Towards model-data comparison of the deglacial temperature evolution in space and time

Nils Weitzel, Heather Andres, Jean-Philippe Baudouin, Oliver Bothe, Andrew Dolman, Lukas Jonkers, Marie Kapsch, Thomas Kleinen, Maximilian May, Uwe Mikolajewicz, Andre Paul, Kira Rehfeld

April 27, 2021

Institute of Environmental Physics, Heidelberg University, Germany

STACY

UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386

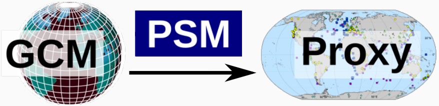
PALMOD GERMAN CLIMATE MODELING INITIATIVE

Emmy Noether-Programm DFG Deutsche Forschungsgemeinschaft

Towards model-data comparison of the deglacial temperature evolution in space and time

N. Weitzel (nweitzel@iup.uni-heidelberg.de), H. Andres, J.-P. Baudouin, O. Bothe, A. Dolman, L. Jonkers, M. Kapsch,
T. Kleinen, M. May, U. Mikolajewicz, A. Paul, K. Rehfeld

Strategy:

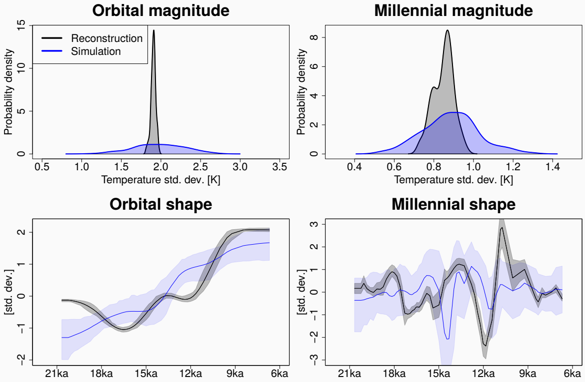


Monte Carlo approach:
Compare probability distributions

Data:
- SST reconstructions from Palmod marine synthesis [1]
- 6 MPI-ESM deglaciation simulations [2, 3]

Pseudo-proxy experiments:
Method identifies order of simulations robustly on zonal and global level

Submission in preparation for Climate of the Past

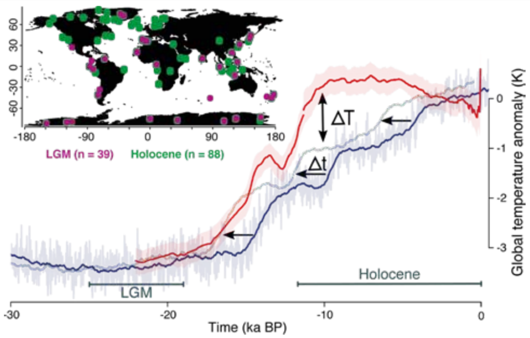


Comparison with SST reconstructions:
- Differences in Northern Hemisphere detected
- Representation of non-climatic processes important

1) Jonkers et al. (2020), ESSD, DOI: 10.5194/essd-12-1053-2020
2) Kleinen et al. (2019), CP, DOI: 10.5194/cp-16-575-2020
3) Mikolajewicz, Kapsch (pers. comm.)

STACY PALMOD GERMAN CLIMATE MODELING INITIATIVE

Need to develop methods which **'quantitatively compare the transient characteristics of both the paleoclimate data and the simulations' [1]**



Requirements

- Applicable to forced and spontaneous oscillations in simulations
- Use existing data syntheses
- Account for quantifiable uncertainties

Q1: Can temperature reconstructions discriminate between simulations?

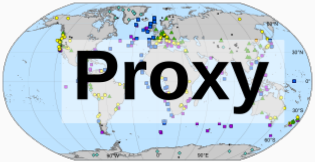
Q2: What can we learn from comparing simulations and reconstructions?

