Future Challenges:

Simulating Climatic Millennial Timescales and

Combining Paleoclimatic Evidence and GCM-based Dynamical Knowledge

Summary

In the past decade, climate research has made considerable progress in understanding and modeling climate on timescales of years to decades. At the same time, increasingly more proxies of climatic variables have been detected. Significant progress has been achieved in aligning these evidences in time. At the "Climate Variability on Multidecadal to Millennial Time Scale" international workshop in De Bilt, The Netherlands, in March 1999, the state of the art was reviewed and discussed. A call was made for utilizing coupled atmosphere-ocean GCMs for simulating and analyzing paleo climatic variability. These attempts should go beyond the traditional approach of using paleo data as boundary forcing; instead coupled ocean-atmosphere GCMs should be used to simulate the transient response to varying forcing factors, like volcanism and orbital parameters, and to interpret paleo climatic evidence in the spirit of data assimilation. For meeting these ends, GCMs must be improved to include biome and ice sheet models; process-based "observational models" linking climatic variables and proxy evidence need to be developed. It is expected that within another decade, detailed reconstructions of the climatic evolution since the last glaciation will be available from proxy data driven GCM simulations.

Introduction

In the past decade, climate research has made considerable progress in understanding climate on timescales of years to decades. General Circulation Models (GCMs) can simulate variability on timescales up to decades adequately. At the same time GCMs have been used to run *time-slice* experiments simulating past equilibrium states, forced by astronomical and boundary conditions (a review of mostly uncoupled simulations is given by Joussaume and Taylor, 1995; coupled simulations have been offered by Kutzbach and Liu, 1997; Montoya et al., 1998; Dong and Valdes, 1998; Hewitt and Mitchell, 1998; Bush and Philander, 1998; Weaver et al., 1998; Montoya et al., 2000). Proxy data have been used to set up the boundary conditions. They have also been used to validate the output of these model simulations. Now that progress towards more powerful computers is ongoing climate modellers can move from decadal timescales on the one hand, and time-slices of past climates on the other hand, to simulating the *transient* behavior of the climate system. More specifically, one can think of the simulation and reconstruction of low-frequency climatic variations during the Holocene, rapid events like the Younger Dryas, the inception/termination of glaciation up to the full glacial/interglacial cycles.

Proxy data are the only source of information for variability on timescales larger than a few decades, or on past (pre-instrumental) climatic behavior. In recent years there has been a growing research effort in reconstructing the time evolution of the climate and its variability on various timescales. Increasingly more proxies of climatic variables have been detected, and there has been a significant effort to align these evidences in time. Climate models are the adequate experimental devices for disentangling the functioning and relevance of the myriads of climate processes involved in generating the full dynamic behavior of the climate system.

During the international workshop "Climate Variability on Multidecadal to Millennial Time Scale" in de Bilt on March 8 and 9, 1999, jointly arranged by the Netherlands Meteorological Institute KNMI and the German Federal Research Laboratory GKSS, these aspects were reviewed and discussed. In the present article, a summary of this process is given . In conclusion of the workshop, a call is made for utilizing coupled atmosphere-ocean GCMs for simulating the transient response of the climate system to varying forcing factors, like volcanism and orbital parameters, and to reconstruct paleo climatic states by interpreting paleo climatic evidence with the help of AOGCMs in the spirit of data assimilation. For meeting these ends, GCMs must be improved to include biome and ice sheet models; process-based "observational models" linking climatic variables and proxy evidence need to be developed. Within another decade, this may result in detailed reconstructions of the climatic evolution since the last glaciation.

