

Recent Progress in Paleoclimate Modeling: Climate Models of Reduced Complexity

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Problems and Opportunities of Paleoclimatic Modeling

Among the topics of climate dynamics, modeling past climate and its changes are a special challenge for many reasons. Forcing functions such as solar luminosity, volcanic events and surface albedo are poorly known and uncertainties in these important quantities limit the usefulness of such simulations. For the same reason there is insufficient data for initialization, which is particularly important for the ocean component in these simulations. Furthermore, the credibility of model experiments crucially depends on the availability of additional independent data with which these simulations can be checked. But the scarcity of data is not the only obstacle in paleoclimate modeling. Most of the paleoclimatic data is proxy and therefore, these data cannot be directly used to force, initialize or verify physical model results (see Schmidt this issue).

Besides these data-related aspects, two major challenges in paleoclimate modeling are the long time scales and the number of components and complexity of processes in the climate system. Models need to be integrated over millennia or more if paleoclimatic modeling is to increase our understanding of past climate processes. Such time scales are beyond the current capability of comprehensive 3-dimensional climate models (CCMs). Among the classical, and still unsolved problems of paleoclimatic modeling are glacial-interglacial cycles. Due to their time scale of many hundreds of years and the truly global extent of the problem, a paleoclimate model must include all components of the climate system, the atmosphere, the ocean, land ice and vegetation. It is therefore a truly coupled problem which involves technical knowledge from all sub-systems. Since the modeling community is still working prefer-

entially in compartments such as the atmosphere, ocean or ice sheets, paleoclimate modeling plays an important role in fostering interdisciplinary activities in modeling and model development. It gathers scientists from different backgrounds around one specific problem.

The required breadth is as much a problem as it is an opportunity. There is a risk, that some aspects of such models are not firmly rooted in their respective disciplines, i.e., the models may use formulations or parameterizations of certain climate system components that are ad hoc or would no longer be used by specialists. This is a tall order for paleoclimate modelers: they need to stay in touch with several disciplines both on a technical and scientific level.

But there are also unique opportunities in paleoclimate modeling. Apart from the fact that most problems require coupled simulations, climate changes in the past were large in amplitude, especially during the last glacial period and glacial-interglacial transitions. Large changes manifest much more clearly the underlying dynamics within and between the climate system components. Models are therefore required to exhibit a much wider range of possible transient behaviour than those which are used to simulate, say, the last 1000 years. The long time scales also represent special requirements regarding the stability of coupled simulations: drifts in certain variables must be much smaller than in integrations over much shorter time scales.

The Need for a Hierarchy of Models

Scientific progress demands more than just the best and most comprehensive models. It has become clear over the last decade that climate modeling benefits from a hierarchy of models. This is because simpler models can elucidate impor-

tant mechanisms in a more transparent way than complex models; they also offer the possibility for extensive sensitivity studies with which the parameter space can be explored systematically. If cleverly used, simplified models often provide useful guiding lines for more realistic models.

A possible ordering criterion in such a model hierarchy could be the number of balance equations which constitute the model. Outside this hierarchy, we mention for completeness Boolean delay models (Ghil *et al.*, 1987), threshold models (e.g., Paillard, 1998) and globally averaged models (e.g. Saltzman & Maasch, 1988). The former two types are not based on balance equations and therefore contain no physics. They instead are based on a fixed set of rules linking various climate variables.

At one extreme of the model hierarchy are the well-known energy balance models (EBMs) of the atmosphere which solve one balance equation for the atmospheric energy content (for a review see North *et al.*, 1983). EBMs contain no dynamics. Fluxes of heat and moisture, which in reality are due to complex atmospheric flows, need to be parameterized. This is a limitation especially in paleoclimatic modeling where one considers entirely different climatic conditions, and a specific parameterization based on modern data may no longer be valid. Today, EBMs remain in use but they merely serve as first-order approximations of the atmospheric component of models of the global ocean circulation, or ocean biogeochemical cycles (Stocker *et al.*, 1992; Fanning & Weaver, 1996; Marchal *et al.*, 1998b; Schmittner & Stocker, 2001).

At the other extreme of the model hierarchy are CCMs. The most sophisticated versions now include the atmosphere, ocean, sea ice, vegetation and biogeochemical cycles.

To run experiments with these models over order 104 years or more remains a long-term goal. Due to their demand on computational and human resources, only few centers worldwide can afford to develop and utilize such models. Therefore, they are, unfortunately, still somewhat prohibitive for paleoclimatic modeling although for some specific problems, such as time slice experiments, they have begun to produce useful results (PMIP, 2000). Very few simulations with CCMs exist that cover specific transient events in the past; e.g., the Younger Dryas cold event (12,700–11,650 yr BP, YD henceforth) (Manabe & Stouffer, 1997; Schiller *et al.*, 1997), and a centennial cooling similar to the 8200-yr event (Hall & Stouffer, 2001).