Step 1) Pseudo-proxy experiments

Step 2) Apply to SST compilation

[1] Weitzel et al. (2019), Figure: Andres et al. (2019), Data: Shakun et al. (2012), Marcott et al. (2013), Smith and Gregory (2012), Rehfeld et al. (2018)

General strategy and challenges



Simulations

- Complete 4d representation
- Depends on model configuration, boundary conditions, internal variability

Proxy system models

- Bridge gap between simulations and reconstructions
- $P = f(C, t)$
- f has stochastic and deterministic components

Temperature reconstructions

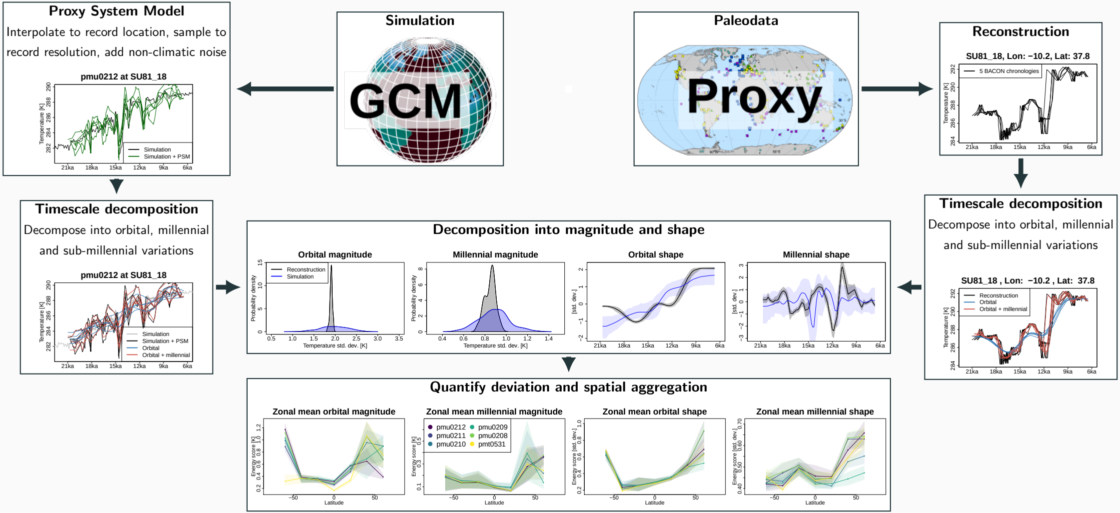
- Limited temporal resolution
- Chronological uncertainties
- Uncertain proxy-climate relationship
- Sparse spatial distribution

nweitzel@iup.uni-heidelberg.de

Model-data comparison strategy

- First, compare each record with simulation at respective location
- Apply **proxy system model** to make reconstructions and simulations more comparable
- Use **Monte Carlo** approach to incorporate uncertainties
- We decompose the time series to score different aspects of the simulations
  - **Timescale decomposition:** Separate non-linear trend from LGM to Holocene **(orbital-scale variations)** from modulating events such as Bolling-Allerod and Younger Dryas **(millennial-scale variations)**
  - **Feature decompositon:** Separate **magnitude of variations** at given timescale (measure by standard deviation) from **shape of temporal evolution** (given by normalized time series)
- Quantify the difference between the resulting **probability distributions**
- Finally, **aggregate scores spatially** to increase robustness of scores

Model-data comparison workflow



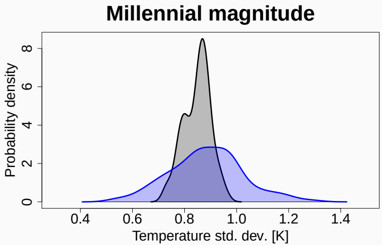
Data: Jonkers et al. (2020), Uwe Mikolajewicz / Marie Kapsch (pers. comm.), Method: Weitzel et al., in prep.

Comparison metric: Integrated square distance ('Energy score')

Energy score in 1D:

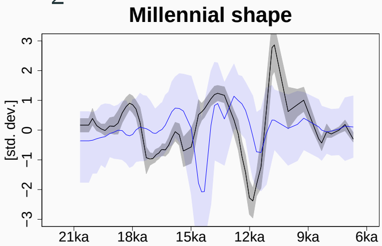
$$\mathrm{ES}(\mathbb{P},\mathbb{Q}) = \int_{-\infty}^{\infty} (F(x) - G(x))^2 \, dx.$$

F, G are cumulative distribution functions of probability distributions $\mathbb{P}, \mathbb{Q}$.



