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Modeling the Holocene – Tools and Their Limits

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With 4 Figures

Abstract

The concepts of quasi-realistic modeling in climate sciences are reviewed.

Models – General

When used in an interdisciplinary context, the term "model" may cause some confusion. For a statistician the "model" is the assumed mathematical form, for a physicist a preform of a theory, for a geographer a description of a terrain and for a an oceanographer a computer code, based on dynamical equations describing the dynamics of the ocean's hydro- and thermodynamics.

In common language models are characterized as "models of something", as if the purpose of the models to be merely that – a device similar of something else. Obviously this is inadequate. Models describe only part of reality, so that model and reality share only some attributes, named "positive analogs" by Hesse (1970), while other ("negative analogs") attributes are different. In a dynamic ocean model, the conservation of mass is a positive analog, but the real ocean is a habitat for life, while the model is a mathematical construct. The purpose of the model is to allow insight into the considered system, by assuming that certain properties of the model are actually valid for the real world as well ("neutral analogs"), even if these attributes are not *known* to be valid for the real world. The constructive part of the model is thus the exploitation of neutral analogs as positive ones. Thus, only specific questions can be addressed with a model, and a model has always a limited spectrum of purposes. Models are "models for something".

In classical thinking, model building is based on ad hoc formulations constructed to satisfy certain observed phenomena derived from other knowledge about the process. Then, the model of process A is another process B that is already understood, like the pendulum or surface waves. Then, for instance, properties of sound waves are hypothesized to be valid for propagation of light. When all aspects of possibly different models of the same process are analyzed in detail, eventually a theory of the process is constructed. Thus, the model is a preform of a theory. The purpose is to gain cognitive understanding of a complex system, by reducing it to the essentials and by deliberately disregarding second order aspects and interactions. Such models are ideally simple, in accordance with the principle of Occam's razor.

When modeling climate variability and interactions during the Holocene, usually quasi-realistic models are used. These models are no longer simple but exhibit a maximum of complexity, which can be handled by contemporary high-speed computers. They are composed of complex descriptions of the various climatic components. The GCMs usually feature only sub-models of the dynamics of the atmosphere, the ocean and the sea ice, while models like CLIMBER (GANOPOLSKY et al. 1997) describe the dynamics in less detail but put more emphasis on vegetation and the role of substances. In the following I limit myself to the group of GCMs.

Quasi-realistic models do not provide immediate insight, but they are meant to act as a virtual laboratory. Only after the application of cognitive models to the output of quasi-realistic models, new knowledge arises from the applications of such models. Without proper theoretical and statistical analysis tools, quasi-realistic models generate mere numbers, and the activity of the modeler is often reduced to simply compare the model with observations without ever using the potential of the model in a constructive manner.

Purposes of Quasi-Realistic Modeling

GCM-type climate models serve a series of purposes, as sketched in Figure 1. They are used for forecasting, e. g. for the occurrence of an El Niño event in the next year, for analysis of incomplete and inaccurate data ("data assimilation"), for the construction of dynamically consistent scenarios of plausible future developments (e. g. anthropogenic climate change), and

Fig. 1 Sketch of purposes of quasi-realistic models in generating either practical knowledge to be used in social context or dynamical insight to further scientific knowledge.

for the generation of large, consistent data sets under controlled conditions ("simulation"). Furthermore, they are used to test specific hypothesis, e. g. on the effect of burning oil wells in Kuwait on the Indian Monsoon.

In Holocene studies, the models are used for simulations and data analysis as well as for testing hypothesis.

Climate as a Random Process

Often, climate is understood as being determined by external factors, like solar radiations, land-sea configuration, topography and bathmetry, composition of the atmosphere (Huntington and Visher 1922). That is, if the time dependent forcing factors are represented by η_t, then the climatic state Ψ_t is thought to be a deterministic function of η_t. This view is fundamentally flawed. Instead, climate is a stochastic system. At any time, given the same external factors η_t a range of consistent climate states Ψ_t are possible. "Randomness" is an adequate cognitive "model" for describing this indeterminacy of climate. The tools of statistics, like the mean and standard deviations or the lag auto-correlation, conveniently describe the range of states. The influence of the external factors takes then the form of a dependency of the statistical moments on the external factors. In the terms of statistics, the climate is *conditioned* and not *determined* by external factors.

This stochastic character stems from the various non-linear chaotic processes in the climate system. In case of Lorenz' famous 3-component system, the source of chaos is easily identified, and the structure of the different solutions can readily be described. The climate system, however, has many more degrees of freedom so that the overall effect of the chaotic components can no longer be discriminated from the mathematical construct of randomness.

