Conclusion: Reconstructing and Modelling Past Oceans

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Katrin J. Meissner

The science of reconstructing past climates has evolved rapidly over the past three decades. Having started as a subdiscipline of geology and geochemistry [Imbrie and Imbrie, 1979], it is today an interdisciplinary research field which unifies a large international scientific community. Some of the most innovative and suprising research in this field has important implications for future climate change. As such, paleoscience is today recognized as being of great relevance to societal concerns. For example, ice core analyzes revealed that greenhouse gas levels are higher today than they have been for hundreds of thousands of years. In other words, anthropogenic impacts are pushing the climate system towards a state for which there is no "reference climate" in paleo records of the Quaternary. Therefore a better understanding of the climate system and feedbacks within the climate system is crucial for our future. Another disconcerting finding of paleoresearch is the fact that the climate system is highly non-linear: in the past, rapid and large amplitude climate change has occured in response to slowly varying, small amplitude forcing. It is critical that policy makers understand what paleoscience has to say about rapid climate change in order to fully understand the significance of future rapid climate change. The UN-sanctioned Intergovernmental Panel on Climate Change (IPCC) recognizes the importance of understanding past climate change to predict future climate scenarios and has devoted an entire chapter in the fourth assessment report (AR4) to paleoclimates.

The ocean's high heat capacity and its ability to transport energy and to sequester and release greenhouse gases give it an important role in helping to determine the state of the planet's climate. Compared to the atmosphere, the ocean has a long response time to perturbations and this makes it a key player in climate change on timescales of hundreds to ten thousands of years. Thus, paleoceanography is a crucial component of paleoclimatic research.

1   A brief historical overview

The reconstruction of paleocean characteristics and dynamics requires climatic detective work. It involves the dating and interpretation of paleoclimatic records as well as the definition of physical and dynamical constraints which specify possible circulation patterns and characteristics. As a single drill core, analysis method or numerical model cannot possibly address fundamental scientific questions regarding past climate change, international cooperative efforts are necessary to construct multiproxy records and evaluate climate models.

The first interdisciplinary project to reconstruct climate began in the 1970s and was led by the marine geologists John Imbrie and Jim Hayes and the geochemist Nick Shackelton. The CLIMAP (Climate: Long-range Investigation, Mapping, and Prediction) project reconstructed the surface of the Earth at the Last Glacial Maximum (LGM) at 21,000 years BP [CLIMAP Project Members, 1976, 1981]. Although the reconstruction was based on ocean sediment proxy data, the expertise of scientists from other disciplines was also sought-after including researchers from the still very new field of climate modelling, for example.

The first climate models evolved from numerical weather prediction models and were developed during the early 1960s. These atmosphere general circulation models (AGCMs) had become the central tool of climate science by the 1970s. The initial focus of modeling past climates was the Last Glacial Maximum (since it represented a very different climate from today and there was a relatively rich amount of proxy data) at 21,000 BP. Some of the first studies were simulations by Williams et al. [1974]; Gates [1976a, b] and Hansen et al. [1984], amongst others. As atmosphere-only models, these simulations relied on boundary conditions (CLIMAP sea surface temperatures, for example). An exhaustive overview of the results of these early model studies can be found in Crowley and North [1991].

Meanwhile, ocean modellers were beginning to build similar models of the ocean (ocean general circulation models or OGCMs). As soon as the first ocean models became operational, it became apparent that the poleward ocean heat transport plays a key factor in climate change and variability [Manabe and Bryan, 1985; Bryan, 1986]. The studies of Bryan [1986] and Manabe and Stouffer [1988] should be highlighted in this context as these early OGCM simulations showed for the first time that multiple equilibria of the thermohaline circulation could exist in more explicit models under identical boundary conditions. This finding resulted in an exhaustive and still ongoing study of the hysteresis behaviour of the thermohaline circulation in response to buoyancy forcing (see Weaver and Hughes [1992] for a thorough early overview paper or some of the more recent studies (Rahmstorf [1995]; Weaver [1995]; Ganopolski and Rahmstorf [2001]; Rahmstorf [2002]; Rahmstorf et al. [2005] amongst many others).