For multivariate distributions (i.e. time series):

$$\mathrm{ES}(\mathbb{P},\mathbb{Q}) = \mathbb{E}_{\mathbb{P},\mathbb{Q}}|X - Y| - \frac{1}{2}\left(\mathbb{E}_{\mathbb{P}}|X - X'| + \mathbb{E}_{\mathbb{Q}}|Y - Y'|\right)$$

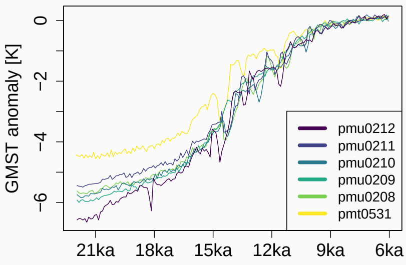


$\mathrm{ES}(\mathbb{P},\mathbb{Q}) \geq 0$; $\quad \mathrm{ES}(\mathbb{P},\mathbb{P}) = 0$; $\quad$ Smaller score = Smaller deviation

Gneiting and Raftery (2007), Thorarinsdottir, Gneiting, and Gissibl (2013)

Data

Simulations



pmu0212: Config 1, GLAC-1D, local MWF

pmu0211: Config 1, ICE-6G, local MWF

pmu0210: Config 2, ICE-6G, global MWF

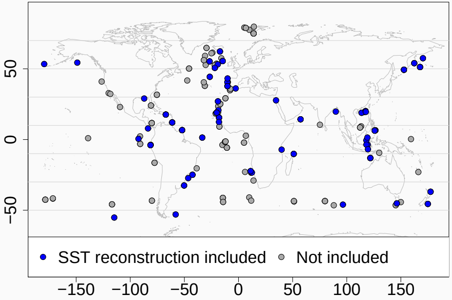
pmu0209: Config 2, ICE-6G, no MWF

pmu0208: Config 2, ICE-6G, local MWF

pmt0531: Config 3, GLAC-1D, local MWF

6 deglacial MPI-ESM simulations with T31GR30 resolution, different model configurations, ice sheet topographies, and meltwater forcing (MWF)

Temperature reconstructions



105 SST records from Palmod marine synthesis (V1.1.0beta), covering period 22-6ka with sub-millennial resolution

Jonkers et al. (2020) and Kleinen, Mikolajewicz, and Brovkin (2020), Uwe Mikolajewicz / Marie Kapsch (pers. comm.)

Pseudo-proxy experiments (PPEs)

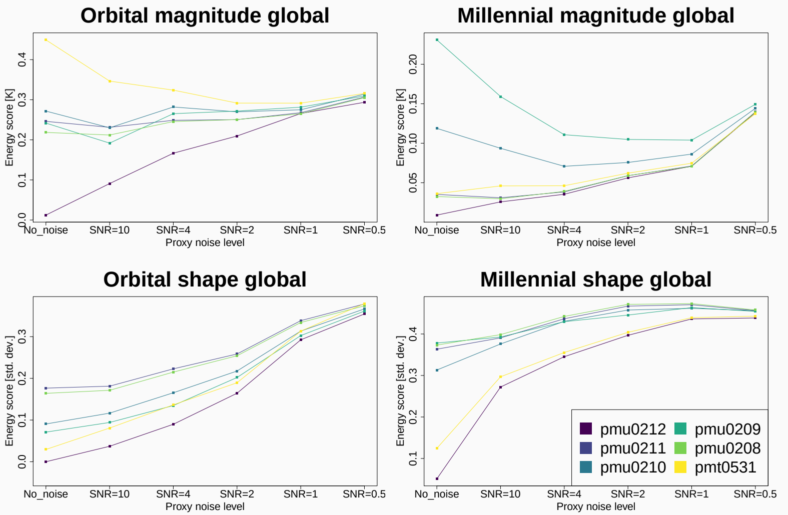
Idea: Test algorithm in controlled environment

1. Choose pmu2012 as reference simulation
2. Simulate pseudo-proxies using the proxy system model
3. Perform model-data comparison between pseudo-proxies and simulations

Main questions:

