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The future of the past—an earth system framework for high resolution paleoclimatology: editorial essay

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Abstract High-resolution paleoclimatology is the study of climate variability and change on interannual to multi-century time scales. Its primary focus is the past few millennia, a period lacking major shifts in external climate forcing and earth system configuration. Large arrays of proxy climate records derived from natural archives have been used to reconstruct aspects of climate in recent centuries. The main approaches used have been empirical and statistical, albeit informed by prior knowledge both of the physics of the climate, and of the processes imprinting climate information in the natural archives. We propose a new direction, in which emerging tools are used to formalize the combination of process knowledge and proxy climate records to better illuminate past climate variability on these time scales of great relevance to human concerns.

1 A turning point

The study of past climates has progressed from the descriptive toward the quantitative over recent decades. As this has proceeded, very considerable gains have been made in understanding the climate system, and, at the same time, greater demands have been placed on the quality and quantity of natural archives of climate information, and on the methods used to translate their contents into climatologically meaningful quantities. Nowhere is this more evident than in the attention given to past climates in the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC) (Jansen et al. 2007).

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These issues concerning data and methods are particularly pressing in the case of work on climate variability and change on time-scales from interannual to multi-century. It is specifically to these time scales that we must look to understand the relationships between global climate change and fluctuations on the temporal (years to a century) and spatial (regions of diameter ~1,000 km or less) scales of direct relevance to immediate human concerns. This problem pertains not only to improved anticipation of the range of possible regional futures, but is also central to the disentangling of natural and anthropogenic variability and change. Here we will consider the present state of readiness of data and methods for the tasks of describing and understanding climate variability and change on these scales, and discuss how both might be improved.

2 Three climatologies

Studies of climate variation on longer time-scales extending from thousands to millions of years (paleoclimatology) concern major changes in the external forcing of climate or of the configuration of the earth system, and hence deal with large, potentially globally coherent or at least synchronous changes. These variations can be captured by a relatively small set of records of the past such as cores from deep ocean sediments, or the longest polar ice cores. Histories of climate derived from natural archives on these long time-scales have provided fruitful inspiration and challenging tests of the capacity of climate models to capture major forced changes in climate.

Climatology based on direct observations in the instrumental period (the last three centuries, at most) has, until the last few decades, dealt with comparatively minor changes in external forcing and earth system configuration. Given that the heat capacity of the oceans is very large in comparison to the effects of these variations, the scope for uniform global shifts in key climate variables is limited, and that for complex spatiotemporal responses is large. As a result, climatology depends on dense global networks of observations (some thousands) of all elements of the climate system, and models (of whatever kind) capable of resolving features as small as 10^3 km.

Thirty years ago, there was little evidence for systematic climate variability on time-scales between the annual cycle and those taking place over tens and hundreds of thousands of years associated with the advances and retreats of the Pleistocene Ice Ages (Mitchell 1976). Hints of such patterns of spatiotemporal variability started to emerge from the instrumental record, and from early applications of historical and natural archives (Lamb 1976). The paucity of such findings prior to the 1970s was most probably due in part to limited understanding of mechanisms, in particular the interactions of the oceans and the atmosphere, and partly due to the brevity of the instrumental record. Global coverage was only available for a few decades, with major gaps in geographical and temporal coverage Although already early in the twentieth century work by Sir Gilbert Walker and others found indications for various large regional to continental scale modes of climate variability, it was the emergence in the late 1970s and early 1980s of an integrated conceptual framework for the El Niño-Southern Oscillation (ENSO) phenomenon that was the first major breakthrough. One reason for its sudden recognition as a global climate phenomenon was perhaps because its characteristic timescale (4–7 years) is a small fraction of the length of the instrumental record (~0.05–0.1), and so a number of realizations had been well measured across many parts of the system. If there were systematic spatiotemporal climate fluctuations on longer time scales (decades to centuries), it would have been difficult or impossible to detect them as recurring events in the instrumental record, as by definition, only one or a few realizations of each could exist in the instrumental record. The instrumental record and the few millennia immediately preceding share a regime of relatively subtle variability in climate forcing and the configuration of the earth system (at least in comparison to glacial/inter-glacial transitions). In order to detect and explain fluctuations on time scales of decades to centuries, dense global networks sensitive enough to document such changes would be needed, but the instrumental networks do not extend significantly into this period. It is, however, the very period within which evidence of decadal to multi-century climatic variability of relevance to modern conditions might be found.

