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A Community-Driven Framework for Climate Reconstructions

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Proxy-based reconstructions of past climate provide insights into externally forced and intrinsic variability over regional to global scales and can be used to place recent trends in a long-term context. Comparisons between these reconstructions and the output of Earth system models provide evaluation opportunities to improve our understanding of climate forcings on time scales that are not adequately represented by the instrumental record. They also provide a heuristic tool to explore mechanisms of climate variability, with implications for future climate projections [*Schmidt et al.*, 2014].

The Past Global Changes (PAGES) project aims to improve understanding of past climate variability. Within this program, PAGES 2k focuses on the past 2000 years—the Common Era (CE)—a period when climate was relatively similar to today and for which proxy records are relatively abundant. A global synthesis of continental-scale temperature changes during the CE was published recently by the *PAGES 2k Consortium* [2013], a group comprising 77 coauthors from 24 countries. The synthesis contributed to a larger assessment of climate change as part of the latest report of the Intergovernmental Panel on Climate Change [*Masson-Delmotte et al.*, 2013], and comparisons with paleoclimate simulations are under way [*Jungclaus et al.*, 2014].

Over the past year, scientists involved in PAGES 2k have been building on previous work and planning for the next phase of the project by developing near-term recommendations and long-term goals. These community-based recommendations are being used by the nine regional PAGES 2k working groups—one each for the Arctic, the global ocean, and every continent—to pursue climate reconstructions that address key questions about climate change that are most relevant and answerable within specific regions. Below are the four top goals with their associated recommendations developed by the PAGES 2k community.

Goal 1: Build a Uniform Open-Access Proxy Climate Database

Access to a large volume of information in a standardized format will accelerate advances in climate science. Specifically, providing user-friendly open access to a comprehensive uniform database incorporating all relevant paleoclimatic data for the past 2000 years in a logical format will spur these advances.

This will facilitate the creation of targeted observational networks, provide test beds for reconstruction methods, and enable comparisons with paleoclimate model simulations. Furthermore, it will fuel future studies that address questions related to specific features of atmospheric-ocean circulation from subregional to global scales, and it can be built upon for use well beyond PAGES 2k. Moving toward a self-describing, open, and universal data archive system will encourage more complete use of existing paleoclimate information, enhance reproducibility, and provide increased transparency [*Emile-Geay and Eshleman*, 2013].

Recommendations: PAGES 2k envisions a publicly accessible, comprehensive database from which researchers can address a broad variety of scientific questions. Criteria for identifying an initial inclusive set of proxy climate records have already been developed (see http://bit.ly/PAGES2k-info), and a data entry template has been created in collaboration with the U.S. National Oceanic and Atmospheric Administration (see http://bit.ly/paleoclimatology_data). The database will include all proxy records that meet these broad criteria, not only those that are used for a particular analysis or that meet more strict criteria. In addition, complete geochronological