In the late 1980s, the COHMAP (Cooperative Holocene Mapping Project) project took the place of CLIMAP in again successfully combining skills of many disciplines into a single interdisciplinary effort. The objective of the COHMAP project was to reconstruct climate conditions at successive 3,000 years intervals from 18,000 BP to present. As climate models had evolved drastically in the 1980s, this time a variety of proxy data sources was used in combination with model simulations to reconstruct paleo environments. Therefore COHMAP was the first interdisciplinary effort to promote the interaction between climate modellers and Quaternary Scientists. Broad data sets were used to define model boundary conditions, in order to test model accuracy and improve our understanding of external and internal climate forcing mechanisms [COHMAP Members, 1988].

The next deciding step forward in the history of climate modelling of past environments was the consideration of biogeochemical cycles as a crucial component of the climate system. Until the early 1990s, the main focus of climate modelling was on physical feedbacks between climate components (mainly the ocean, atmosphere and sea ice), but a few researchers had begun to investigate the importance of biogeochemical cycles as early as the mid-1980s. These first simulations were carried out using 3-box models [Knox and McElroy,

1984; Sarmiento and Toggweiler, 1984; Siegenthaler and Wenk, 1984] and highlighted an important aspect of the marine carbon cycle: The CO_2 content of the warm (low latitude) surface ocean and hence also of the atmosphere is regulated by the surface waters of the cold high-latitude box. This finding is referred to as the Harvardton-Bear effect after the authors' three institutions (Havard, Princeton and Bern) and has important implications for paleoclimate conditions with reduced atmospheric CO_2 [Broecker et al., 1999]. The growing evidence over the last 20 years is that a better quantification of biogeochemical interactions is critical in the understanding of climate change and variability and this has led to the development of biogeochemical processes in box models [Stephens and Keeling, 2000; Toggweiler, 1999; Gildor et al., 2002] and OGCMs. As a result, the first paleoclimate model studies including oceanic and/or global biogeochemical processes in OGCMs started to appear in the early 1990s [Heinze et al., 1991] and are still being developed (Schmittner [2005] amongst others).

Today there are several interdisciplinary alliances which aim to catalyze and compare studies from a wide range of different research groups with a diverse set of research tools. These groups include the Coupled Carbon Cycle Climate Model Intercomparison Project (C4MIP), PAGES (Past Global Changes), RAPID (Rapid Climate Change) and PMIP (Paleoclimate Modeling INtercomparison Project) which will be discussed in Section 4.

2   Classification of Climate Models

The theoretical approach to paleoceanography uses quantitative ocean and climate models to reconstruct paleoconditions of the ocean and interpret observations. A number of different ocean and coupled climate models have been used in the past and a brief overview of the hierarchy and use of these models in the broad research area of paleoceanography will now be given (for an extensive overview of numerical climate models, the reader is referred to McGuffie and Henderson-Sellers [2001]).

2.1   Conceptual Models

Climate Models can be split into two categories, conceptional and numerical models. Whereas conceptual models provide non- or semi-quantitive, nondynamic simulations of paleoclimate, numerical models are quantitative and can be dynamic [Parrish, 1998]. One of the first paleoclimate studies using a conceptual model is described in Nairn and Smithwick [1976]. Other purely conceptual models of the atmosphere [Parrish, 1982] and ocean [Ziegler et al., 1981] were used for paleoclimate studies in the late 1970s and early 1980s. The next step up in the hierarchy of climate models are the numerical conceptual models. These models are still very simple and take only a few processes into account, but make use of computer power. To understand the usefulness of these simple models, consider the following example.

The 100,000 year rhythm of the major glacial-interglacial cycles during the past 700,000 years is thought to be tied to the changing eccentricity of the Earth's orbit (which has characteristic periods of 95,000, 131,000, 413,000 and 2.1 million years) in what is commonly referred to as Milankovitch theory. Challengers of this theory argue that these changes result in very small changes in insolation and are unlikely to drive the climate system. Also,

the 413,000 period of eccentricity resulted in minimal insolation changes during the warm interglacial episode about 400,000 years ago. The proxy records show an especially warm interglacial during that time contrary to all predictions solely based on insolation in the Northern Hemisphere. Paillard [1998] developed two simple multi-equilibria ice models which were able to give more insight into Milankovitch forcing and the warm interglacial episode. With his two very simple multi-equilibria models, Paillard [1998] successfully simulated both - the transition from a 41 to 100 kyr period in the glacial-interglacial cycle as well as a warm interglacial 400,000 years ago.