Our focus is the study of climate variability and change on these time-scales ("high-resolution paleoclimatology"). Much progress has been made based on the development and use of networks of proxy records of climate derived from human and natural archives, such as early instrumental records, historical documents, ice cores, tree rings, coral bands, freshwater and marine sediments, speleothems, borehole temperature logs, lake levels and glacier extent. These networks differ from the instrumental networks of the last one to two centuries in being less dense (~10 to ~1,000 records) and increasingly sparse as one goes back in time, less uniform in spatial distribution, and comprising a very wide range of "ad hoc" sensors whose responses to climate arise from their geologic, ecologic or evolutionary history (Baumgartner et al. 1989). The variables from these "sensors" that may yield climate information ("climate proxies") vary in a number of important respects, such as differing sensitivities to one or more climatic or environmental factors, differing seasonal responses, frequency-dependent reactions to climate, potentially non-linear relationships, varying spatial representativeness and confounding time-varying changes in the mechanisms of their formation or preservation. It is in order to deal with these specific characteristics of so-called "high-resolution climate proxy records" (those capable of recording climate on decadal or smaller time-steps) that the present methods of high-resolution paleoclimatology have been developed, in the context of the characteristically subtle and complex patterns of spatiotemporal variation of the Late Holocene.

3 Methods of high-resolution paleoclimatology

The basic strategy has been to identify variables ("climate proxies") in natural archives (for example the thickness of annual bands in a laminated sediment) that are expected to have a simple, quantifiable relationship with a local climate variable of interest, to construct a time series of such values, and then to transform this into an estimated time series of the climate variable. This may be done by inference based on existing knowledge of the mechanisms of formation of the climate proxy or by development of a statistical transfer function that should be informed by this existing knowledge.

The most common approach is the empirical–statistical one, which usually depends on establishing robust linear relationships between the climate proxy and the climate variable, most often expressed as a seasonal mean temperature or sum of precipitation in the case of land-based natural archives. These relationships are then applied to the climate proxies for the periods before the instrumental period in order to illuminate the variability of the climate variable for centuries or millennia past. Geographically large-scale reconstructions are based on networks of such records, and a variety of calculation strategies, some of considerable complexity.

This approach is built on a number of assumptions. Most fundamentally, it is assumed that the range of conditions relevant to the formation of the proxy record in the past contains that of the period of calibration and validation. It is also assumed that the form of the relationship between the proxy record and the climate variable being reconstructed remained unchanged through time. Dependence on these assumptions has long been recognized, in the study of Earth History in general (the Uniformitarian Principle), and in high-resolution paleoclimatology in particular. This is one of the reasons for the emphasis on using proxy records from a variety of natural archives to provide independent sources of information when drawing conclusions about the climate of some period in the past. Thus Fritts et al. (1980) compare tree-ring based reconstructions of climate in the Great Plains in 1849 with written records from the westward migration taking place at that time, and Mann et al. (2000, 2008) show that their main conclusions about Northern Hemisphere temperature over the past 400–1,200 years do not change when tree rings, for example, are excluded. It has also long been recognized that it is surprising that linear models work well for so many proxy records. For example, Hughes (2002) wrote: “Many factors are known to influence the variability of tree-ring features, and so it is remarkable that many hundreds of tree-ring chronologies have been shown to have strong, linear correlations with climate variables such as seasonal mean temperature or total precipitation”. Even so, Fritts (1976, pp 400–401) makes it plain that the use of linear statistical models is a compromise, in part dictated by the shortness of instrumental records available for calibration. It should be emphasized, however, that this empirical–statistical approach has met with considerable success when checked against independent sources of information, and against state-of-the-art climate models (Jansen et al. 2007). That is to say, the nature and scale of variability in Northern Hemisphere temperature estimated from proxy climate records over the last several centuries corresponds well with the output from forced climate models covering this period. The only data entering these models were reconstructions of forcing, such as solar input, the effects of volcanic eruptions, and so on, and thus the proxy-based reconstructions and the models are independent of one another. This suggests that the effects of any breaches of the assumptions mentioned above have been of minimal significance, at least in the case of such very large geographic scales.