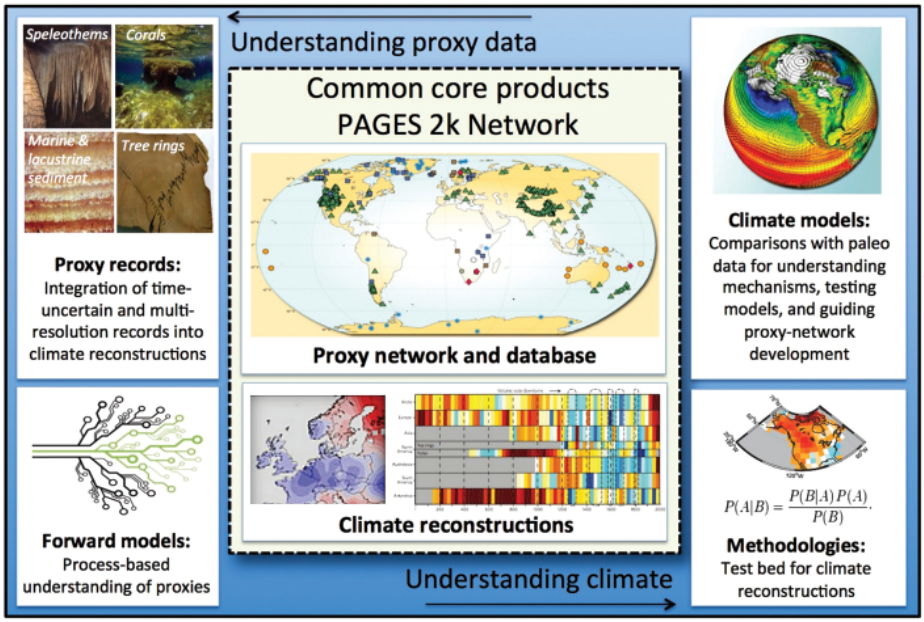

Fig. 1. The Past Global Changes (PAGES) 2k community has developed recommendations aimed at facilitating a global synthesis of proxy climate information. (middle) Near-term goals aim to generate a uniform suite of core products. In tandem, efforts are under way to improve understanding of (left) proxy records, including new process-based approaches, and understanding of (right) climate variability and change, including new climate reconstruction methods and comparisons with climate simulations.

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data are needed for time-uncertain proxy records, including layer-counted archives such as corals, ice cores, and varved sediments [*Comboul et al.,* 2014].

Data managers and group leaders for each region will work with project participants to ensure that data sets are published in ways that enable tracking and accurate citation. Data-oriented publications and international data repositories now issue digital object identifiers (DOIs) or other unique identifiers for data sets that can be cited as part of future synthesis products.

Goal 2: Integrate Multiresolution Proxy Records

Three of the nine PAGES 2k regions have reconstructed temperatures from the beginning of the first millennium CE to present. Reconstructions from the Arctic, Europe, and Antarctica suggest that temperatures were higher during some intervals of the early first millennium than during the 20th century [*PAGES 2k Consortium,* 2013].

Additional proxy records that cover the entire CE are needed to investigate decadal- to centennial-scale responses of climate to changes in radiative forcing as well as internal variability at these time scales. Many proxy records that span the past 2000 years are not annually resolved, however, and in some regions, most of the available records of any length lack annual resolution. Statistical approaches have been developed for combining proxy evidence derived from annually resolved and lower-resolution archives [e.g., *Hanhijärvi et al.,* 2013], including some that incorporate time uncertainty in proxy records [*Anchukaitis and Tierney,* 2013].

Nonetheless, integrating multiresolution records into a composite climate reconstruction is an ongoing challenge. For example, preservation of interannual variability is critical when assessing the structure and probability of extreme events, including the climate response to volcanic eruptions, a key target in data-model comparisons. At the same time, records with decadal to centennial resolution (along with their estimates of uncertainty) are important constraints on low-frequency responses of the climate system.

Recommendations: While combining annual and lower-resolution time series is an important goal, accurately calibrating lower-resolution and time-uncertain proxy records to specific climate variables remains an area of active research. Thus, the PAGES 2k community recommends that the regional groups generate two independent reconstructions: one based on annually (to seasonally) resolved proxies and the other at lower resolution. Fully independent reconstructions will allow mutual validation during their overlapping time intervals and spectral ranges and will help test methods for fusing high- and low-resolution paleoclimate data.

In the long term, the PAGES 2k community recommends the continued development of methods that incorporate network, observational, and chronological uncertainty into quantitative estimates of past climate variability, including approaches that allow for quantitative calibration and validation of low-frequency variability.

Goal 3: Develop Multivariate Climate Reconstructions

Although temperature reconstructions are needed to study the Earth's energy balance, freshwater fluxes are arguably more immediately meaningful for ecosystem services and societal needs and will support detection and attribution exercises. Reconstructing hydrological change is challenging because of greater inherent spatial heterogeneity of hydroclimatic variables; additionally, covariance with temperature responses in paleoclimatic archives can complicate their integration into reconstruction of a single regionally averaged and time-averaged target variable.