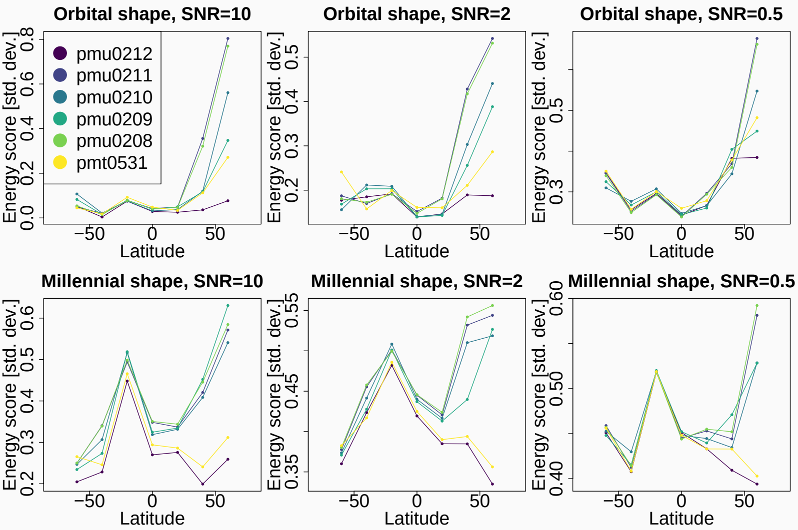
- What is influence of non-climatic noise processes in proxy system model?
  We test for signal-to-noise ratios of reconstructions from very high (SNR=10) to very low (SNR=0.5). The underlying truth is given by the 'No_noise' experiment
- On which spatial aggregation scales are results robust?
  We aggregate scores from individual records globally and zonally

Results: successful discrimination on a global level



- Robust simulation order for SNR$\geq$2
- Very similar model configurations mostly indistinguishable

Can we distinguish MPI-ESM simulations zonally? Yes, if SNR $\geq$ 2

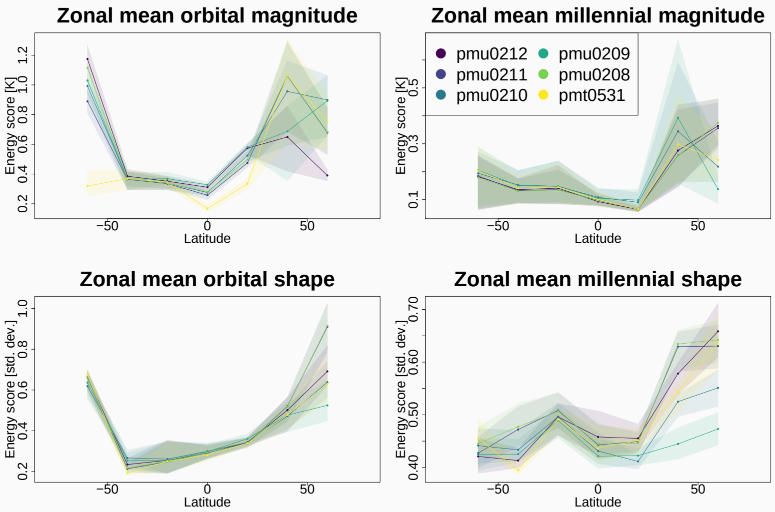


- Largest ensemble spread of scores in Northern Hemisphere mid-to-high latitudes
- Robust simulation order for SNR$\geq$2

SST reconstructions vs. MPI-ESM simulations

- Compare 6 MPI-ESM simulations with SST reconstructions
- To account for the unknown non-climatic noise structure, we employ three different temporal autocorrelation structures (white noise, AR1, powerlaw) and four different signal-to-noise ratios, SNR=$\{2, 4, 6, 8\}$, for the non-climatic noise process
- Scores are averaged over zonal bands
- Shaded areas on the next slide show the range of scores for the different noise configurations, while thick lines are averages over all noise configurations

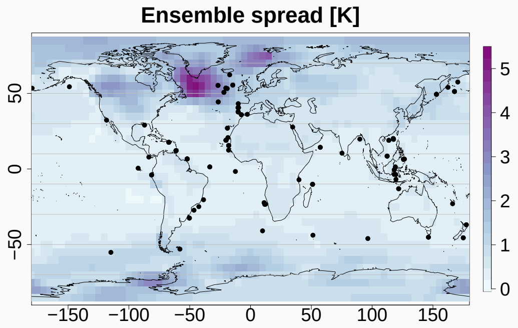
Results



- Largest performance differences between simulations in Northern Hemisphere
- Strong influence of SNR on magnitude scores
- MWF-related fluctuations do not fit with reconstructions