Perhaps the most important short-coming of high-resolution paleoclimatology as presently practiced is the limited, or at best informal, approach taken to making use of what is already known about the physics of the climate system and about the cryological, geomorphic, ecological or biological processes that imprint climate information in natural archives. This knowledge can, in principle, be used to constrain climatic interpretations of natural archives to those that are mechanistically reasonable (in terms of the processes forming them), and consistent with the known physics of the climate system. Arguably the second most important short-coming is the ad hoc approach often taken to the assessment of uncertainties in reconstructions. We propose a new direction for high-resolution paleoclimatology, which takes advantage of advances in process understanding and the growing capacity to capture that understanding in models of the climate system and of the formation of climate proxies. We will explain how this approach could lead to a better and more formal integration of data from natural archives and process understanding in reconstructing the behavior of the climate system on inter-annual to multi-century time-scales.

4 A new direction

In the existing paradigm of high-resolution paleoclimatology, variables describing the state or content of natural archives (proxy climate records) are transformed into estimates of local climate variables, such as winter half-year precipitation, mean summer temperature, or gauged river flow over the hydrologic year. Alternatively they are used to calculate regional averages, spatiotemporal patterns (climate field reconstructions) or even circulation indices, based on the association between local climate variables and these larger-scale features. This approach made good use of the limited climate information available 30 years ago, was in principle simple and repeatable, could draw on existing statistical understanding, and produced results in a form familiar to climatologists. On the other hand, it imposed strong limitations on the climate proxies that could be used, and likely led to loss of useful climate information that could not be captured by the linear, although multivariate, models used. Furthermore, it imposed a particularly stringent variant of the uniformitarian assumption, where most of the variability of the climate proxy must be driven by variables looking like and behaving in their quality as entries from the Monthly Weather Reports for the whole reconstructed and calibration periods.

In reality, the mechanistic links between climate and the formation of the natural archives from which proxy climate records have been derived involve quantities that may differ markedly from regular meteorological variables. It is becoming very clear that, for example, a stable isotope field does not simply reflect a combination of local temperatures and precipitation/evaporation (Hoffmann et al. 2005; Schmidt et al. 2007). Rather, isotopic maps are complex response surfaces that integrate source area conditions, transport processes, local deposition events, active biology and then diagenesis. The same could be said for maps of tree-ring width or densities that often reflect much more detailed, and non-linear information than simply summer time mean temperature and soil moisture (see, for example, Evans et al. 2006; Vaganov et al. 2006). In essence, each proxy "field" could be regarded as a unique variable, analogous to the meteorological variables that are used to describe the climate. It is important that we start "seeing" the processes behind the climate proxies that in their spatiotemporal setting store climatically relevant information, and using this more complete information in combination with existing understanding of the climate system.

Therefore, a suite of forward models to predict proxy response to climate should be systematically included in high resolution climate models. It is, of course, essential that these forward models be as simple as possible while still capturing the essential features of the relationship between environment, including climate, and the formation of the climate proxies, and that they be validated rigorously against a wide range of observations of climate proxies. Thus, in the case of forced, transient runs of climate models, fields of synthetic proxy records would be generated, and checked against observed climate proxies (for example, tree-ring width, or δ^{18}O of annual bands in corals), not against statistical estimates of traditional climate variables derived from such proxy records. Such an approach also opens up the prospect of more directly applying the techniques of data assimilation to the combination of proxy records and climate models.

The new direction that we propose for high-resolution paleoclimatology uses such developments to perform data assimilation of proxy climate records within a full earth system framework. While not strictly comparable with their counterparts in the instrumental period, where high-quality observations generally dominate over bounding constraints, new methods are already being developed that make use of dynamical process models (sometimes even full climate models) in addition to actual, yet noisy, climate records. In essence, these integrated methods exploit elements of the earth system framework that are both dynamically interpretable and at the same time help constrain individual uncertainties. Such new methods should help to formalize the combination of diverse kinds of information and thus offer a solid and more complete, quantitative approach for evaluating uncertainties.

