Combining ocean models and proxy data

Paleo-ocean state estimation with the MIT general circulation model

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In Short

- Combining an ocean model with proxy data via data assimilation is used to reduce uncertainties in paleo ocean simulations.
- We develop a particle filter method for paleo-ocean state and parameter estimation.
- The method is applied to estimate the state of the ocean during the Last Glacial Maximum.

This project is part of the German Climate Modeling Initiative PalMod [1]. The overarching goal of PalMod is to simulate the complete last glacial cycle, i.e. the last 120 kyrs, with comprehensive Earth system models. Understanding past climate states is essential for predicting future climate change. Validating climate models by applying them to climate states that were very different from today's, is important to deepen our trust in models and hence, in their projections for future climate.

Our project focuses on the development and application of a data assimilation (DA) method to estimate the state of the ocean during the Last Glacial Maximum (19-23 kyr BP, LGM) with an ocean general circulation model and proxy data. The LGM was a climatic state substantially different from today's and the large-scale patterns of the ocean circulation during this time remain uncertain. Reconstructions from proxy data as well as from model studies have large uncertainties and different studies show a broad range of possibilities of the ocean state during that time. Uncertainties in paleo-climate modeling origin, for example, from uncertain boundary conditions, uncertainties in model parameters, and other model errors. Proxy data, on the other hand, have great uncertainties regarding the imprint of the climate signal in the proxy, disturbances during the deposition, and measurement errors. Combining climate models with proxy data and their respective uncertainties via DA, is a powerful means to obtain more reliable estimates of the climate's state. Our DA method focuses on optimizing uncertain model parameters and boundary conditions including atmospheric forcing, such as precipitation and air temperature. A successful estimate obtained by such a DA method is consistent with the physics incorporated in the model and with the proxy data within their respective error bounds. Data assimilation is frequently used in the field of weather forecasting, but it is still not well-established in the community of paleoclimatology because available proxy data is very sparse and comprehensive data sets of past climate states have only become available in the past years.

We employ the Massachusetts Institute of Technology general circulation model (MITgcm), a coupled ocean-sea ice general circulation model. The model uses a cubed-sphere grid with 192 x 32 horizontal grid cells, resulting in a resolution of about 2.8°, and 15 vertical levels. The low resolution of the model enables us to perform long steady-state simulations, running about 2000 model-years to a quasi-steady state. The MITgcm is enhanced with a water isotope module [2] that gives us the possibility to simulate the oxygen isotopic ratio ($\delta^{18}O$) of seawater and use $\delta^{18}O$ data from the LGM to constrain our estimate. The isotopic ratio of seawater is preserved in the shells of planktic and benthic foraminifera and deposited in the sediment. The simulated isotopic composition of water and the temperature can be used to compute the isotopic composition of calcite and be compared to reconstructed data from sediment cores.

A recent state estimate of the LGM ocean was obtained by Kurahashi-Nakamura et al. (2017) with the adjoint method [3]. The method requires the adjoint of the model code, which can be obtained by "automatic differentiation" of the model code. This is not applicable to many models. Moreover, it does not readily provide an uncertainty estimate of the solution. We therefore aim at developing a DA method that provides an error estimate and that is independent of the existence of an adjoint, such that it can be applied with other models used within in the PalMod project.

Our method is an ensemble-type "Particle filter method" following e.g. [4]. It is based on the Bayesian framework and explores the multidimensional probability density function (pdf) of the parameters in an efficient way without the requirement of a Gaussian assumption. The method uses a tempering approach, in which the accuracy of the data is increased in each iteration to avoid ensemble collapse. The method yields an approximation of the posterior pdf and therefore an estimate of the parameters and their uncertainties. Respectively, the resulting model ensemble provides an estimate of the state of the global ocean and its uncertainty.

