change across monsoon Asia, which included famines and significant political reorganization within India (Sinha et al., 2007), the collapse of the Yuan dynasty in China (Zhang et al, 2008); and the Khmer civilization of Angkor Wat fame in Cambodia (Buckley et al., 2010). Although the relationship between climate and societal change is complex and not necessarily deterministic, the close temporal association between droughts and widespread societal changes across monsoon Asia at that time strongly suggests that monsoon droughts may have played a major role in shaping these societal changes.

Conclusion

The case for synchronous droughts in recent monsoon reconstructions across widely separated regions is compelling and suggests that the monsoon circulation in Asia can "lock" into a drought-prone mode that may last for years to decades. Understanding the ocean-atmosphere dynamics that trigger such droughts is important in order to anticipate the likelihood of their reoccurrence today. The spatiotemporal patterns of monsoon rainfall over Asia are complex and vary from year to year (Fig. 1). This complexity stems from interactions between rain-bearing synoptic-scale systems, which are propagated from the oceans onto the land, mid-latitude weather systems, ocean-atmosphere dynamics over the Equatorial Indian Ocean, and the Walker circulation in the tropical Pacific. Periodic perturbations in coupled modes of ocean-atmosphere variability, such as the El Niño Southern Oscillation, and/or dynamical processes intrinsic to the monsoon system such as quasi-periodic episodes of intense ("Active") and reduced ("Break") monsoon rainfall, are key processes that are known to orchestrate substantial precipitation anomalies over large parts of Asia. The societal implications of these new findings suggest that the narrow view of the monsoon taken from the instrumental data alone may lull us into a false sense of security. Thus a longer term and a fuller range of monsoon variability, as documented in the recent proxy records, should be urgently incorporated into future drought management and mitigation planning.

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An emerging paradigm: Process-based climate reconstructions

Malcolm K. Hughes[1], J. Guiot[2] and C.M. Ammann[3]

[1]Laboratory of Tree-Ring Research, University of Arizona, Tucson, USA; mhughes@ltrr.arizona.edu
[2]CEREGE, CNRS/Aix-Marseille University, Aix-en-Provence, France; [3]National Center for Atmospheric Research, Boulder, USA

Emerging techniques and concepts offer ways to improve the use of process knowledge in reconstructions of past climate, and to make more comprehensive estimates of the uncertainties associated with them.

The last few decades have seen extraordinary progress in the reconstruction of past climates using natural and human archives (Jones et al., 2009; Wanner et al., 2008). At the same time, our understanding of the climate system has deepened, strongly motivating development of new methods of integrating observations and model analyses. To continue this progress, it would be desirable to use all the climate information we can extract from natural archives. Frequently, only those aspects of the records are used that lend themselves to linear transformation into estimates of conventional climate quantities, such as mean seasonal temperatures or seasonal totals of precipitation. However, one can readily point to robust climatic information in natural archives that does not fit conveniently into a linear regression model (e.g., see Kelly et al., 1989). A way forward is offered by increased use of process-based forward models that capture the main features of the environmental control of the formation of natural archives (Fig. 1).

Focus on process

Each proxy archive represents a record of climate that was generated through physical, chemical and/or biological processes. Reconstructions of climate represent attempts to turn this around in order to get back to the climate information. Statistical solutions (most often regression) are used to identify simple, usually linear, relationships over a period covered by both proxy and instrumental climate records. This approach therefore reduces the problem to identifying a single climatic driver of the local proxy record stored in the natural archive, a driver that is assumed to be dominant at all times.

Two recent articles (Guiot et al., 2009; Hughes and Ammann, 2009) discuss converging trends in the use of modern understanding of proxy-forming processes. They point to important emerging tools and capabilities in exploring climates of the past that could help avoid the limitations of current empirical-statistical methods.

Guiot et al. (2009) focused on the Holocene and the Last Glacial Maximum, periods spanning major shifts in both forcing and the state of the climate system. Emphasizing paleovegetation records, Guiot et al. (2000) proposed a move from empirical-statistical models to the inversion of forward models of the formation of such natural archives (Fig. 1). For sediment data with relatively low accumulation rates, the current statistical solution is to use spatial data to calibrate a relationship between proxy and climate and to apply this "space-for-time" relationship to information on past vegetation so that the climate can be inferred. This approach assumes that the laws producing the natural archive remained constant throughout space and time (uniformitarian principle). However, when non-climatic factors such as atmospheric CO_2 concentration have changed during the period analyzed or with respect to the present, this assumption may have been violated. This is a major motivation for moving towards process-based models to better capture vegetation changes according to a realistic set of all major forcing variables, whether climatic or not.