It is an essential prerequisite of such an approach that the actual mechanisms leading to the proxy climate records to be used are well enough understood to be modeled effectively. A good forward model requires not only a good understanding of the key processes that are responsible for generating the signal (proxy climate record) in the archive, but it also needs appropriate sources of estimates for the parameters and a reasonable understanding of various levels of uncertainties related to the raw proxy data. For many proxy records there are large bodies of literature dealing with such issues (e.g. for a recent overview of the current state see Jones et al. 2009), but for successful proxy modeling there is now a need to formalize them explicitly because any reconstruction outcomes can only be as good as the input.

Finally, another crucial requirement for these new synthesis methods concerns a good understanding of changes in external perturbations or boundary conditions. If the climate of a region is directly or indirectly modulated by radiative forcing, then it is essential to have a well-dated and reasonably accurate forcing history. Although including such external factors in the reconstruction itself has been regarded as potentially circular, the new data-integration (assimilation) methods are designed to make use of all available information so that all constraints of the system are satisfied. For the recent past, the dominant external forcings include the natural aspects of solar variability and explosive volcanisms, and anthropogenic perturbations that arise from changes in atmospheric greenhouse gas concentrations, emissions of various aerosol and changes to the land surface through land use. That these forcings are reasonably well established, at least at a hemispheric scale, can indirectly be seen when climate models driven exclusively with external forcing estimates reproduce the primary temporal structure of Northern Hemisphere temperature as derived from multiple hemispheric level proxy reconstructions that did not make use of forcing information (Jansen et al. 2007).

5 Synthesis through broad paleo data assimilation and model integration

Climate reconstructions can be achieved in a broad continuum of approaches. These must be based on good understanding of individual proxies and utilize the range of constraints provided by a network of observed information while increasingly including dynamical controls. In fact, there is already a suite of tools being explored that can loosely be labeled as data assimilation approaches. Some are more oriented to the observed proxy data while entraining a limited amount of process (model) information; others are founded on model simulations where observations help to guide the selection among possible ensemble members (Fig. 1). Here we briefly describe a range of techniques, starting with those primarily dependent on observed data, and moving to those using known processes in nature as formalized in models.

Multi-proxy cross-validation A powerful method to reduce uncertainty is achieved if—in simple terms—the climatic implications of one proxy can be used to predict another, fully independent proxy, especially if the second proxy is indicative of a different climate or environmental quantity. The question is not simply whether their "wiggles" more or less correspond, but whether the timing and absolute amplitude of change in proxies in different parts of the system are consistent with the best available physical understanding of it. For example, if there are proxy records of precipitation in a catchment, and of lake levels in a closed basin at the foot of the drainage, it should be possible to use a proxy-derived history of water availability to drive a hydrologic model of the relationship between precipitation and flow, and then between flow and the level of the closed basin lake (Graham and Hughes 2007). The model output of lake level should reflect low or high stands known from independent, for example geomorphological, evidence. This approach has the great advantage of providing a strong challenge to the proxy climate records, one which would increase in strength as more records in different components of the system are added. A special case of proxy-cross-validation can also be achieved in space where, e.g., proxy-based reconstructions are performed for individual sub-regions (Briffa et al. 2008). The outcomes for neighboring sub-regions should, given the length-scale of the climate field, be in reasonable agreement. When applied to a broad continental scale, large-scale coherent patterns substantially raise the confidence in individual reconstructions.

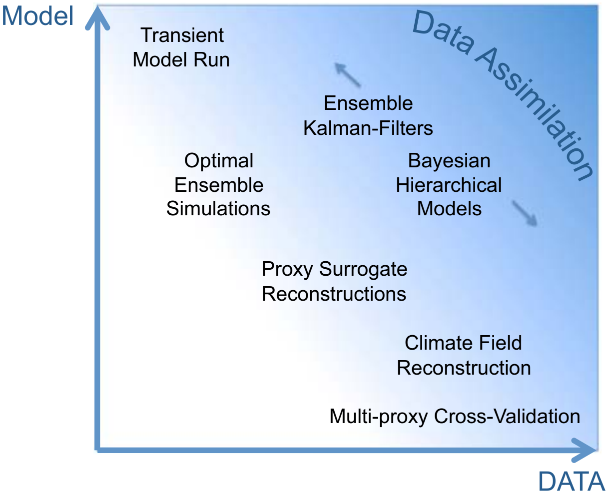

Fig. 1 A schematic illustration of the relationships between methods requiring detailed process understanding (lesser to greater on vertical axis *bottom* to *top*) and those depending on data (lesser to greater on horizontal axis *left* to *right*)