For the development and testing of the method we used pseudo-proxy data. The data was sam-

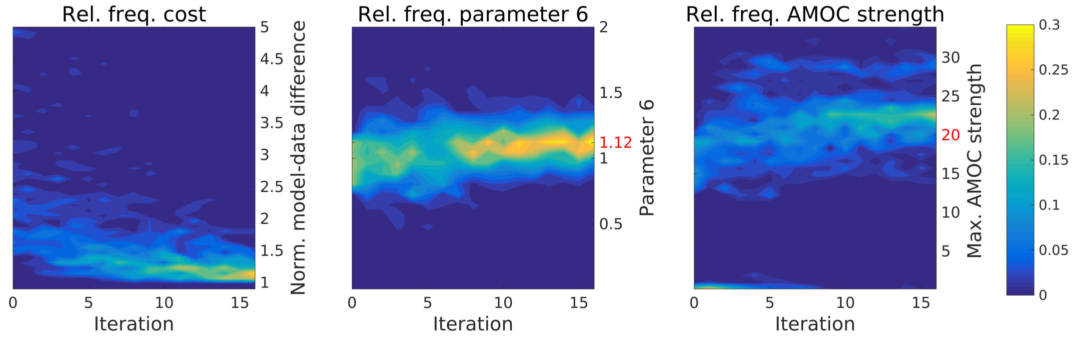

Figure 1: *Relative frequency of the model-data misfit (cost), parameter 6 (multiplier for the mean precipitation over the Pacific), and the max. AMOC strength in the ensemble during the optimization process.*

pled from a "target" model simulation at locations where data is available for the LGM and an error was added to the data to include the uncertainty that is present in real LGM data. Our results demonstrate that the method is capable of efficiently estimating up to 9 parameters. Figure 1 shows results from an experiment where we estimated the global mean air temperature, the north-to-south and the high-to-low latitudinal gradient of air temperature, the mean precipitation over the three oceans (Atlantic, Indic and Pacific) and the mean isotopic composition of precipitation over the three oceans. In 16 iterations the model-data misfit is reduced, and the target parameters and the strength of the Atlantic Meridional Overturning Circulation (AMOC) in our target run are faithfully reconstructed.

To apply our method to estimate the state of the ocean during the LGM, we use a global reconstruction of the glacial sea surface temperature (SST) [5] and existing data sets of $\delta^{18}O_c$ anomalies [6–8] reconstructed from planktic and benthic foraminifera. We performed a first experiment optimizing the nine parameters mentioned above. The simulated first guess, i.e. not optimized, $\delta^{18}O_c$ anomalies are too low in low latitudes compared with the data. During the optimization higher anomalies are achieved by lower SST through reduced air temperature in low latitudes. The lower air temperature, however, increases the SST model-data misfit (Fig. 2). $\delta^{18}O_c$ depends on temperature and $\delta^{18}O_{sw}$. Possibly, adjustments of the SST through the air temperature might be accounting for an error in $\delta^{18}O_{sw}$. Errors in surface $\delta^{18}O_{sw}$ might arise from errors in the isotopic composition of water vapor over the ocean's surface, which is not yet optimized. More parameters, for example the mean isotopic composition of water vapor over the surface of the Atlantic, Pacific and Indian Oceans, are necessary to achieve a reduction of the model-data misfit for all data types simultaneously. The previous results are very encouraging and the next step is to investigate if the method is capable of estimating more parameters in a reasonable amount of time and to achieve a successful estimate of the LGM ocean.

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http://www.marum.de

More Information

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Project Partners

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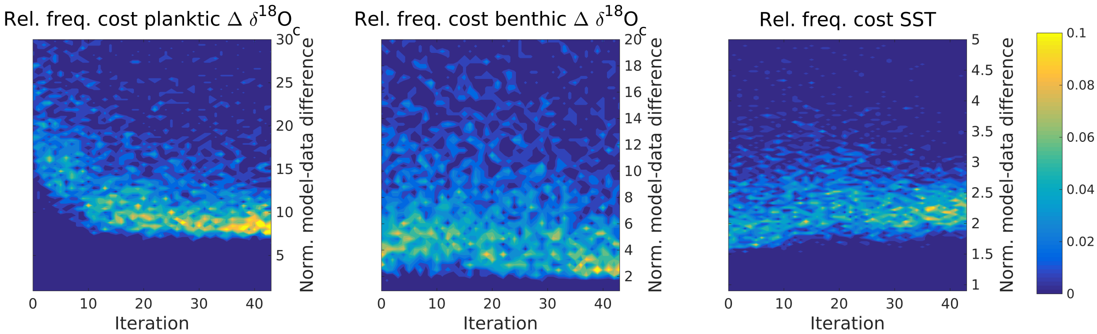

Figure 2: *Relative frequency of the model-data misfit (cost) for the three data types in the ensemble during the optimization process for the LGM ocean.*