DIVING INTO THE PAST

A Paleo Data–Model Comparison Workshop on the Late Glacial and Holocene

Nils Weitzel, Sebastian Wagner, Jesper Sjolte, Marlene Klockmann, Oliver Bothe, Heather Andres, Lev Tarasov, Kira Rehfeld, Eduardo Zorita, Martin Widmann, Philipp Sommer, Gerd Schädler, Patrick Ludwig, Florian Kapp, Lukas Jonkers, Javier García-Pintado, Florian Fuhrmann, Andrew Dolman, Anne Dallmeyer, and Tim Brücher

Understanding changes in the climate of the late Pleistocene and the Holocene has long been a research topic. Studies rely on different sources of information, ranging from terrestrial and marine archives to a hierarchy of climate modeling activities. In contrast to the climate of the last millennium, novel approaches are necessary to bridge the different temporal and spatial representations of the various archives and the climate models, and to achieve a robust understanding of climate variability and climate processes on centennial-to-millennial time scales.

On the one hand, paleoclimate archives typically have a coarser temporal and spatial resolution on longer—for example, glacial—time scales than on shorter—late Holocene—time scales. They also commonly have poorer age constraints and are more uncertain. However, larger climate forcing occurred, giving a better signal-to-noise ratio for these longer time scales. On the other hand, climate modeling approaches based on comprehensive Earth system models (ESMs) need to take into account additional components and processes within the Earth system that are either not present or of secondary importance within the late Holocene, our current interglacial period, such as the emergence and vanishing of vast ice sheets or continental uplift. Indeed, the climate modeling community has yet to prove the feasibility of transient fully coupled ESM simulations over a complete glacial cycle.

Addressing these issues requires expert knowledge from different fields, including critical assessment of paleoclimate data quality; technical and statistical tools to compare and analyze archives; and the exploitation of presently available and upcoming transient simulations with comprehensive ESMs. Experts of the respective fields gathered in Hamburg, Germany, for a 3-day workshop[1] to discuss long-standing

WORKSHOP ON THE COMPARISON OF PALEOCLIMATE DATA AND SIMULATIONS OVER TIME PERIODS UP TO THE LAST GLACIAL CYCLE

What: An international group of approximately 30 scientists with background and expertise in global and regional climate modeling, statistics, and climate proxy data discussed the state of the art, progress, and challenges in comparing global and regional climate simulations to paleoclimate data and reconstructions. The group focused on achieving robust comparisons in view of the uncertainties associated with simulations and paleo data.

When: 16–18 April 2018

Where: Hamburg, Germany

[1] The workshop was organized and supported by the Helmholtz Center Geesthacht. Further support came from the University of Hamburg and Paleo Modelling (PalMod), the German climate modeling initiative (www.palmod.de). PalMod is part of the Research for Sustainability initiative (FONA; www.fona.de) funded by the German Federal Ministry of Education and Research (BMBF).

research questions, the development of methods for comparing model output and paleo data, and guidance for a community-wide effort on studying the Late Glacial and Holocene. The workshop was embedded in the German climate modeling initiative PalMod, which aims at performing transient simulations of the last glacial cycle using a suite of state-of-the-art ESMs.

THE BACKBONE: STATE OF THE ART OF GLACIAL AND HOLOCENE PALEOCLIMATE RESEARCH. Introductory talks and discussions highlighted the already existing simulations over time periods from the last 1,000 to 130,000 years as well as the many efforts of synthesizing proxy records. Despite the availability of these paleo data products, validating the climate simulations is challenging and seldom done.

Uncertainty emerged as a dominant topic for comparison of paleoclimate data and ESM output. Paleo data uncertainties concern dating, the relationship between the proxy sensor and environmental fields, and measurement. Often, researchers reduce these into a single error term. On the other hand, ESM uncertainties include initial and boundary conditions as well as structural uncertainties that encapsulate the irreducible difference between model and reality.

Discussions noted the need for systematic strategies for model–data comparisons to account for all these uncertainties. Bayesian frameworks offer a rigorous approach to draw inferences about the past given paleo data, model output, and specification of these uncertainties. There are also recent applications of data assimilation to combine empirical data and simulations for obtaining state estimates, including transient paleo reanalyses.