Climate field reconstructions Rather than testing the consistency between different closely spaced proxies, field reconstruction methods utilize the large-scale spatial coherence among the proxy records of a widely distributed network. Because the climate system has a strong tendency to exhibit a limited set of primary modes of variability, the spatially distributed effects of these modes can be extracted from the joint variations across the proxy network. Although no model-data are used, the underlying primary modes of variability represent the system's preferred dynamics, including its spatial teleconnections. To the extent that the network of climate proxy records captures these primary modes, they may be used to estimate weights (contributions) for each mode at any time interval. Combining the weighted patterns associated with the various modes of variability results in the reconstructed large-scale climate fields (Fritts 1991; Mann et al. 1998).

The methods described so far make no explicit use of process models within the reconstruction process. Now we discuss approaches that increasingly build in small or even large-scale dynamical processes. At one end (Fig. 1) are direct transient climate model simulations that have no knowledge of the proxy record of climate. Their only connection to the real world is through the imposed histories of boundary conditions and external forcings (Crowley 2000). However, climate models, even if forced with perfect external forcing histories, will not reproduce the unforced real-world internal variability. It is also possible that the model lacks certain processes (physics) that cause a modulation of internal variability. Any comparison of observed proxy records with model output is hampered by this strong spatiotemporal difference resulting from the random "weather", and only large-scale integrated quantities (e.g. Northern Hemisphere temperature) might be well simulated (Ammann et al. 2007). However, there are many ways one can still make use of the models' geophysical constraints on spatial variability, and we list some of the recent applications in this rapidly growing field.

Proxy surrogate reconstructions One relatively simple means of exploring a likely geophysical consistency between a set of well-dated climate proxy records and model output is provided by the technique called the Proxy-Surrogate-Reconstructions (PSR). It explores the (full) climate variability space described by a large number of observational or climate model fields (Graham et al. 2007). The procedure simply searches for the closest sample of a spatial field to a set of spatially predefined locations where proxy climate data are available. This approach is similar to methods applied in weather forecasting before the shift to operational model-based projections. The downside, however, is that, by design, any time-evolution in the climate fields is lost because the reconstruction will simply be a reordering of the suite of realizations in the model or instrumental archive.

Optimal ensemble simulations This is conceptually similar to PSR but more explicitly explores the time evolution of climate through quasi-ensemble modeling with an efficient earth system model of intermediate complexity (EMICs) (Goosse et al. 2006). For each proxy time step, usually a year, a suite of simulations is run with slightly perturbed initial conditions. This ensemble set is then compared to the next available observations, and the member that most closely matches the proxy data is retained while the other ensemble members are discarded (thus quasi-ensemble). The retained output is then itself used as initial condition for the next suite of perturbed ensemble simulations stepping forward to the next proxy time step. In this way, the model retains some information of the past although in only a single version.

Data assimilation using ensemble Kalman-filters This method is the foundation of modern instrumental reanalysis efforts. Simply put, it employs a large evolving ensemble of weather/climate model runs that are continuously nudged towards the next observations. Rather than discarding any members, this method carries along all of the ensemble members through the full time period covered by observations (proxy climate records). The distinct advantage of this approach, particularly under conditions where the observational information is both sparse in space and noisy in quality, is that multiple possible solutions that are difficult to distinguish at any one time are allowed to evolve. Both the similarity of any ensemble member to the observed proxy data at the respective locations and the information about the amount of nudging that was necessary to stay close to observations provide quantitative measures of success of a particular ensemble member at any time. A challenge in a paleoclimate application of the traditional data-assimilation methods is that the observations are not instantaneous measures of an atmospheric or oceanic state. Rather they are time averages (annual, seasonal, ...) that are in most cases only related to climate quantities. It will be essential to explore how to deal with these issues before proceeding in this direction (e.g., Dirren and Hakim 2005).