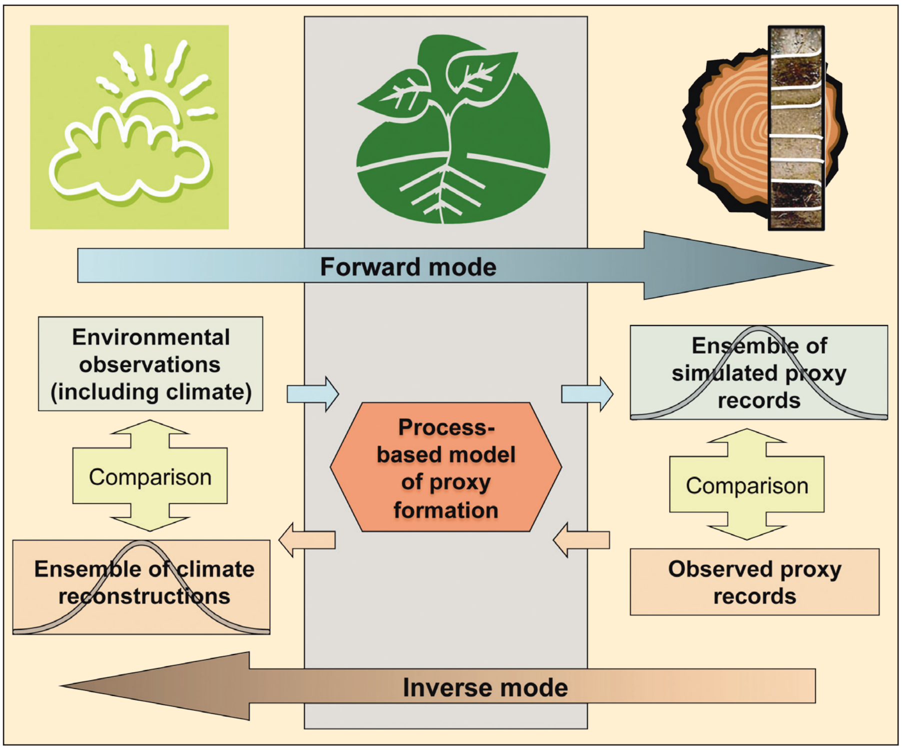

*Figure 1: Schematic view of the use of process-based forward models in climate reconstruction. In the forward mode, environmental data drive the forward model to produce an ensemble of simulated proxy records, whose distribution represents the range of variability due to known and quantified uncertainties. These are evaluated by comparison (**yellow**) with observed proxy records. In the inverse mode, observed proxy records drive the inverted process model to produce an ensemble of climate reconstructions, the distribution of which similarly represents the range of variability due to known and quantified uncertainties in the proxy data and the process model. The ensemble of climate reconstructions is in turn evaluated by comparison (**yellow**) with observed climate data. The central, gray, block represents topics in need of increased and intensified research, namely, the processes forming proxy records and the modeling of them.*

Hughes and Ammann (2009) focused on high-resolution paleoclimatology over the last few millennia, considering records such as annually layered sediments, coral growth bands, annual layers in polar and high-elevation ice, tree rings and documentary sources. They similarly propose a formalization of the combination of process knowledge (of the Earth System and of the formation of proxies) and proxy records. They argue that although calibration and verification of statistical transfer functions are frequently found to be robust, these proxy-to-climate relationships