GCM-type climate models contain many chaotic processes, so that the output of such models appears as random as the development of the real world. In a strict sense, a model simulation can be strictly replicated, if the initial state and the forcing is in all miniscule details identical and if the computer system is unchanged. However, just changing one insignificant digit in the initial state will cause the modeled system to develop differently – but still statistically consistently.

Different Approaches to Construct the Random Process "Climate" and to Reconstruct a Specific Trajectory

The classical modes of running a climate model for paleoclimatic purposes are

"Free Simulation": $\Psi_{t+1} = F(\Psi_t)$ and

"Forced Simulation": $\Psi_{t+1} = F(\Psi_t;\eta_t)$

with η_t = green gas concentrations
or aerosol concentrations
or solar output (incl. orbital configuration)
or topography (e. g., ice sheets)
or vegetation

where F represents the climate model. The time step *t* in the models is less than one hour, but the output is stored usually only every 6 or 12 hours. Some modelers store even less frequently, e. g. only monthly means.

In both cases, the system is integrated forward for many tens or hundreds years. In the "free" simulations, also named "control runs", the forcing is constant, apart from a fixed annual cycle, and representative for contemporary conditions. Thus, such free simulations generate a realization of present-day climate. Such simulations allow the determination of non-observable climatic quantities and their interdependency with other aspects. They also provide us with an estimate about the *natural variability* unrelated to external forcing factors. As an example, Figure 2 shows the variations of area-averaged temperatures during a 1000-year control run. The curves all show a slow downward trend, indicating that the model has not yet completely reached equilibrium between ocean and atmosphere. More significant, though, are the variations: In Europe, a mean temperature anomaly (e. g., deviation from the long-term mean) of more than 0.5 K prevails for about 50 years at about year 600.

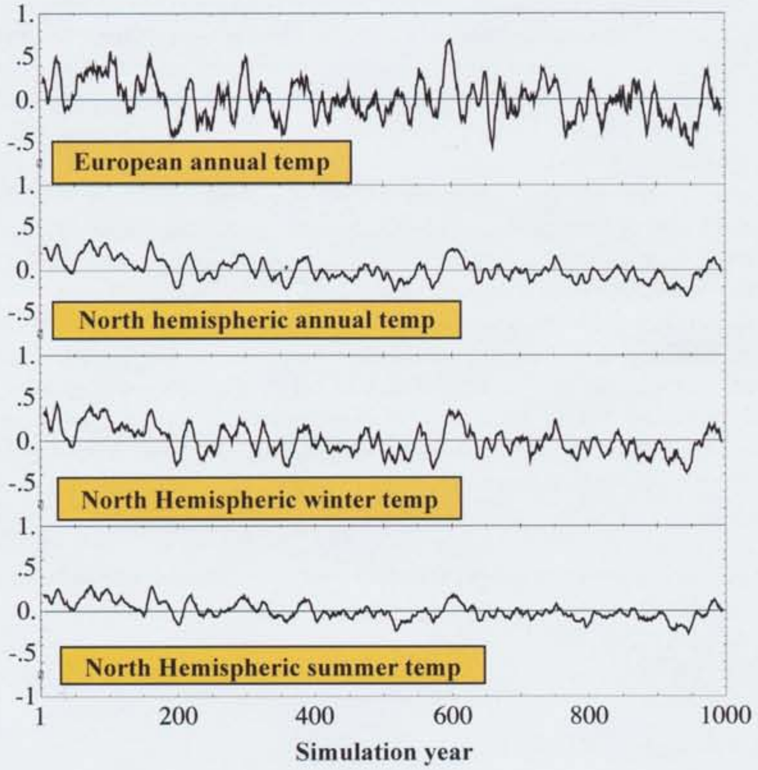

Fig. 2 Time series of area-averaged temperatures simulated in a "free simulation" with a GCM-type climate model (featuring both atmosphere and ocean). From ZORITA (pers. comm.)

In "forced runs" forcing factors are specified according to paleoclimatic knowledge. These factors may be set to constant values – this is done in "time slice experiments", in attempts to simulate for instance the LGM or the Eemian. Figure 3 shows as an example the response in terms of annual mean temperature to a change in the carbon dioxide concentration in atmosphere and of the orbital parameters as characteristic for the Eemian. For the Holocene it seems possible to specify these factors as time dependent, at least for the last two thousand years. A forced simulation of the last 500 years has recently been completed. Changed solar radiation, the effect of large volcanic eruptions, changing concentrations of radiatively active gases and substances were included. A first exciting result is that the Late Maunder Minimum (LMM), often identified with a Little Ice Age, seems to be reproduced, with widespread and persistent cooling in Europe. Figure 4 shows the difference of winter temperatures simulated during the LMM, as a response to time dependent solar output and the presence of volcanic aerosols. The pattern and intensity is fully consistent with contemporary reports and observations.