Better mechanistic understanding of proxy systems can reduce the uncertainty on the proxy side, and improved reconstructions of boundary conditions may reduce the simulation uncertainty. One talk proposed developing new methods that are less sensitive to the uncertainties.

Working groups subsequently focused on 1) Holocene climate, 2) late-glacial and deglaciation climate, and 3) metrics and tools for model–data comparisons. Flexible and active exchanges between those breakout groups led to lively discussions.

HOLOCENE PALEO DATA–SIMULATION MISMATCHES. The Holocene discussion group identified discrepancies between paleo data and simulations, for example, 1) the disagreement between simulated and reconstructed temperature trends and 2) inconsistent warming patterns. For example, simulations of the third phase of the Paleoclimate Modelling Intercomparison Project (PMIP3) give a homogeneous mid-Holocene warming over Europe, while pollen-based reconstructions indicate a dipole-like pattern with warming over northern Europe and cooling over southern Europe. Working hypotheses for the mismatch between patterns may be the coarse resolution of ESMs, or that the pollen data represent environmental variables different from the simulated meteorological variables used for comparison.

Part of the discussion focused on the potential gains from transient ESM simulations, proxy system models, and regional climate models. Transient Holocene simulations are an ongoing community effort, and a growing number of them are available. Those model results can clarify the role of internal climate variability for Holocene temperature trends and large-scale patterns. Methods for comparisons need

AFFILIATIONS: Weitzel and Kapp—Institut für Geowissenschaften und Meteorologie, Universität Bonn, Bonn, Germany; Wagner, Klockmann, Bothe, and Zorita—Institute of Coastal Research, Helmholtz-Zentrum Geesthacht, Geesthacht, Germany; Sjolte—Quaternary Sciences, Department of Geology, Lund University, Lund, Sweden; Andres and Tarasov—Department of Physics and Physical Oceanography, Memorial University of Newfoundland, St. John's, Newfoundland and Labrador, Canada; Rehfeld—Institut für Umweltphysik, Universität Heidelberg, Heidelberg, Germany; Widmann—School of Geography, Earth and Environmental Sciences, University of Birmingham, Birmingham, United Kingdom; Sommer—Institute of Earth Surface Dynamics (IDYST), University of Lausanne, Lausanne, Switzerland; Schädler and Ludwig—Institute of Meteorology and Climate Research, Karlsruhe Institute of Technology, Karlsruhe, Germany; Jonkers and García-Pintado—Center for Marine Environmental Sciences (MARUM), University of Bremen, Bremen, Germany; Fuhrmann—Institut für Geowissenschaften, Johannes Gutenberg-Universität Mainz, Mainz, Germany; Dolman—Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Potsdam, Germany; Dallmeyer—Max Planck Institute for Meteorology, Hamburg, Germany; Brücher—GEOMAR Helmholtz Centre for Ocean Research Kiel, Kiel, Germany
CORRESPONDING AUTHOR: Oliver Bothe, oliver.bothe@hzg.de

DOI:10.1175/BAMS-D-18-0169.1

In final form 26 June 2018

to be able to take into account seasonal biases in the proxy archives. Using the output of transient simulations to drive proxy system models of, for example, tree rings and sediments can reduce the uncertainty caused by calibration and nonclimatic processes in the comparison between individual paleoclimate records and the simulated climate.

Regional climate models complement these approaches to reduce mismatches. To date, few regional simulations exist for the Holocene. The group plans time-slice simulations of the mid-Holocene (6 kyr before present) for the European Coordinated Regional Downscaling Experiment (CORDEX) domain and greater Greenland, and a series of comparisons with pollen, tree ring, and isotope data. The expectation is that the increased model resolution can reduce the disagreements between the simulations and the paleo data.

A FEATURE-MATCHING ALGORITHM FOR THE DEGLACIATION. The aim of the deglaciation working group was to answer the question, What can we devise that will allow someone to quantitatively compare a transient deglacial simulation and paleoclimate data? Potential strategies need to satisfy three requirements: 1) they quantitatively compare the transient characteristics of both the paleoclimate data and the simulations, 2) they work with already existing data records and simulations, and 3) they can become publicly available within a short time frame.