Climate Models of Reduced Complexity

For many years, there existed a gap in the hierarchy of climate models. This gap has been closed in recent years due to the development of models of reduced complexity, also referred to as “Earth System Models of Intermediate Complexity”. There are three strategies to formulate such models.

The first strategy is based on a rigorous reduction of the set of balance equations by reducing the dimensions. For example, an ocean model component of reduced complexity was obtained by zonally averaging the equations of motion (e.g., Marotzke *et al.*, 1988; Wright & Stouffer, 1991). This implies that the focus of investigations is restricted to the latitude-depth structure of the flow and to a priori chosen time scales which are accessible with these models. Similar averaging has also been used for the atmosphere (Gallée *et al.*, 1991). The difference in the deep ocean circulation between the Pacific and the Atlantic is a climatically important feature which is represented in multi-basin versions of zonally averaged models (Stouffer & Wright, 1991b). This ocean component can be coupled to an EBM (Stouffer *et al.*, 1992), or to an atmospheric module which has some zonal resolution but

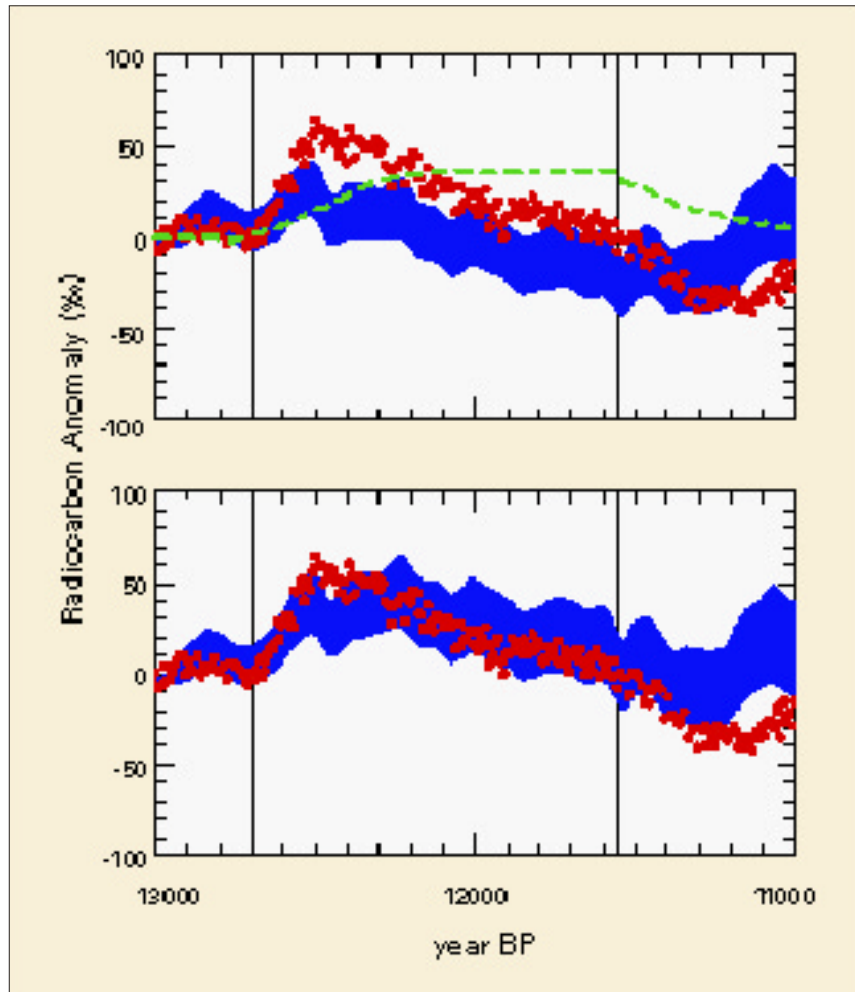


Figure 1: Comparison between $\Delta^{14}\text{C}$ anomalies from the Cariaco basin record and atmospheric $\Delta^{14}\text{C}$ anomalies simulated by a model of reduced complexity (from Marchal *et al.*, 2001). The observed $\Delta^{14}\text{C}$ record (red circles) is from Hughen *et al.* (2000). a: Anomalies simulated with variable deep ocean ventilation and constant production of atmospheric ^{14}C (dashed green line), and mean $\Delta^{14}\text{C}$ anomalies from 100 model experiments with constant ventilation and variable production (solid blue line). b: Mean $\Delta^{14}\text{C}$ anomalies from 100 model experiments with variable ventilation and variable production (solid line). Each experiment has a different random selection of production values between 17 and 11 kyr BP (13 to 11 kyr shown here) consistent with the production rates reconstructed from the Greenland ice core record (Muscheler *et al.*, 2000). The shaded area in panels a and b illustrates one standard deviation of $\Delta^{14}\text{C}$ for the Monte Carlo simulations. The two vertical lines in each panel denote the onset and termination of the YD as dated in the GRIP ice core.

whose dynamics is entirely parameterised involving a large number of tunable parameters (Petoukhov *et al.*, 2000).