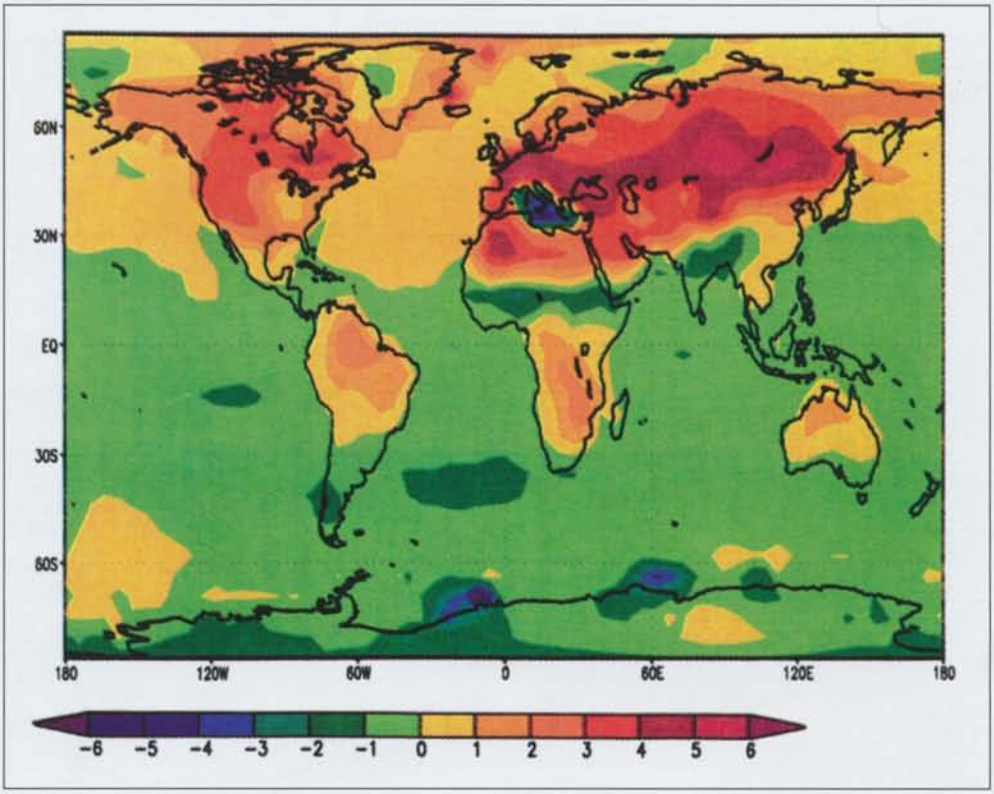

Fig. 3 Simulated difference in annual mean temperatures during the Eemian and today (MONTOYA et al. 1999)

This fine result, the reproduction of the European LMM, means that the temperature simulation in the model is a positive analog to reality. After this finding, the model becomes a powerful scientific tool, by assuming that climatic anomalies simulated outside Europe prevailed also during the LMM. Clearly, observations from the Northern North Atlantic are hardly available for the time 1675–1710, so that phenomena in the Northern North Atlantic are neutral analogs. It turns out that in parallel to the climatic anomalies in Europe a large salt anomaly, associated with very strong regional cooling, was formed and persisted for several decades (not shown). Thus, the model provides us with a plausible hypothesis about the dynamical background of the LMM.

As said before, GCM return a dynamically consistent realization, exhibiting variations due to changing external factors and due to the internal variability. For short time scales, the internal variability is dominant, but for longer time scales the importance of the internal variability becomes smaller than that of the external factors. Thus, for shorter time scales, and these cover certainly decades of years, forced simulations will fail to reproduce the details of the development. In case of the LMM the overall cooling was simulated realistically, but the details, such as winters that were exceptionally cold, or relatively warm, are not recovered. For achieving such a reconstruction, a different strategy is needed.