None of the model-based methods discussed in this section have directly taken the processes of proxy formation into account. A complete synthesis of information in the form of a paleoclimate data-assimilation would have to include complexities and uncertainties at all levels, for proxy and climate dynamics alike. Recently, one particular new family of methods has been given attention because it provides a tremendously flexible framework for combining process and statistical models of many flavors. This could be very valuable for integrating the full suite of different paleoclimate records and accounting for their differences in sensitivity to climate, resolutions, possible temporal biases, etc.

Bayesian hierarchical models (BHMs) The core idea of this approach is to formally separate the proxy climate records from the process descriptions. Using large Monte-Carlo-type analyses to simulate joint solutions for the proxy series and the specified processes, the distributions of the reconstructions and the model parameters provide unprecedented opportunities to explore all levels of uncertainty, even specifically for different time scales (Haslett et al. 2006). Additionally, the inherent flexibility of the formal framework of a BHM (Banerjee et al. 2004; Wikle and Berliner 2005) is well suited for the diversity of paleo information, because the data-level description of any proxy climate record is directly tailored to its own characteristics that can be completely independent of that for other proxies. At the same time, there is no limit to the complexity of the guiding processes that describe the climate fields. This level can be as simple as an auto-regressive model representing memory of the climate system, but it can be expanded to include, for example, radiative forcing and elaborate geophysical dynamics. In fact, conceptually one could build in a full climate model and with this essentially embed the ensemble Kalman-filter data-assimilation machinery. The Bayesian Hierarchical framework provides the necessary formal structure to handle proxies and fundamental physical processes of climate together, and to identify what joint realizations of the climate fields best connect all the pieces of information. Because of the integrated nature of the data, the answers are going to be significantly more robust than if inferences were drawn from one or a set of individual proxy series.

One of the challenges for climate research in general, and paleoclimatology in particular, is the fact that using straight-forward process models linking proxy climate records to climatic variables might not be enough. In fact, in many cases it might be necessary to go further than this. Because of the strong human influence on all aspects of the environment, the world in which proxy climate records are collected and calibrated may well increasingly differ in relevant non-climatic respects from the period whose climate we wish to explore. For example, there has been discussion of a possible influence on tree-ring formation of increased atmospheric concentrations of carbon dioxide, although there has been no convincing demonstration of this. Similarly, acidification of the oceans might affect the formation of proxy climate records in natural archives such as corals. The deposition of particulates on ice-caps could affect the likelihood of summer melting at the surface, and so on. Therefore, both the general climate model as well as the forced process models of the proxy climate records discussed in the previous paragraph should ideally be capable of dealing with these effects explicitly, when there is a strong case that they could be introducing a change in the climate response of the natural archives. Obviously, this can dramatically increase the required level of complexity of the underlying model. Only a true earth system approach to modeling and data assimilation can achieve this, one in which all major components affecting climate and those affecting the natural archives are dealt with explicitly. Such dynamical process models include, for example, detailed representation of the carbon cycle, and of the role of vegetation in interactions between the atmosphere and the land surface. A great advantage of these integrated methods is that they exploit elements of the earth system framework that are both dynamically interpretable and at the same time help constrain individual uncertainties.