1. Model validation

Coupled (atmosphere, ocean, cryosphere) GCMs are not yet in the status of simulating long-timescale behavior up to full ice-age cycles, since some essential components are not yet implemented, such as ice sheets and biomes. However, multi-millenia model simulations are feasible already now. Several multi-century or millennial runs with unchanging external conditions have been executed and documented (von Storch, 1994; Covey et al., 1996; Manabe and Stouffer, 1996; Tett et al., 1996; von Storch et al., 1997, 1999; Voss et al., 1998). Multi-century simulations with time varying forcing have rarely been done so far (Cubasch et al., 1997). For such simulations, reliable time series of forcing factors need to be reconstructed from proxy data. Apart from the known orbital forcing, little is available at present. Largely unknown forcing factors range from the injection of volcanic aerosols, greenhouse gas concentrations, solar input, land use and vegetation to orography. Also other factors under discussion, such as cosmic ray forcing (van Geel et al., 1999) should be considered. Ideally, this information should be provided in probabilistic terms.

Before the output of these long-term simulations may serve as a virtual reality to address a series of dynamical questions, the model simulations need to be validated in various respects. Validation techniques, for checking consistency of a model simulation with observed statistics, have been developed in the past decades (von Storch and Zwiers, 1999). However, their application is not obvious for century and millennia long simulations due to limited spatial and temporal coverage of available proxy data, timescale limitations (Jones et al., 1998), seasonal limitations (Shabalova and Weber, 1998), dating inaccuracies, etc. As a prerequisite for combining proxy data and climate models, the proxy data archive must be made homogeneous, in particular with respect to timing. Some proxy records (like tree-rings) are absolutely dated. For other types of data a "universal time scale" must be constructed and dating uncertainties (e.g. in the case of ^{14}C-dated records) must be taken into account. Also, appropriate spatial pooling (of data records at "nearby" locations) and other measures to avoid sample peculiarities are needed (Jones, 1995). The task of comparing GCM data to proxy data is hampered by the problem of inherent uncertainty and ambiguity of the latter. Indeed, often the climate signal in proxy data is very noisy and is reflecting the combined effect of several climatic variables (like temperature, precipitation, atmospheric transports, etc.).

An additional, conceptual problem with the comparison of a GCM simulation to the paleoclimatic record is the fact that the external forces acting upon climate are not determining its state but merely condition it. Climate may be seen as a random process, whose parameters are determined by the external forces - but each realization of the climate trajectory, as simulated by an AOGCM, is a random realisation of this process. That is, it can not be expected that the simulation reproduce in detail the paleo climatic states reconstructed from paleo evidence. Therefore, simulations should be done in *ensemble* mode reflecting the inherent uncertainty of the climatic process.This could be achieved by varying e.g. the forcing within its range of uncertainty or varying the initial state. The observed paleo climatic state should be a credible member of the ensemble. It may be the case that the climatic signal excited by the forcing is comparable to the internal variability.

2. Dynamics

Once validated, quasi-realistic climate models can be used for the investigation of various dynamical aspects of the climate system. As already mentioned, the signal-to-noise ratio of variability excited by external factors and of internally generated variability needs to be determined. Also, rapid events like the Younger Dryas might be interpreted as a (forced or random) shift from one climatic state to another in a multiple-equilibrium nonlinear system. Alternatively, they may be purely externally forced.

According to the theory of the stochastic climate model, an essential mechanisms for the generation of low-frequency variability is the presence of negative feedback mechanisms as well as short term fluctuations. Here, 'short-term' indicates timescales up to decadal while 'low-frequency' indicates longer timescales. Multi-millennia runs will help to answer the question, to what extent the observed low-frequency climate variability is related to this internal mechanism and, alternatively, to external forcings. Theoretically ambitious problems of discriminating between the presence of non-linearity and stochasticity in the climate system as well as the role of high-frequency variability for the emergence of low-frequency variability can be tackled with extensive realistic modeled data sets.

GCMs provide detailed and dynamically consistent data, but fail to provide immediate knowledge about the dynamics of the system and its subsystems. Such knowledge is acquired by the construction of reduced models. That is, theoreticians are encouraged to build *simple models of complex models* in an attempt to isolate the first order processes. Thus, such simpler models are not meant to be superior to GCMs in terms of the resolved dynamics, but to be significantly reduced in terms of complexity while retaining the significant properties of the full models. The simpler models should be built in hierarchies, ranging from maxiumum reduced systems as PIPs (Achatz and Branstator, 1999; Kwasniok, 1996) or EOFs (Selten, 1995) and EBMs (Crowley and North, 1991) to dynamical models of intermediate complexity as CLIMBER (Ganopolski et al., 1997) or ECBILT (Haarsma et al., 1999; Weber, 2000).