2.2 Numerical Models

It is, of course, impossible to build an exact model of the climate system; for the ocean alone, the position and momentum of approximately 5×10^{46} molecules would have to be calculated at each instant of time. Instead, the ocean, atmosphere, sea ice, or land surface is split into discrete macroscopic elements with measurable characteristics such as temperature, density, velocity, etc. The state of and exchange between these discrete elements follow physical laws and can therefore be determined with numerical models. Small scale processes within each element can also influence the large scale pattern and therefore have to be parametrized. Existing ocean (and climate) models differ in regards to:

- their temporal and spatial resolution (resolution is defined as the spatial scale which defines the boundary between processes that are resolved by the model and those which are parametrized)

- the nature of processes which are resolved (for example, some models include biogeochemical cycles whereas other models resolve physical processes only)

- the number of subsystems taken into account (for example, an ocean model needs boundary conditions at the surface which can either be provided by data, or by an atmosphere model which is physically interacting with the ocean model)

As the different subsystems (ocean, atmosphere, sea ice, continental ice sheets, vegetation, etc.) of the climate system interact with each other in a complex manner and on a very broad range of timescales, climate modelling reduces to the process of identifying isolable subsystems and processes that are relevant to the problem at hand. While identifying these subsystems and processes, the researcher has also to keep in mind that these processes have to be suitable to be simulated by limited mathematical models and will provide results in a reasonable computational time [Crowley and North, 1991].

The simplest class of climate models includes one-dimensional Energy Balance Models which were first developed by Budyko [1969] and Sellers [1969]. It is interesting to note that these simple models yield two stable solutions under present day boundary conditions: the present day climate and a completely frozen Earth (also called "Snowball Earth").

2.2.1 General Circulation Models

Because the boundary data for paleoclimatic simulations tend to contain large uncertainties, global models are better suited for this research area than regional models. The most com-

prehensive results are of course given by global general circulation models (GCMs). GCMs consist of a three-dimensional representation of the ocean (or atmosphere) and are to date the most complex models available. They are built on the conservation equations of momentum, mass and tracers and can include parametrizations of the carbon cycle or atmospheric chemistry. When run in an uncoupled mode (atmosphere or ocean model only) they rely on reconstructed data specifying the boundary conditions at the bottom of the atmosphere (or surface of the ocean). For example, as already mentioned in Section 1, numerous modelling studies restored the ocean surface characteristics to the CLIMAP data set [CLIMAP Project Members, 1976] for simulations of the Last Glacial Maximum (e.g. Fichefet et al. [1994]).

A better approach is to use coupled ocean-atmosphere models; by computing the surface boundary conditions, one can bypass the data problem. For example, atmosphere general circulation models (AGCMs) coupled to a mixed-layer ocean are still commonly used. This type of model predicts changes in sea-surface temperatures and sea ice by treating the ocean as though it were a layer of water of constant depth (typically 50 meters), heat transports within the ocean being specified and remaining constant while climate changes. With a constant heat transport in the ocean, these models are quite limited for simulations under very different climatic conditions [Bice et al., 2000]. The most complex models in use today are coupled atmosphere-ocean general circulation models (AOGCMs, e.g. Bush and Philander [1998]). Some recent models include the biosphere, carbon cycle and atmospheric chemistry as well. However, coupled ocean-atmosphere GCMs often need flux adjustments. Flux adjustments balance surface fluxes at the ocean-atmosphere interface to avoid a numerical drift of the coupled system. As flux adjustments have been "tuned" to the present day climate, the use of these adjustments to simulate past climates is not very reliable. However, some recent studies use coupled atmosphere-ocean GCMs which do not need artificial flux adjustments (e.g. LeGrande et al. [2006]).

