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Diving into the past – A paleo data-model comparison workshop on the Late Glacial and Holocene

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ABSTRACT

Workshop title: 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 modelling, statistics, and climate proxy data discussed 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

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 modelling 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 of the climate models, and to achieve a robust understanding of climate variability and climate processes on centennial-to-millennial timescales.

On the one hand, paleoclimate archives typically have a coarser temporal and spatial resolution on longer, e.g., 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 modelling 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, such as the emergence and vanishing of vast ice sheets or continental uplift. Indeed the climate modelling 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 for a three-day workshop[1] to discuss long-standing 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 modelling initiative PalMod, which aims at performing transient simulations of the last glacial cycle using a suite of state-of-the-art ESMs.

1. 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

[1]The workshop was organized and supported by the Helmholtz Center Geesthacht. Further support came from the University of Hamburg and PalMod, the German Climate Modelling 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).

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, which are less sensitive to the uncertainties.

Working groups subsequently focused on (i) Holocene climate, (ii) late-glacial and deglaciation climate, and (iii) metrics and tools for model-data comparisons. Flexible and active exchanges between those breakout groups led to lively discussions.

2. Holocene paleo-data-simulation mismatches

The Holocene discussion group identified discrepancies between paleo data and simulations, e.g., (1) the disagreement between simulated and reconstructed temperature trends and (2) inconsistent warming patterns. For example, the PMIP3 simulations 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 represents 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 is available. Those model results can clarify the role of internal climate variability for Holocene temperature trends and large-scale patterns. Methods for comparisons need 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 e.g. tree-rings and sediments can reduce the uncertainty due to calibration and non-climatic 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 BP) for the European 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.

3. A feature-matching algorithm for the deglaciation

The aim of the deglaciation working group was: 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 pre-defined 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 is 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 methods steps requires a penalty term to safeguard against overfitting. Initial tests of the methodology at the workshop used the TRACE-21ka simulation (Liu et al. 2009) and paleoclimate data from Shakun et al. (2012).

4. Towards 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.

Due to 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 non-uniform spatio-temporal 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 is insufficient to infer parameters like correlation structures, additional sources of information can help, such as multi-model reference ensembles, and large ensembles with simplified models.

So far, paleoclimatology only uses few of the metrics for the comparison of probability distributions that are available in the literature. 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.

5. Future directions

The paleo community and, in turn, PalMod 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 (a) to import simulation output and paleo data, (b) to account for the non-uniform spatio-temporal coverage of paleo data, (c) 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 groups 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 within the years to come and we invite all interested colleagues to contribute.

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