Recommendations: The next generation of PAGES 2k climate reconstructions should target reconstructions of hydroclimate as well as temperature. In some cases, it may be possible to reconstruct specific hydroclimate variables. In many cases, however, it may be impossible to distinguish the combined influences of temperature and precipitation in the proxy records. In these cases, the PAGES 2k community recommends the reconstruction of targets that combine multiple climate influences (see additional supporting information in the online version of this article for examples). An alternative approach is to exploit covariances between temperature and hydroclimate using multiple proxies with response to bivariate climate variability to simultaneously infer the joint distribution of both target variables [*Tolwinski-Ward et al.,* 2014].

In the long term, forward, process-based models of proxy formation are needed for explicitly representing multivariate, nonlinear, and potentially nonstationary relationships between the proxy and climate systems [*Evans et al.,* 2013]. Forward models are also an important component of hierarchical methods [*Tingley et al.,* 2012] and data assimilation [*Steiger et al.,* 2014], allowing process-based understanding to be incorporated into reconstruction techniques.

Goal 4: Improve the Spatial Resolution of the Reconstructions

PAGES 2k Consortium [2013] reconstructed mean surface temperatures averaged over continental-scale regions. In addition, four of the nine PAGES 2k regions (Asia, Europe, North America, and South America) have already reconstructed temperature in a spatially explicit gridded format.

These climate field reconstructions (CFRs) reveal dynamical signatures of past climate change and variability that are important for diagnosing their underlying causes [*Masson-Delmotte et al.,* 2013]. CFRs can be used for detailed comparisons with climate model simulations and are therefore an important product of the PAGES 2k project. The choice of CFR method can strongly influence the resulting reconstruction and its interpretation [e.g., *Wang et al.,* 2014].

Furthermore, methods that impose a space-time structure based on a modern calibration period assume that such patterns are stationary over time, and some implicitly consider remote teleconnection to be stable. Analysis of reconstructions using pseudoproxy experiments suggests that CFRs are most robust where the density of proxy records with strong climate signals is sufficiently high [*Smerdon et al.,* 2011].

Recommendations: To facilitate a timely global synthesis of uniform reconstructions that includes areas where data coverage is relatively sparse, the PAGES 2k community recommends the reconstruction of climate means over large-scale (subcontinental and oceanic) areas, while parallel progress is made in developing the next generation of CFR methods.

These subcontinental spatial units can be chosen to coincide not only with regions of high observational density but also with spatial domains defined by large-scale climate features. This will increase the spatial degrees of freedom beyond that of the *PAGES 2k Consortium* [2013] synthesis and provide clear targets for observation and model comparisons while honoring limitations imposed by current data availability. In addition, error analyses are needed that take into account the analytical and inherent uncertainties of the input data and propagate them through the entire inference and reconstruction process.

Simultaneously, efforts are progressing to advance reconstruction methods, and our community foresees substantial progress within the next few years. New CFR methods, forward models, improved age-depth modeling, and improvements in incorporating age uncertainty will bring consistency to efforts by the regional groups, as well as benefits to the reconstructions themselves.

Toward a Complete Picture of Past Climate

In addition to the recommendations above, other PAGES working groups are addressing longer-term challenges associated with understanding the climate of the CE. Collectively, these activities will provide a millennial-scale, spatiotemporal, and process-based perspective on recent and projected future climate change and variability.

PAGES 2k encourages participation by all investigators interested in this community-wide project. The project's working groups continue to grow, sourced from the broad paleoclimate science community. PAGES 2k is committed to providing researchers with opportunities to integrate their work into high-impact, multiauthored papers that address big-picture research questions. For more information and to join this effort, please visit the PAGES 2k website (http://bit.ly/PAGES2k-info) to sign up for circulars and to find

contact information for regional working groups.

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