2.2.2 Earth System Models of Intermediate Complexity

Earth System Models of Intermediate Complexity (EMICs, Claussen et al. [2002]) have been developed recently to bridge the gap between simple, conceptual models (such as box models or EBMs) and comprehensive general circulation models (GCMs). EMICs include most of the processes described in comprehensive models, but in a more reduced (parametrized) form. As climate subsystems other than the atmosphere and ocean also play an important role in climate change (continental ice sheets, sea ice and land surface processes, for example), the class of Earth System Models explicitly simulates the interactions among several components of the natural Earth system. The advantage of EMICs lies in their computational efficiency, which allows for long-term climate simulations over several tens to thousands of years. Also, the large number of processes described in EMICs enables the user to investigate interactions and feedbacks within the climate system in a broad range of sensitivity experiments [Kubatzki and Claussen, 2003]. EMICs are used to explore the parameter space, develop analysis methods, and analyze the response of climate over long timescales. The modelling community is continuously integrating new processes and subsystems in their models to obtain a better representation of the climate system dynamics. For example, there is growing evidence that biogeochemical interactions between the subsystems are more important than initially

thought (carbon cycle, nitrogen cycle, methane, etc.) and most of the EMICs used as of today include some parametrization of oceanic and even global biogeochemical cycles (Bern 2.5D climate model, CLIMBER-2, CLIMBER 3α, GENIE, ISAM-2, LOVECLIM, MIT Integrated Global System Model, MoBidiC, UVic Earth System Model).

Earth System Models of Intermediate Complexity are today widely used for paleoceanographic and paleoclimate simulations.

3 Models and Proxy Data

The interpretation of paleoproxy data is an ongoing challenge for paleoclimate scientists. As a striking example, one could compare the studies of Clark et al. [2002] and Bond et al. [2001]. Both papers are highly regarded, yet draw opposite conclusions from the atmospheric δ^{14}C record. Whereas Bond et al. [2001] relates the variability of atmospheric δ^{14}C to changes in solar radiation, Clark et al. [2002] interprets the same type of record as a signature of variability in the thermohaline circulation and ocean heat transport. On the other hand, model simulations of past climates depend strongly on boundary conditions, assumptions and the model used for the study. The simulated climate for a certain time span can be radically different depending on the model and boundary conditions used. Interpretation of measured paleoclimate data is thus urgently needed through collaboration between modellers and observers.

3.1 Data Assimilation

One possible approach to combine proxy data with climate models is that of "data assimilation". Data assimilation involves the construction of a field that accommodates best the information obtained from paleoproxies with the physical (and dynamical) constraints of the climate system using coupled climate models (e.g. Paul and Schäfer-Neth [2005]). Thus the models help to physically interpret the rather local proxy data in a global context. Inverse models, for example, seek for a compromise between the hydrographic and paleoproxy data. They determine circulation and biogeochemical characteristics by fitting the model to datasets of temperature, salinity, oxygen, nutrients, radiocarbon etc. For example, Winguth et al. [2002] used an inverse method [Wunsch, 1997] by which an OGCM (the Hamburg large-scale geostrophic OGCM LSG) can be adjusted to fit the paleonutrient data in order to reproduce ocean circulation and surface boundary conditions for the Last Glacial Maximum (LGM). The results of this assimilation study confirm that the North Atlantic Deep Water was shallower and the North Atlantic Intermediate Water stronger during the LGM compared to present day. The optimized glacial circulation pattern in the Southern Ocean are consistent with the Cd/Ca measurements but cannot explain changes in δ^{13}C.

Other modellers use a more empirical approach by realizing several model simulations and comparing the simulated characteristics to paleodata. For example, Schmittner et al. [2002] compared simulated changes in sea surface properties for a large variety of overturning strengths with different reconstruction sets. In this study, the results were found to depend strongly on the data set used. Sea surface temperature reconstructions from CLIMAP

[CLIMAP Project Members, 1976, 1981] and earlier salinity reconstructions based on plank-tonic foraminifera [Seidov et al., 1996; Duplessy et al., 1991; Sarnthein et al., 1995] are most consistent with a significant reduction of the circulation, while recent reconstructions using dynocyst assemblages [de Vernal et al., 2000] allow no unequivocal conclusion.

