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Climate Workshop Urges Interdisciplinary Paleo Simulations, Analyses

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 this evidence in time.

A workshop earlier this year on the state of the art of climate variability studies called for utilizing coupled atmosphere-ocean general circulation models (GCMs) for simulating and analyzing paleoclimatic variability. A fresh attempt is warranted to systematically combine the skills of climate modelers, climate diagnosticians, and paleoclimatologists, agreed participants at the workshop, "Climate Variability on Multidecadal to Millennial Timescales", sponsored jointly by the Royal Netherlands Meteorological Institute KNMI and the German Federal Research Laboratory GKSS.

Because of advances in modeling, data analysis, and paleoclimatic evidence, two major research tasks are ripe for investigation, participants said. One is to understand the detailed dynamical behavior of the climate system on multidecadal to millennial timescales; the other is to reconstruct and understand the transient climatic evolution on these timescales as conditioned by external forcing and detailed by internal (chaotic or stochastic) processes.

Although emphasis is growing in the paleoclimate community on transient climate simulations with different types of forcing, participants advocated several additional steps to "complete the circle" of model-data intercomparisons. Suggested was a more rigorous statistical evaluation of model-data differences that more explicitly includes errors and uncertainties in both data and models. Also urged were application of statistical and dynamical downscaling methods to simulate microclimates of sites from which data are available and increased emphasis on directly simulating the proxy data. Participants likewise supported utilization of data assimilation techniques currently employed in other areas of oceanography and meteorology.

To meet these ends, simulations must be done in ensemble mode, and a hierarchy of climate models must be employed. Also, process-based "observational models" linking (micro-) 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.

Coupled GCMs, involving atmosphere, ocean, and sea-ice, are not yet adequate to simulate long-timescale behavior up to full ice age cycles, since some essential components are not implemented, such as ice sheets and biomes. However, multimillenia model simulations (mostly with unchanging external conditions) are feasible now. For forced simulations [see, e.g., *Cubasch et al.*, 1997], 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 to greenhouse gas concentrations, solar input, orography, land use, and vegetation. Other factors under discussion, such as cosmic ray forcing [*van Geel et al.*, 1999], also should be considered. Ideally, this information should be provided in probabilistic terms.

Before the output of these long-term simulations may yield synthetic data 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 uncertainties (for example, in the case of ^{14}C-dated records), and so forth. Also needed are appropriate spatial pooling of data records at "nearby" locations and other measures to avoid sample peculiarities.

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 reflects the combined effect of several climatic variables (such as temperature, precipitation, and atmospheric transports).

An additional problem is that external forces acting upon climate do not determine 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 is a random realization of this process. In other words, it cannot be expected that a model simulation reproduce in detail the paleoclimatic states reconstructed from paleoevidence.

Simulations should therefore be done in ensemble mode reflecting the inherent uncertainty of the climatic process. This could be achieved by, for example, varying the forcing within its range of uncertainty or varying the initial state. The observed paleoclimatic state should be a credible member of the ensemble. It may be the case that the climatic signal excited by the forcing is comparable in magnitude to the internal variability.

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. Theoreticians are encouraged to build simple models out of complex models in an attempt to isolate the first order processes. Such simpler models are not meant to be superior to GCMs in terms of 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 maximum reduced systems (such as those based on, for example, empirical orthogonal functions) to energy balance models and dynamical models of intermediate complexity, such as the CLIMBER model [*Ganopolski et al.*, 1997] or the ECBilt model [*Selten et al.*, 1999]. Intermediate-complexity models can be used to estimate the relative importance of different processes and components in the system inducing a climatic response.

Already a number of time-slice simulations with models of intermediate complexity exist. Results are within the range simulated by GCMs. Because of their computational efficiency, such models can more fully explore the phase space than GCMs and thus indicate potentially interesting regions. This may provide guidelines for GCM experiments, especially with regard to ensemble simulations.

Present day paleoclimatology 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 instance, the effect of temperature anomalies on tree rings can be offset by concurrent precipitation anomalies. Therefore, observational models should be developed that relate weather states to features such as tree rings, lake varves, or ice-core isotopes.

Such observational models may be constructed dynamically or empirically. First examples are being published [e.g., by *Reichert et al.*, 1999]. Actually, a host of such models may be derived from the large body of techniques developed for downscaling. 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. It can also be applied for data assimilation.

Data assimilation techniques developed in operational meteorology and oceanography have been designed to transfer the observational evidence as forcing terms into the evolution equations of a dynamical model. These techniques could be used to combine proxy data and GCM climate modeling—one could nudge a model's 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 invertible. Their partial indetermination is actually an advantage, as in this way a manifold of consistent large-scale states is available for nudging the dynamical model, and the one that is most consistent with the overall dynamical state will be chosen. It is expected that within another decade, proxy-data driven GCM simulations will yield detailed reconstructions of the climatic evolution since the last glaciation.

The workshop, "Climate Variability on Multidecadal to Millennial Timescales," was held in De Bilt, the Netherlands, March 8-9, 1999.

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