To this end, the group outlined a feature-matching algorithm and corresponding metrics that compare the spatial and temporal progression of large-scale climate changes of the last deglaciation, like the Bølling–Allerød or Younger Dryas. The method shifts simulated time series in time to match the paleoclimate data optimally with respect to a predefined metric. It then evaluates a global diagnostic of choice at this optimal shift. Secondary adjustments are made to proxy time series at every location where data are available, constrained by local age uncertainties. Three metrics evaluate the global shift of the timing of the simulated and reconstructed events, the spatial progression of the signal in time, and the overall multivariate pattern and strength of the signal. Each of the method's steps requires a penalty term to safeguard against overfitting. Initial tests of the methodology at the workshop used output of the Simulation of the Transient Climate of the Last 21,000 Years (TraCE-21ka, Liu et al. 2009) and paleoclimate data from Shakun et al. (2012).

TOWARD A FRAMEWORK FOR COMPARING PALEO DATA AND SIMULATIONS. One line of thinking among participants was that comparisons of model and data should measure the discrepancy between corresponding probability distributions to account for uncertainties in both products. Thus, a third, method-oriented group worked on formalizing this idea while also developing a concept for an easy-to-use toolbox. In this context, strategies for comparisons have to deal with the various sources of uncertainty, design suitable metrics to compare the resulting probability distributions, and lead to guidelines for the planned toolbox.

Because of the uncertainty in upscaling climate field reconstructions from individual paleo records, the group deemed it preferable to do site-by-site comparisons of paleoclimate records and simulation output rather than comparisons of gridded products. The downside of this approach is the nonuniform spatiotemporal coverage of paleo data and the correlations between proxy samples. To avoid misleading results when calculating summary statistics, a multivariate evaluation is necessary. If paleoclimate data alone are insufficient to infer parameters like correlation structures, then additional sources of information can help, such as multimodel reference ensembles and large ensembles with simplified models.

So far, paleoclimatology uses only a few of the metrics that are available in the literature for the comparison of probability distributions. Mathematical theory advises the use of proper score functions. These can either summarize the discrepancy between all the information contained in the corresponding probability distributions or focus on specific properties, like the change of the mean climate state between two time slices or the climate variability at different periods.

FUTURE DIRECTIONS. The paleo community and in turn PalMod, the German climate modeling initiative, has to face the issue of developing easy-to-use methods for the challenging task of model–data comparison. Obviously, one workshop cannot solve all long-standing questions, but the spirit of the interdisciplinary meeting fostered collaborations and refreshed momentum to develop concepts for a more sophisticated data–model comparison suited for paleoclimatology. This dedication resulted in a variety of concrete initiatives.

The workshop highlighted the need for a toolbox for interactive model–data comparisons. The methods-oriented group and the deglaciation group will cooperate on a cookbook for robust comparisons between simulations and paleo observations. Concepts and issues identified by the groups will feed into the toolbox and the cookbook. An initial version of the toolbox has to include at least computational methods 1) to import simulation output and paleo data; 2) to account for the nonuniform spatiotemporal coverage of paleo data; and 3) to consider published uncertainty estimates, plus a set of well-established metrics and examples of publicly available simulations and paleo data syntheses. There are plans for subsequent expansions.

Moreover, the Holocene working group initiated new regional climate simulations to assist in developing new model–data comparison approaches for addressing urgent questions on the Holocene time scale. The development of the deglaciation group's feature-matching algorithm is ongoing. It will finally become part of the toolbox and the cookbook.

The discussions initialized at the Hamburg meeting will continue for years to come and we invite all interested colleagues to contribute.

REFERENCES

Liu, Z., and Coauthors, 2009: Transient simulation of last deglaciation with a new mechanism for Bølling-Allerød warming. *Science*, **325**, 310–314, https://doi.org/10.1126/science.1171041.

Shakun, J. D., and Coauthors, 2012: Global warming preceded by increasing carbon dioxide concentrations during the last deglaciation. *Nature*, **484**, 49–54, https://doi.org/10.1038/nature10915.