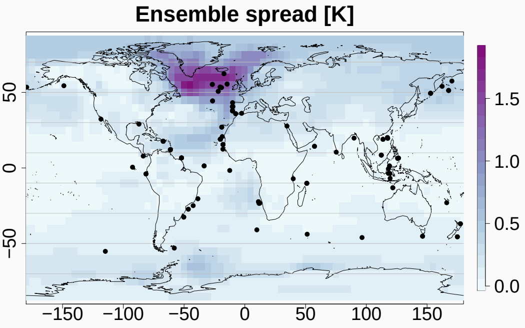
Highest chance in regions with large ensemble spread

Orbital magnitude



- High latitudes
- Greenland, Antarctica, North America

Millennial magnitude

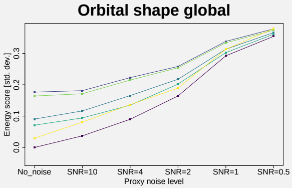


- Across the Atlantic
- Greenland, Europe

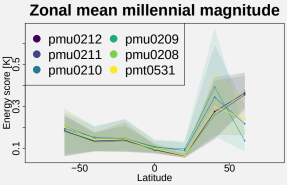
nweitzel@iup.uni-heidelberg.de

Conclusions and outlook

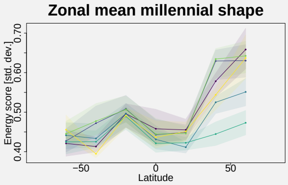
Model order robustly detected in pseudo-proxy experiments



Good estimates for non-climatic noise process important



Largest performance differences between simulations in Northern Hemisphere



Next steps:

- more detailed **spatial analysis**
- use **process-based PSMs**
- include **more reconstructions**

For questions and discussion:

- use the **live chat** on Tuesday, April 27
- contact me through the **EGU networking functions**
- **e-mail:** nweitzel@iup.uni-heidelberg.de

References i

Andres et al. "An integrated proxy and simulation data initiative for the Holocene and the last deglaciation". In: PAGES Magazine 26 (2019), p. 85. DOI: 10.22498/pages.26.2.85.

Gneiting and Raftery. "Strictly Proper Scoring Rules, Prediction, and Estimation". In: JASA 102 (2007), pp. 359–378. DOI: 10.1198/016214506000001437.

Jonkers et al. "Integrating palaeoclimate time series with rich metadata for uncertainty modelling: strategy and documentation of the PalMod 130k marine palaeoclimate data synthesis". In: ESSD 12 (2020), pp. 1053–1081. DOI: 10.5194/essd-12-1053-2020.

Kleinen, Mikolajewicz, and Brovkin. “Terrestrial methane emissions from the Last Glacial Maximum to the preindustrial period”. In: CP 16 (2020), pp. 575–595. DOI: 10.5194/cp-16-575-2020.

Marcott et al. “A Reconstruction of Regional and Global Temperature for the Past 11,300 Years”. In: Science 339 (2013), pp. 1198–1201. DOI: 10.1126/science.1228026.

Rehfeld et al. “Global patterns of declining temperature variability from the Last Glacial Maximum to the Holocene”. In: Nature 554 (2018), pp. 356–359. DOI: 10.1038/nature25454.

R. S. Smith and Jonathan Gregory. “The last glacial cycle: Transient simulations with an AOGCM”. In: Climate Dynamics 38 (2012), pp. 1545–1559. DOI: 10.1007/s00382-011-1283-y.

- Shakun et al. "Global warming preceded by increasing carbon dioxide concentrations during the last deglaciation". In: Nature 484 (2012), pp. 49–55. DOI: 10.1038/nature10915.
- Thorarinsdottir, Gneiting, and Gissibl. "Using Proper Divergence Functions to Evaluate Climate Models". In: SIAM/ASA Journal on Uncertainty Quantification 1 (2013), pp. 522–534. DOI: 10.1137/130907550.
- Weitzel et al. "Diving into the Past: A Paleo Data-Model Comparison Workshop on the Late Glacial and Holocene". In: BAMS 100 (2019), pp. 1–4. DOI: 10.1175/BAMS-D-18-0169.1.