Already, a number of time-slice simulations with models of intermediate complexity exist. Results are within the range simulated by GCMs. Due to their computational efficiency, such models can more fully explore the phase pace than GCMs and thus indicate potentially interesting regions. This may provide guidelines for GCM experiments, especially with regard to ensemble simulations. Intermediate-complexity models can also be used to estimate the relative importance of different processes and components in the system inducing a climatic respons (e.g. Ganapolski et al., 1998).

A number of applied aspects can be addressed as well on the basis of model simulations. A recently developed and highly visible application is the estimation of the climate noise, against which the reality of ongoing anthropogenic climate change has to be tested (e.g., Hegerl et al., 1996, Zwiers, 1999). Similar techniques could be used to determine dynamically consistent space-time patterns of the past respons to, for instance, variations in the oceanic heat transport or changes in the external forcing (weighted against the concurrent climatic noise). Model simulations will thus help the exploratory paleoclimatologists to define their data collection strategies, by providing guidance for sensitive areas and variables. In this manner expected patterns of variability, including rapid events, can be documented or falsified.

3. Reconstruction of pre-instrumental climate

Obviously it would be of great interest to understand which geo-climatic configuration spawned spectacular events as the Maunder Minimum (Wanner et al., 1995) or the Younger Dryas, and what the climate changes were when prehistoric civilizations rose and fell. At the same time, insight in the past variations of climate statistics in a world, geographically similar to the present one, would be of great practical use to assess presently ongoing variations.

The present day paleoclimatolgy relates proxies to climate through observational models which are invertible empirical rules, relating local climate variables to proxy data. However, different weather configurations can result in the same proxy data. For instances, the effect of temperature anomalies on tree rings can be offset by concurrent precipitation anomalies. Therefore, observational models should be developed which relate weather states to features such as tree ring densities, lake varves or ice core isotopes.

Such observational models may be constructed dynamically or empirically. First examples of dynamically or empirically defined observational models have been published (Winguth, 1997; Reichert et al., 1999); actually a host of such models may be derived from the large body of techniques developed for *downscaling* (e.g., von Storch, 1995; Wilby and Wigley, 1997). When inverted, such *upscaling models* may be used to reconstruct past climatic states, such as the North Atlantic Oscillation (Appenzeller et al., 1998). The observational model may be used for assessing implications of past (as well as future) climate change through downscaling and for validating GCMs. They can also be applied for data assimilation.

4. Data assimilation

Data assimilation techniques developed in operational meteorology and oceanography (e.g. Robinson et al., 1998) have been designed to transfer the observational evidence as forcing terms into the evolution equations of a dynamical model (GCM). These techniques could be used to combine proxy data and GCM climate modeling, i.e. one could nudge the models climate toward an 'observed' state. Observational models relate states well described by GCMs to unresolved -but observable- features such as proxy data. Such models are in general not be invertible. Their partial indetermination is actually an advantage, as in this way a manifold of consistent large scale states are available for nudging the dynamical model, and the one which is most consistent with the overall dynamical state will be chosen. It is expected that within another decade, detailed reconstructions of the climatic evolution since the last glaciation will be available from proxy data driven GCM simulations.

5. Conclusion

We suggest that a fresh attempt is warranted to systematically combine the skills of climate modellers, climate diagnosticians and paleoclimatologists. In view of the new opportunities in modelling, in data analysis and paleoclimatic evidences, two major research tasks are ripe to
be approached:

- Understanding the detailed dynamical behavior of the climate system on timescales of centuries and millennia.
- Reconstructing and understanding the transient climatic evolution on timescales of centuries and millennia as conditioned by the external forcing and detailed by internal chaotic or stochastic processes.

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