The disconcerting results of these two examples point to one of the most important challenges one encounters when combining paleoproxy data and climate models: the scale difference. Climate models reproduce large-scale features (reflecting global differential heating, the impact of large-scale topography, etc.) whereas smallscale features (secondary mountain ranges, marginal seas, etc.) are not well described because of insufficient resolution [Renssen et al., 2004]. On the other hand, the spatial and temporal sampling of proxy data is sparse. Therefore, the local character of proxy records might show the signature of local events which are not resolved in a global model with coarse resolution. Also, the proxy data usually reflects seasonal phenomena which might be mis-interpreted as representing annual averages.

The uncertainties of paleoproxy reconstructions combined with the highly non-linear nature of the climate system makes a complete agreement between models and proxy data impossible. Therefore, palaeodata assimilation schemes may be seen as an "estimate of the probability distribution functions of past climatic features and model parameters" [Crucifix, 2005b].

3.2   Integrating proxy data into models

Another possible approach is to incorporate paleoproxy data (δ^{18}O, δD, δ^{14}C, δ^{13}C, δ^{10}Be, etc.) as prognostic active tracers in climate models. These climate models can then be run under constant forcing to reproduce pattern of proxy data for a certain equilibrium climate state (e.g. the Last Glacial Maximum) which can be compared to observed proxy data obtained from ice cores, marine sediments and other records. Additionally, time-dependent (or transient) experiments can be performed under time-varying forcings (such as meltwater events or changing solar activity) to produce timeseries which can be directly compared to the proxy record. This has been done with uncoupled ocean (or atmosphere) general circulation models (e.g. Schmidt [1999]; Werner et al. [2000]; Butzin et al. [2005]), vegetation models [Kaplan et al., 2002] and continental ice sheet models (e.g. Clarke et al. [2005]). However, the importance of interactions between atmosphere, oceans and other systems such as the biosphere and the cryosphere point to the necessity of using coupled models. To date, there have been only a few studies simulating paleoproxy data with either coupled ocean-atmosphere GCMs or Earth System Models (e.g. LeGrande et al. [2006]; Crucifix [2005a]; Roche et al. [2004]; Meissner et al. [2003]; Stocker and Wright [1996]). These quantitative comparisons between climate models and paleoproxies are one of the key foci in paleoclimate modelling as they will allow for improved interpretation of the paleoproxy records.

A third way to bridge the gap between the modelling and proxy data approach is to find locations of proxy data records of special interest with the use of climate models. A simulation including prognostic paleoproxy tracers can determine the geographical region of greatest impact on a given paleoproxy data during a given climate event (e.g. Meissner et al. [2003]).

3.3 Testing and evaluating models

Finally, geological data provide us with the only way of verifying climate models. Even though paleoproxy data are point measurements whereas climate models operate on large grid cells, paleoproxy time series offer anchor points to test and evaluate models. In addition, sensitivity experiments can be performed to describe mechanisms which assess the model response. Thus, numerical simulations of past climates constitute an independent test of the performance and reliability of the climate models that are used for future climate change scenarios [Crucifix et al., 2005].

In conclusion, large amounts of paleoproxy data have been retrieved from various types of archives, but attempts to use numerical models for verification and interpretation of this data are sparse. The science of using three-dimensional climate models to interpret paleo records is still in its infancy.