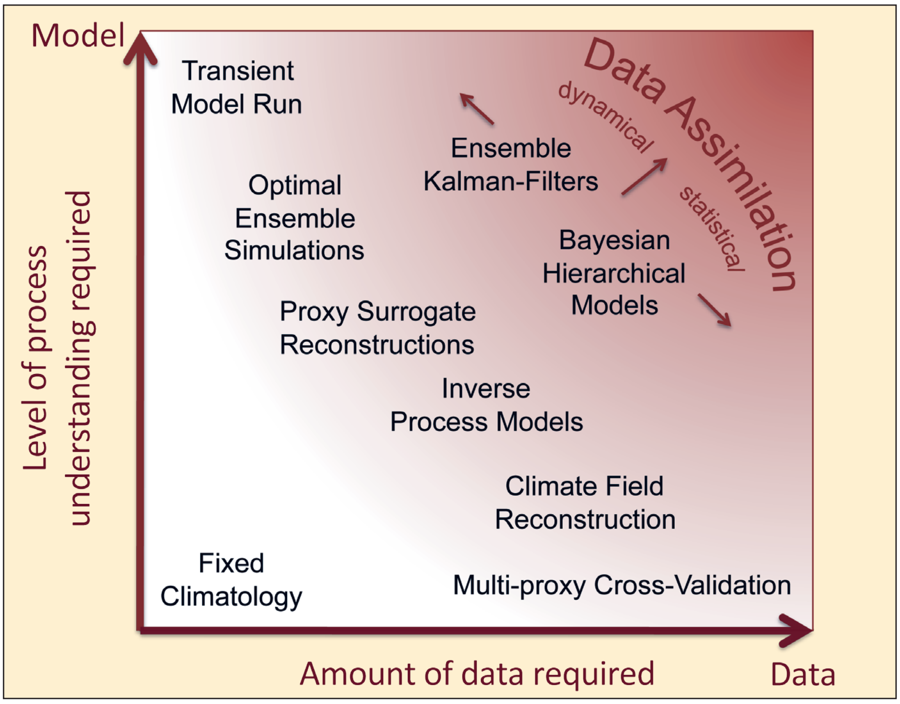

Figure 2: A schematic illustration of the relationships between methods requiring increasingly detailed process understanding (y-axis) and those depending on increasing amounts of data (x-axis). For a fuller explanation please see Hughes and Ammann (2009) from where this figure has been modified to include the inversion of process models indicated in Figure 1.

may differ in sensitivity across timescales (see also Guiot et al., 2010), and in some cases also be influenced by changes in unidentified or unmeasured factors influencing the formation of the archive. The challenge is that the instrumental period usually used for calibration of proxy records in the empirical-statistical approach overlaps with massive and widespread environmental modifications in all aspects of the Earth's surface environment. Therefore, reconstructions are likely to inspire greater confidence if they are based on models that also appropriately include important forcing factors for archive formation that may differ in instrumental and pre-instrumental times.

Towards new ways of using proxies

Consider the possibilities of a situation in which we had sufficient understanding of the formation of individual proxy records to construct "forward models" that would be driven by climate and other environmental data, and could be tested against actual observed proxy records (e.g., see Evans et al., 2006). Successful "forward models" could then be "inverted" so as to extract climate information from the proxy data (Fig. 1).

Other intriguing possibilities are emerging (Fig. 2). When coupled with forward models of proxy formation, advances in understanding of the climate system enables approaches that are very different to the existing "climate reconstruction" paradigms. For example, imagine an ensemble of forced climate model runs producing, through a proxy model, an ensemble of time series of simulated proxy fields, e.g., synthetic tree-ring records arrayed as geographic fields, or synthetic coral skeleton isotope or elemental record series. These could then be tested against existing observed natural archives for the same period. Such comparisons could be used to examine the uncertainties in both the model and the proxy data. This in turn could be used to focus attention on aspects of both data and model where it is important to make improvements (Fig. 2).

Implications for PAGES scientists

There is now a pressing need for renewed emphasis on quantitative, mechanistic understanding of how natural archives are formed. This should be given high priority in all aspects of paleoclimatology. Research on mechanisms of natural archive formation needs to be targeted to meet the needs of simple forward models of broad generality. Their parameters should have direct physical, chemical or biological meaning in the natural world, and should be measurable quantities.

In contrast to empirical-statistical models, forward models of formation of natural archives can explicitly account for potential time-dependent biases and errors, such as diagenesis in sediment-based proxies, or changing replication and age/size trend in tree rings. Moreover, by using process models, the reconstructions can finally make use of all the known climate information contained in the proxies and thus benefit from their wider Earth System context (e.g., atmospheric composition, effects of Milankovitch variations, temperature vs. moisture influence, temperature vs. salinity effects). This extends their applicability and reduces the risk of violating the uniformitarian principle.

These forward models have another very important advantage. They can be invaluable in developing new and more complete ways of evaluating and presenting all kinds of errors associated with reconstructions of past climate. As both Guiot et al. (2009) and Hughes and Ammann (2009) point out, a number of approaches to achieve this are available or are under active development (Li et al., in press) (Fig. 2). These range from largely data-driven approaches to those that explicitly combine existing understanding of natural archive formation (that is, forward models) and of climate with treatment of multiple sources of uncertainty (e.g., Bayesian hierarchical approaches). Both providers and users of proxy climate records must be jointly engaged in the development of these techniques.

