemann, 1996).

This study of the natural Earth system dynamics in the (geologically) recent past suggests that Saharan desertification at the end of the mid-Holocene was presumably a natural phenomenon. Deforestation by neolithic people apparently happened in some places (Pachur, personal communication), but Saharan desertification can be explained without taking it. On the other side, the strong climate and vegetation change should have had a profound impact on the neolithic society. It has been suggested that the foundation of high civilization along the Nile river was influence, perhaps even dominated by people’s migration from the increasingly arid Sahara to the more fertile banks of river Nile.

The threat of abrupt climate change

Often, anthropogenically induced climate change is viewed upon as steady global warming. However, future climate change may also come as unexpected, large and rapid climate system changes.

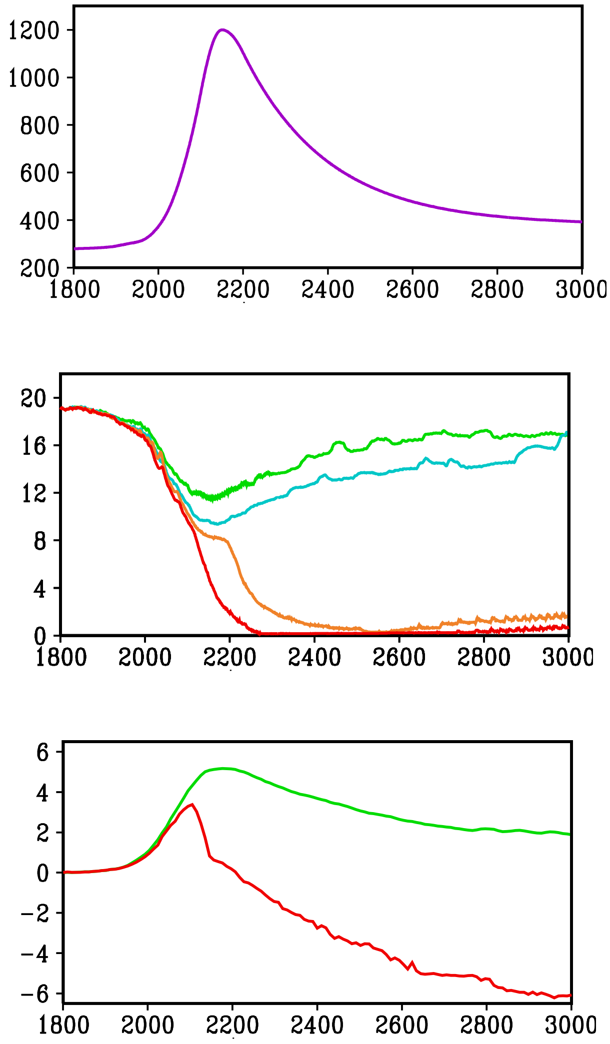

Fig. 7: Upper figure: The CO_2-forcing starting with observed CO_2-concentration, continuing according to the IPCC IS92e scenario to the year 2100. After 2100, CO_2-concentrations are assumed to peak in 2150 and to decline thereafter. Middle figure: The response of the simulated thermohaline circulation without any artificial freshwater input into the North Atlantic (green line). The blue, orange, and red curves are scenarios with additional freshwater input (+0.1 Sv, +0.15 Sv, +0.2 Sv, respectively.1 Sv = 1 Sverdrup = 10^6 m^3/s). Lower figure: Change in winter temperatures over the North Atlantic and North-West Europe region (right figure). Figures are taken - with modifications - from Rahmstorf and Ganopolski (1999).

Palaeoclimatic evidence suggests (e.g., Bond et al., 1993) that some past climate shifts were associated with changes in the formation of North Atlantic deep water. There is a consensus today that the thermohaline circulation of the World Ocean is to a large degree driven from the high-latitude North Atlantic through the production of North Atlantic deep water. Sinking of surface water in the Greenland–Iceland–Norwegian Sea and in the Labrador Sea initiates an overturning-circulation cell on the meridional plane in which northward transport of upper-ocean warm water is balanced by deep return flow of cold water, imposing a strong northward heat flux in both the North and South Atlantic. This heating system makes the northern North Atlantic about 4°C warmer than corresponding latitudes in the Pacific and is responsible for the mild climate of Western Europe. Variations in North Atlantic deep water formation therefore have the potential to cause significant climate change in the North Atlantic region.

Moreover, the pioneering work by Stommel (1961) suggests that the thermohaline circulation is a non-linear system which is highly sensitive to freshwater forcing such as changes in melt-water flow from glaciers or changes in precipitation in the North Atlantic region. Formation of North Atlantic deep water may collapse if a certain threshold is exceeded and it can show a hysteresis behaviour. There are studies (e.g., Manabe and Stouffer, 1994; Stocker and Schmittner, 1977; Rahmstorf and Ganopolski, 1999) which indicate that abrupt changes in North Atlantic deep water formation could happen if anthropogenic emissions of greenhouse gases continue to rise unchecked (see Figure 7)The potential impacts of an abrupt decrease in the production of North Atlantic Deep Water can hardly be underestimated. First rough estimates (M. Blum, Potsdam Institute for Climate Impact Research, personal communication) indicate that wheat yields in regions of central Europe could drop by 50 per cent. Hence it seems desirable to strictly avoid such drastic changes in the natural Earth system. The work by Stocker and Schmittner (1997) provide some guidance, how this can be achieved. Their work suggests that the onset of an abrupt decrease in North Atlantic Deep Water formation depends not only the amplitude of CO_2-emissions, but also on the rate of emissions. The Earth system stays on the “safe” side, i.e., with North Atlantic Deep Water forming, when the rate of emissions is sufficiently slow - which is an important conclusion with respect to global Earth system management.

Summary

Analysis of the natural Earth system generally relies on a hierarchy of simulation models. Depending on the nature of questions asked and the pertinent time scales, there are, on the one extreme, zero-dimensional tutorial or conceptual models like those in the “Daisyworld family”. At the other extreme, three-dimensional comprehensive models, e.g. coupled atmospheric and oceanic circulation with explicit geography and high spatio-temporal resolution, are under development in several groups.

During the IGBP (International Geosphere-Biosphere Programme) Congress in Shonan Village, Japan, May 1999, and the IGBP workshop on EMICs in Potsdam, Germany, June 1999, it became more widely recognized that models of intermediate complexity could be very valuable in exploring the interactions between all components of the natural Earth system, and that the results could be a more realistic than those from conceptual models. These meetings have pointed at the potential that EMICs even might have for the policy guidance process, such as the IPCC (the Intergovernmental Panel on Climate Change).

Finally, it should be emphasized that EMICs are considered to be one part of the above mentioned hierarchy of simulation models. EMICs are not likely to replace comprehensive nor conceptual models, but they offer a unique possibility to investigate interactions and feedbacks at the large scale while largely maintaining the geographic integrity of the natural Earth system.

Acknowledgement

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