4 International Programs

Today, there are several international and interdisciplinary programs to coordinate and encourage the systematic study of past climates. For example, the Paleoclimate Modeling Intercomparison Project was launched in 1992 and is endorsed by the World Climate Research Programme (WCRP) and the International Geosphere-Biosphere Programme (IGBP). Its first phase focused on the Last Glacial Maximum (LGM) and the mid-Holocene (6 kyr BP) and was designed to test and compare atmospheric components of climate models [Harrison et al., 2002]. Phase I of PMIP met with considerable success, with 67 model experiments archived in a central database and over 70 papers published in the refereed literature [Crucifix et al., 2005]. One of the most important conclusions arising from this initial phase of PMIP was the recognition of the importance of ocean and land surface (vegetation) feedbacks in the climate system. In 2002, the PMIP steering committee decided to launch PMIP Phase II which focuses on coupled ocean-atmosphere (OAGCM) and ocean-atmosphere-vegetation models (OAVGCM). It also expanded the set of standard experiments to include simulations of the previous interglacial/glacial transition (glacial inception at 115 kBP), the Younger Dryas (12.7 - 11.7 kBP), the early Holocene (9 kBP) and the abrupt cooling event 8.2 kBP [Crucifix et al., 2005].

Rapid Climate Change (RAPID), a six year program (2001-2007) of the Natural Environment Research Council aims to investigate the causes of rapid climate change, with a main focus on the role of the thermohaline circulation. Using a combinations of present day observations, paleoproxy data and climate models, RAPID seeks to assess the probability and magnitude of future climate change (Rapid Climate Science Plan, available at http://www.noc.soton.ac.uk/rapid/rapid.php).

PAst Global changES (PAGES) is a core project of the International Geosphere-Biosphere Program (IGBP) and is funded by the U.S. and Swiss National Science Foundations, and the National Oceanic and Atmospheric Administration (NOAA). It acts as an umbrella organization to facilitate international collaborations and interdisciplinary science. PAGES does

not fund individual research, but it sponsors workshops, symposia and conferences. PAGES' scope of interest includes the physical climate system, biogeochemical cycles, ecosystem processes, biodiversity, and human dimensions, on different time scales such as the Pleistocene, the Holocene, the last millennium and the recent past. Over 3800 scientists in more than 100 countries around the world currently subscribe to PAGES (http://www.pages.unibe.ch/).

The Global Analysis, Interpretation and Modelling Task Force (GAIM) is a component of the International Geosphere Biosphere Program (IGBP) of the International Council of Scientific Unions (ICSU). GAIM aims to advance the study of the coupled dynamics of Earth Systems with emphasis on the biogeochemical processes using both data and models. Modelling projects are structured by topic (CO_2, trace gases and climate-vegetation interactions) and time period (paleo (from 20 kBP), fossil fuel (from 200 BP), contemporary (from 20 BP) and future). For example, the Ocean Carbon Cycle Model Intercomparison Project (OCMIP) and the Coupled Carbon Cycle Climate Model Intercomparison Project (C4MIP) are two of the GAIM continuing current projects (http://gaim.unh.edu).

The commission on Palaeoclimate (PALCOMM) is one of the five commissions of the International Union for Quaternary Research (INQUA). Although mostly data oriented, PALCOMM also assists the comparisons of paleo data and models. Its overall objective is a better understanding of Quaternary climatic perturbations, transitions and abrupt events.

Finally, DEKLIM (German Climate Research Programme), a 37 million Euro project funded by the Federal Ministry of Education and Research, dedicated one of its four major research areas to Paleoclimate Research. The program seeks to (a) enhance our understanding of the climate system, (b) support young scientists and (c) invigorate international cooperation.

5   Conclusion

Understanding the Earth's past environments is not only a fascinating research field satisfying human curiosity, it is also essential in order to make predictions for the future. Today, several international and interdisciplinary collaborations help to develop common international science directions and ensure that important scientific questions are addressed in a coherent manner. Scientists in each of the two classic schools of paleoceanography (reconstructions through proxy data and theoretical quantitative analysis using models) are more and more exchanging expertise and working together for a better understanding of the past oceanographic environment. However, inherent problems associated with the poor spatial and temporal resolution of proxy data as well as uncertainties related to the proxy data themselves make their interpretation difficult and sometimes impossible. There is an urgent need for the creation of new well-calibrated and time-resolved paleo data records. At the same time, models are limited by resolved processes, resolution and the quality of boundary conditions. Overall, there is much progress to be made in both fields. In spite of these problems, the geological data as well as model simulations provide a substantial set of results which gives us some insight on how the ocean and the whole climate system functions. This knowledge is of ultimate importance to understand and predict future climate changes due to anthropogenic perturbations.

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