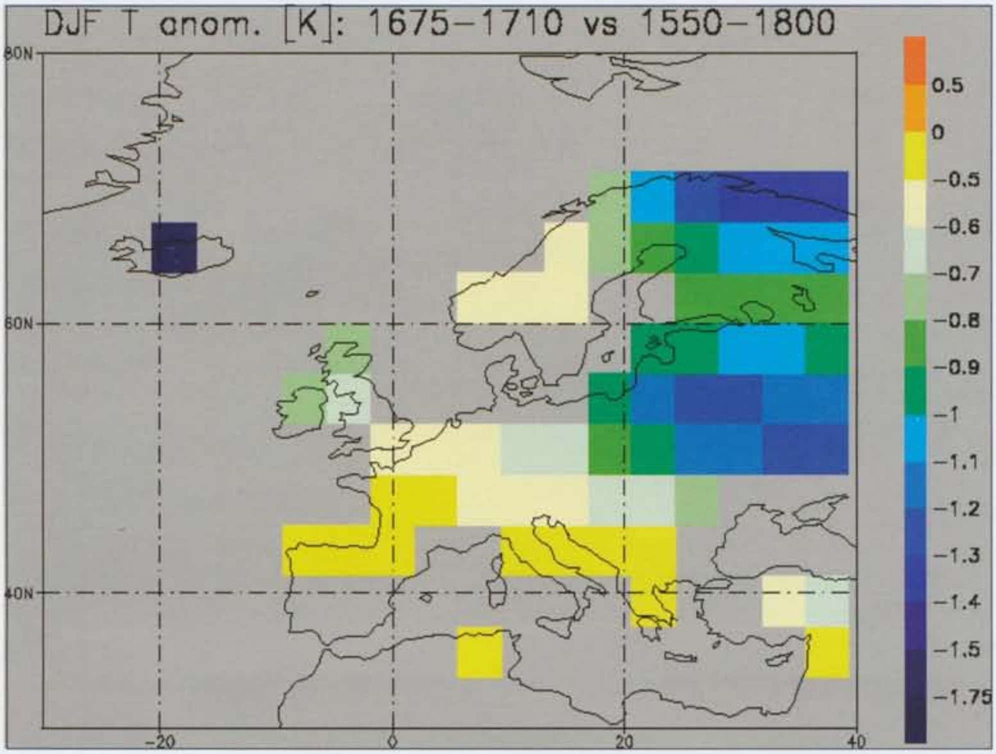

Fig. 4 Simulated difference of winter temperature in Europe, 1675–1710 (Late Maunder Minimum) vs. 1550–1800

Presently the DATUN method (Data assimilation through upscaling and nudging) is developed and tested (von Storch et al. 2000). The idea is to use the state-space formulation, with a state space equation, representing our dynamical knowledge (i.e., the GCM), and an observation equation, encoding our knowledge about the relationship between dynamical quantities and proxy data from paleoclimatic archives.

State space equation $\Psi_{t+1} = F(\Psi_t;\eta_t) + \varepsilon_t$

Observation equation $d_t = G(\Psi_t) + \delta_t$

with ε_t, δ_t = model and observation errors

F = dynamical model

G = observation model

Both models are known to be inaccurate. This system is integrated by first integrating the GCM as in a forced simulation. In a second step the expected proxy-data are determined. The difference of the actual and the expected proxy-data is used to correct the state suggested by the GCM in the first step. Formally this process is written as

Forward integration:

$$\Psi^*_{t+1} = F(\Psi_t;\eta_t)$$
$$d^*_{t+1} = G(\Psi^*_{t+1})$$
$$\Psi_{t+1} = \Psi^*_{t+1} + K(d^*_{t+1} - d_{t+1})$$

with a suitable operator K.

The state variables Ψ must be of large-scale for, first, exerting an efficient control on the overall climatic system and, second, not to suppress the synoptic variability. Thus the observation model G should be an downscaling model, linking large-scale features to local proxy data.[1] The "inverse" operator K is an *upscaling* operator, which maps local proxy data to large-scale features like the intensity of the Antarctic Oscillation. The final correction step is done with nudging in the large-scale pattern space.

Tests are presently underway. It is expected that at least three large-scale state variables are needed, representing the two circumpolar midlatitude patterns (AAO and AO) and one representing the tropical troposphere.

Further Reading

A detailed discussion about modeling, from various angles, is offered in the Proceedings of the "GKSS School on Environmental Research" dealing with "Models in Environmental Research (von Storch and Flöser 2000). A technical description of climate modeling for lay people with a good background in natural sciences is offered by von Storch et al. (1999).

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1 Ideally, dynamical downscaling models should be included in the GCMs. First attempts to model the formation of tree ring growth are underway (Reichert, pers. comm.). See also recommendations by Weber and von Storch (1999).

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