Final thoughts

We do not propose the abandonment of present methods but rather an expansion of the toolkit PAGES scientists have available. The approaches used in many parts of paleoclimatology were developed 30 or 40 years ago, and were creative and productive responses to the situation we faced then. We now have a much richer set of records, a more diverse and powerful set of tools for analyzing and using them, and benefit from great advances in knowledge of the workings of the climate system. Let's find ways to incorporate this improved understanding of how natural archives are formed into the exploration of the past, using the tools and concepts available in the 21st century!

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Workshop on modeling Holocene climate evolution

Bremen, Germany, 16 June 2010

Gerrit Lohmann and workshop participants

Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, Germany; Gerrit.Lohmann@awi.de

The major objective of this workshop was to investigate the spatio-temporal pattern of Holocene climate changes as derived from transient integrations with climate models of different complexity; from comprehensive global climate models to models of intermediate complexity and statistical-conceptual models. For the 23 participants from Germany, The Netherlands, Switzerland and Norway, this was the first step in comparing data with models and may develop into a benchmark for models used in the assessment of future climate change. The Priority Research Program "Integrated analysis of interglacial climate dynamics" (INTERDYNAMIC; www.interdynamik.de; funded by the German Research Foundation; Schulz and Paul, 2009) formed the framework for the workshop. INTERDYNAMIC is based on an integrated approach in paleoclimate research, in which all available paleoclimate archives are combined with results from Earth System models to gain insights into the dynamics of climate variations during interglacials.

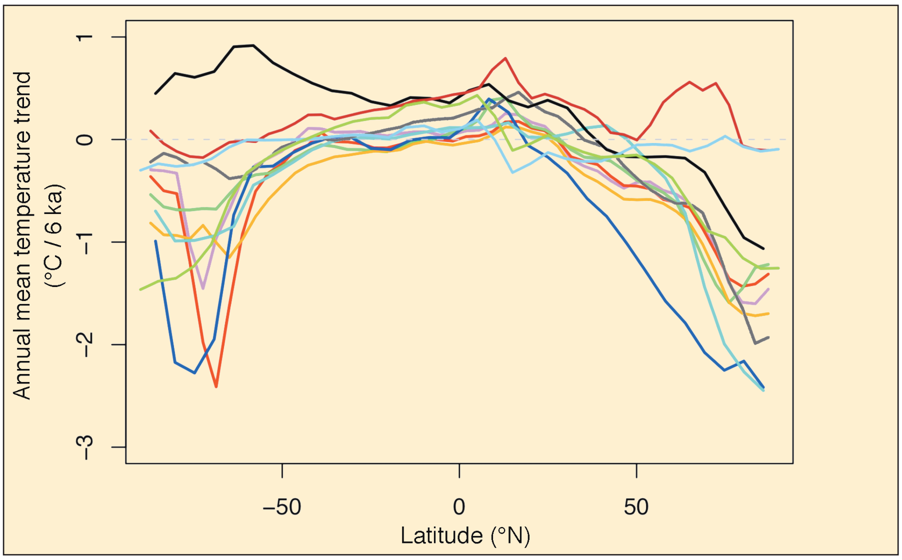

Figure 1: Zonal mean temperature trend from 6 ka BP to the pre-industrial climate as obtained from different climate simulations, forced by Earth's orbital parameters and fixed levels of greenhouse gas concentrations. Most models show a high latitude cooling and low latitude warming. In an upcoming manuscript, it will be disclosed which model shows which temperature trends.

For the paleomodel intercomparison, we compared the results from scenarios with identical forcing for the mid- to late-Holocene period: varying Earth's orbital parameters, fixed level of greenhouse gas concentrations, fixed land-sea mask and orography. All major paleoclimate modeling groups in Germany are involved in this initiative, as well as some European groups working on transient Holocene simulations. Members of the Paleoclimate Dynamics Group at the Alfred Wegener Institute for Polar and Marine Research in Bremerhaven created a data set for the available transient simulations. Posters were prepared in advance, allowing for comparison of the results with common analyses programs and discussions on the results. In addition to participation by the paleoclimate modeling community, some colleagues from the data reconstruction side were also involved. One major issue, affecting both the modeling and reconstruction side, is the quantification of uncertainties and the evaluation of trend and variability patterns beyond a single proxy and beyond a single model simulation. The goal is now to obtain robust results of