The last millennium paleoclimate reconstruction (PR) challenge Given the suite of uncertainties and limitations connected to proxy and short instrumental data, it is very difficult to derive a reconstruction method that is capable of explicitly dealing with all issues, and thus some compromises must, inevitably, be made. At the same time, many existing methods might be reasonably well suited to study particular aspects of past variability and change (Ammann and Wahl 2007). However, we do not have a solid quantitative understanding of the strengths and weaknesses of each method. When different methods are applied to the same time period and spatial domain, how different are their results and inherent uncertainties, and to what is each method particularly sensitive? Differences could result from limitations in the included proxy climate records' ability to record climate across different time scales; the sampling distribution (network); or possibly the method itself or its underlying assumptions. To assess the influence of all these uncertainties, the last millennium paleoclimate reconstruction (PR) challenge is being developed to offer an experimental test bed for systematically gauging the ability of the various methods to recover the true underlying climate. The climate data are drawn from output of fully coupled climate system models that provide geophysically realistic spatiotemporal variations across various climate fields. Thus the target of reconstructions will be fully known. Using a suite of simple to increasingly complex and more realistic proxy forward models (process models), networks of pseudo-proxy records are generated that consist of transformed climate model information. These model-derived samples, together with a short instrumental-quality like dataset that overlaps with a short period of the pseudo-proxy data, can then be used for reconstruction by the various methods. Because the target of the reconstruction is known, i.e. the full model output, each method and application can be tested in its ability to reconstruct the climate. Such tests include the relatively simple problem of large-scale averages (such as the Northern Hemisphere mean temperature), but are particularly useful when focusing on regional scale variability and trends. A special effort is going to be put into exploring how well moisture fields, and possibly atmospheric circulation structures through air pressure distribution, can successfully be reconstructed. This setting allows for the systematic evaluation of the effect of realistic as well as worst-case scenarios with regard to proxy representation of climate and how the various reconstruction methods are capable of dealing with these issues. The key question, ultimately, is to find out how well the suite of reconstruction methods, if applied to a realistic set of pseudo-proxy data, are able to reproduce the underlying climate, not knowing the actual target climate (achieved in a double-blind approach). Of particular interest in such an exercise is how well uncertainties are estimated and what parts of the underlying signal are well constrained. At the same time, it will be important to evaluate if the climate reconstructions might miss important variations in climate on this virtual (model) planet. The PR-Challenge is just beginning. Information can be found on the PAGES Web site: http://www.pages.unibe.ch/science/prchallenge/.

6 Final thoughts

There is a great deal of relevant understanding available of what is physically possible in the climate system, and of the processes by which proxy climate records are embedded in natural archives. It makes no sense to treat the reconstruction of past climate using proxy climate records as an uninformed statistical exercise. This has been recognized since the beginning of high-resolution paleoclimatology. Informal approaches to incorporating such understanding in the design of reconstruction procedures and in the interpretation of their results are to be found in very many published works in this field. It is now becoming possible to formalize this testing of proxy climate records and climate system understanding against one another, using a combination of models of the climate system and of the processes embedding climate information in natural archives.

The study of the processes by which climate proxy records are formed is central to this approach, and such work should be accorded high priority. Equally, the success of the approach discussed here depends on the availability of good estimates of the major external forcings of the climate system relevant to time scales from interannual to multi-century.

Successful identification of climate change at regional scales depends on detailed knowledge of the natural variability that comes superposed on forced responses. The separation of these forms of variability is not easy, yet it is absolutely necessary if we want to more accurately and quantitatively predict future changes. Rather than simply projecting forward (potentially random or spurious) trends at the end of the instrumental record, careful "expectation control" utilizes both knowledge about the typical propagation of initial conditions and solid understanding of geophysical processes that translate external forcing into a systematic climate response. Such a systematic response is not simply a shift in the mean condition, but it can come just as well in a change in variability or change in the probability of certain events happening.

Long proxy climate records and reconstructions therefore not only provide ways of extending the instrumental record back in time (albeit with increasing uncertainty), but, more importantly, reconstructions contain a rich database from which one can isolate systematic regional climate responses to repeated forcing events. Most external forcings show numerous variations which are quite solidly documented—at least with regard to their temporal occurrence (e.g., independent measures of repeated solar cycles, or the deposition of volcanic sulfate in polar ice). Therefore, combining geophysical process understanding of the forcings and the earth system response within the proxy climate records, one can formulate regionally specific benchmarks of how and why a response to future forcing is to be expected. Using the high-resolution paleoclimatic record as a backdrop then prevents over-attribution of recent trends exclusively to the forced response. A good case in point would be the observed strong positive trend in the Northern Annular Mode, or NAO/AO, during the 1990s that was directly attributed to the greenhouse effect. Because climate models did not exhibit such a strong trend, they were labeled as significantly too weak in their response to the greenhouse forcing. Simply increasing the ensemble size of the simulations did not fix this problem because the expected target was wrong (Selten et al. 2004). Better consultation of the paleoclimate records might have provided an cautionary perspective, one that was ultimately confirmed by the relaxation of the NAM towards more average values.

Finally, beyond the descriptions of what has happened, the attribution of past climate variations or changes to internal or external drivers remains an important task, and one that can only be fulfilled in a framework of process understanding. Seamless identification of forced climate variability and change from the past all the way to the present is ultimately the goal of high-resolution paleoclimatology because it provides the necessary baseline against which climate models that are used for future projections and predictions can be tested.

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