The second strategy is to couple model components of different complexity. Three-dimensional ocean circulation models combined with a latitude-longitude EBM (Fanning & Weaver, 1997), or with an atmospheric circulation model of reduced dynamics (Opsteegh *et al.*, 1998), can be integrated for many thousands of years thanks to the relative simplicity of the atmosphere.

The third, and completely alternative strategy is to approximate CCMs by a set of mathematical

functions which describe their linear behaviour (Joos *et al.*, 1996). These “pulse response models” are extremely efficient substitutes for the complex models as long as the climate remains close to the initial state.

Overall, models of reduced complexity are highly useful tools in paleoclimate research provided they are wisely employed. Clearly, they cannot replace CCMs because they only consider a limited set of constraints that are important in the climate system. Their weakness is the incompleteness of dynamics, and their reduced resolution. Their strength, on the other hand, is their

computational efficiency which permits extensive sensitivity studies, ensemble or even Monte-Carlo simulations. Single simulations with reduced models are not particularly useful even if they may happen to agree well with paleoclimatic data. Rather, these models serve as key tools in the process of quantitative hypothesis-building and testing, not only in paleoclimatology but in climate dynamics in general (e.g., Stocker & Schmittner, 1997).

Recent Paleoclimatic Simulations Using Models of Reduced Complexity

Here we revisit a few recent examples of paleoclimatic simulations using models of reduced complexity. The climate of the last glacial maximum (LGM) has long been a target for modelers, although the concept of an "equilibrium climate state" representative of the lowest sea level stand is probably flawed, given the very long response time of continental ice sheets. Two models of reduced complexity presented equilibrium states that are consistent with paleoclimatic data (Ganopolski *et al.*, 1998; Weaver *et al.*, 1998). Common to both simulations, however, is a certain amount of tuning, especially with respect to the freshwater balance of the North Atlantic.

Ocean circulation proxies from North Atlantic sediments document a reduced and possibly shallower thermohaline overturning cell during the LGM. The temptation is large to adjust the forcing of these models such that the simulated ocean circulation under glacial boundary conditions agrees with these features. In this case, further independent constraints must be used to lend credibility to such simulations. Given this and serious discrepancies between different paleo-ocean circulation proxies for the LGM (e.g., Boyle, 1992; Yu *et al.*, 1996), we think that we are still very far from a satisfactory understanding of the LGM climate. Moreover, there is a growing availability of further constraints afforded by emerging new paleoceanographic and paleo-terrestrial data (Mix *et al.*, 2001). These data are best employed if the models

also include biogeochemical modules which yield variables that can be directly compared to the proxy data.

Multiple climate states have been suggested as an explanation for rapid climate changes during the last glaciation (Dansgaard/Oeschger, D/O events). Oeschger and colleagues (1984) proposed that the climate operates like a "flip-flop" system. This was confirmed by a model of reduced complexity that exhibited such behaviour in response to changes in the freshwater balance of the North Atlantic (Stocker & Wright, 1991a). It turned out that this property is robust and appears in the entire model hierarchy (e.g., Mikolajewicz & Maier-Reimer, 1994). Quantitatively, however, it depends, strongly on model parameters. In most models, abrupt climate change is triggered by changes in the freshwater fluxes delivered to the North Atlantic. This is an external, prescribed forcing to the climate models, and such simulations are unable to resolve the "chicken-and-egg" question of abrupt climate change. This is the case in simulations of a YD-type event (e.g., Marchal *et al.*, 1999), and also in a recent simulation of a series of abrupt events (Ganopolski & Rahmstorf, 2001). Simulating YD-type events with large freshwater fluxes just prior to the event is in conflict with the apparent lead of a rapid rise of sea level about 1000 years before the onset of YD (Bard *et al.*, 1996). Similarly, a model which has multiple states in only a very narrow range of freshwater flux anomalies, can be forced with a weak 1500-yr freshwater cycle to exhibit D/O-type events (Ganopolski & Rahmstorf, 2001). Because of the imposed periodic forcing, events also appear on that time scale. But this is inconsistent with the variable recurrence time of D/O events observed in the Greenland ice core record (Dansgaard *et al.*, 1993).

