Reconstructing Late Holocene Climate

Studying the past few millennia, the Late Holocene, can help us better understand modern-day natural climate variability. With this in mind, a group of paleoclimate researchers and climate modelers recently convened at a workshop to discuss three distinct approaches to reconstructing Late Holocene climate history.

The first approach involves calibrating long-term proxy climate indicators against modern instrumental records to estimate past patterns [e.g., *Mann et al.*, 1998; *Luterbacher et al.*, 1999]. The second employs numerical modeling of the forced component of climate change using estimates of past climate forcings to drive climate model integrations [e.g., *Crowley*, 2000]. The third approach involves the direct assimilation of paleoclimate data into climate model integrations and uses statistical models to "upscale" the proxy data to large-scale patterns of atmospheric circulation, in a manner similar to the assimilation of meteorological information into numerical weather forecasting models [e.g., *Weber and von Storch*, 1999]. In addition, process-based forward models are being used to model proxy indicators themselves [e.g., *Weber and von Storch*, 1999].

These approaches have complementary strengths and weaknesses. The first method allows estimation of the unique trajectory taken by the observed climate, but assumes that relationships between proxy indicators and climate remain stable over time. The second approach estimates only the forced component of past climate variability, and may be compromised by uncertainties in past radiative forcing, as well as by imperfect representation of modeled physical processes. The third approach represents a hybrid of the first two; it prescribes the dynamical evolution of the system from climate physics, but is "nudged" toward the observed climate by the proxy data. This method is more resistant to biases specific to purely empirical or model-based approaches, but it is relatively untested.

An important workshop theme involved resolving differences between empirical, large-scale temperature reconstructions that employ varying combinations of proxy data such as tree rings, corals, ice cores, sediments, and documentary information. Although different Northern Hemisphere temperature reconstructions of the past 1000 years show broad similarities, those emphasizing higher-latitude summer data exhibit a more distinct "Little Ice Age" (LIA) during the 16th–19th centuries. Different reconstructions were shown to converge, however, when differences in the target seasonality and spatial domain were taken into account. Since half the surface area of the globe lies within the tropics and sub-tropics, the relative paucity of tropical and Southern Hemisphere proxy records was identified as a primary remaining source of uncertainty. Methodological issues regarding proxy-based climate reconstructions were also addressed. Results from forced and control-coupled model integrations demonstrated that calibration of paleoclimate indicators against a non-stationary twentieth-century climate is unlikely to introduce any significant bias. A new "Age Band Decomposition" standardization method demonstrated prospects for obtaining enhanced, low-frequency variability from tree-ring data, but further work is necessary to evaluate the possible impacts of ecological stresses on trees. A joint analysis of tree-ring and coral data demonstrated complementary frequency-domain information in these two data sources.

Reconstructions of patterns of climate variability such as the El Niño Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO) and regional hydrologic patterns were also discussed. An analysis of a large number of tropical Pacific coral records demonstrated enhanced decadal variability and attenuated inter-annual variability in ENSO during the mid/late 19th century. A new NAO reconstruction employing a combined 19th/20th century calibration period was shown to verify well against the longest instrumental records, in contrast with earlier reconstructions. Support was provided for the hypothesis that multi-century trends in the NAO may primarily be responsible for the distinct LIA and Medieval Warm Period evident in Europe and other regions in the North Atlantic. Extreme variations in hydrologic balance were demonstrated for many regions, including East Africa and the U.S. Great Plains. Major population centers have been influenced by significant changes in hydrologic balance over the late Holocene, particularly in intervals around 4200 and 8200 years B.P. Drought in the United States in past centuries appears to have occurred with a few characteristic spatial patterns, some which appear connected with ENSO.

Various relevant modeling experiments were discussed. An energy balance model (EBM) forced by estimated changes in radiative forcing—solar radiation, volcanic activity, greenhouse gas concentrations, and aerosols—was used to estimate the temperature response over the past millennium. A similar GCM experiment simulated the last 500 years. The model simulations explain most decade-century scale variations in reconstructed Northern Hemisphere temperature over the past millennium. In the EBM, however, discrepancies are observed during the 19th century; the modeled hemispheric temperature increases while proxy and instrumental records show slight cooling. Borehole temperature reconstructions portray a colder past few centuries than do proxy estimates, but considerable uncertainty surrounds the interpretation of the borehole data. A high, prescribed EBM sensitivity to radiative forcing is more consistent with the large past cooling inferred from borehole data; a moderate sensitivity agrees more closely with proxy temperature reconstructions. The GCM results presented support higher temperature sensitivity.

Process-based models were used to generate synthetic records of glacial mass balance and sea level based on both intermediate-complexity models and GCM simulations, employing both unforced and forced integrations. Simulated synthetic data were used to validate the model's response in the hydrological cycle and to analyze mechanisms underlying reconstructed low-frequency variations. Such process-based models make it possible to perform model-data intercomparisons on the level of the proxy itself instead of having to use reconstructed climatic variables. However, they require a detailed understanding of local meteorological processes, as well as of the complicated physical, biological, or chemical processes determining the proxy. A promising, though quite preliminary, new model of tree-ring growth was also presented.

Preliminary results from a relatively untested, but promising, approach to paleoclimate reconstruction, termed Data Assimilation Through Upscaling and Nudging (DATUN), were presented. The aim of this method is to obtain a physically–based best guess of large-scale atmospheric states during the pre-instrumental era. In the first step, modes of low-frequency atmospheric variability—for example, the NAO—are reconstructed from proxy data. In the second step, the large-scale variability in the coupled atmosphere-ocean GCM is "nudged" toward states that are both close to the reconstructed atmospheric state and consistent with the model's physics. Although the DATUN concept was considered appealing, an inter-comparison of results based on a range of models, sensitivities, and physical parameterizations was considered essential.

Several key recommendations emerged from the workshop. An expanded network of paleoclimate data is needed to reduce the current level of uncertainty in empirical climate reconstructions. More proxy records are especially needed in low-latitude regions such as Africa, much of the Southern Hemisphere, and ENSO-sensitive regions. An internationally coordinated effort to update key proxy networks is required. Extension of climate reconstructions back in time will require the use of lower-resolution proxies such as lake and ocean sediments, speleothems, and sclerosponges that provide sufficient resolution to resolve decade-century scale variability over several millennia. The stability of climate/proxy relationships needs to be more fully investigated. The sources of differences between temperature reconstructions from different data sources must be resolved, and histories of radiative forcings in past centuries better constrained, for more confident assessments of climate sensitivity. Finally, forward proxy models should be further developed and validated.

Participants supported a coordinated international paleoclimate proxy re-analysis of the 19th and 20th centuries. Such an interdisciplinary project would focus on issues in forward modeling, data assimilation, proxy calibration, and the identification of significant gaps in information. The results could feasibly provide a framework for prioritizing the collection of new proxy data.

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