In these recent examples, models of reduced complexity exhibited interesting results, but the basic question of abrupt climate change is not solved. One robust lesson is that the freshwater balance of the

North Atlantic, its amplitude and spatial distribution are the crucial determinants. More realistic models and an attempt to reconstruct better the hydrological cycle from paleodata in the North Atlantic, as well as in the tropical Atlantic (Peterson *et al.*, 2000), are urgently needed to make progress.

If physical models are complemented by biogeochemical modules, the gap between proxy data and model results can be significantly reduced. Such models can simulate carbon isotopes (^{12}C , ^{13}C , and ^{14}C) in the ocean and the atmosphere, all of which are important indicators of climate change. These models also contain a number of tunable parameters: they can only be calibrated using data for the modern ocean (Marchal *et al.*, 1998b). This model has been used to simulate changes of atmospheric CO_2 due to large ocean-atmosphere reorganisations (Marchal *et al.*, 1998a; 1999). Extensive sensitivity studies indicated that accompanying changes in the ocean carbon cycle produce atmospheric CO_2 signals of only about 20 ppm consistent with ice core data (Indermühle *et al.*, 2000). Models of reduced complexity can even be used to guide the interpretation of novel paleoceanographic tracers (Marchal *et al.*, 2000). Again, in this case, specific further simulations with physical-biogeochemical CCMs would be desirable to corroborate the results and to overcome the limited spatial resolution.

There has been a debate about what caused the changes in atmospheric radiocarbon content ($\Delta^{14}\text{C}$) during the YD. The high $\Delta^{14}\text{C}$ values of the early YD as found in the varved sediment record of Cariaco Basin were traditionally ascribed to a reduction in deep ocean ventilation at the onset of the cold event (Hughen *et al.*, 1996; Stocker & Wright, 1996). This was put into question based on a recent record from Polish lake sediments, which suggests that these $\Delta^{14}\text{C}$ levels are overestimated and were instead driven by changes in atmospheric ^{14}C production (Goslar *et al.*, 2000). A recent reconstruction of ^{14}C pro-

duction based on ice cores also suggested that most of the $\Delta^{14}\text{C}$ changes during the YD can be attributed to production changes (Muscheler *et al.*, 2000). The new, higher resolution ^{14}C record from the Cariaco basin shows that $\Delta^{14}\text{C}$ changes were synchronous with the YD onset and termination, pointing again to a climatic influence on these changes (Hughen *et al.*, 2000).

A model of reduced complexity is able to reconcile the conflicting interpretations of the $\Delta^{14}\text{C}$ changes during the YD (Marchal *et al.*, 2001). Model experiments with variable ocean ventilation and constant production are inconsistent with the Cariaco Basin record (Fig. 1a, dashed line). Monte-Carlo simulations conducted to constrain the effect on $\Delta^{14}\text{C}$ of uncertainties in the reconstructed ^{14}C production changes. These suggest that the scatter in the lake data set is too large to exclude the probable change in deep ocean ventilation at the onset of the YD. The fit to the high $\Delta^{14}\text{C}$ levels throughout the YD is generally better when both ocean ventilation and production are allowed to vary (Fig. 1b, solid line). The early $\Delta^{14}\text{C}$ drawdown that was initiated during the first half of the YD, on the other hand, could be due entirely to production changes (Fig. 1a). The rapid $\Delta^{14}\text{C}$ rise at the YD onset is still not fully explained. This study illustrates how the direct comparison of paleodata with extensive simulations from a model of reduced complexity can be used to assess the robustness of various interpretations of a paleoclimatic archives and to identify gaps in our quantitative understanding which require further attention.

Outlook

There are a few obvious steps in the development of simplified models. The role of vegetation in climate change has been emphasized in the past few years. Its representation in models of reduced complexity is necessarily limited because vegetation cover is highly heterogeneous. This requires a high degree of parameterization. For long-term integration over glacial-interglacial

cycles, terrestrial ice sheets should be included. Difficulties here will arise with the hydrological cycle in these models since this determines the accumulation of snow on the ice surfaces.

Perhaps a more promising area of development is biogeochemical cycles. This is because paleoclimatic data are often influenced by or directly indicate changes in these cycles. This permits the direct comparison of model outputs and paleodata. The carbon cycle, including isotopes, has provided important information about abrupt change.

For credibility of simplified models needs to be constantly demonstrated by a careful comparison with observations and results from CCMs. Only after this confidence-building process, can novel results produced by reduced models have a wider impact. Modelers must go beyond single-simulation studies by exploiting the computational efficiency of these models. The production of extensive simulations is a major justification of such models in paleoclimate investigations. Model simulations have poor scientific value unless they are corroborated by cleverly designed sensitivity experiments. Such investigations are currently not possible with CCMs.

The forte of climate models of reduced complexity remains hypothesis building and testing. Reduced models thus have the potential to make new discoveries of processes and climate behaviour, which can then be investigated in more detail using CCMs.

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