A global climatology of the ocean surface during the Last Glacial Maximum mapped on a regular grid (GLOMAP) – Final response to referee comments

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Response to Anonymous Referee #1

We are thankful to the referee for the helpful and constructive comments that will surely improve our manuscript.

General comments

The authors state is that the Data-Interpolating Variational Analysis method is also capable of analyzing much sparser data. In the paper there is no real comparison or assessment of other methods that would allow the author to make this statement. So I would encourage the authors to add a few lines explaining their choice, maybe by adding some details on the methods that could justify their choice for the present study would be relevant and comparing with the methods employed to create CLIMAP and GLAMAP climatologies.

- In response to the valid concern raised by both referees, in the revised manuscript we will provide a test of the method by, as proposed by the second referee, withholding a certain fraction of the data, make a fit to the remaining data using DIVA, then compare the fit to the withheld data.
- Furthermore, we will take the opportunity to explain our choice of using DIVA – for example, DIVA takes the coastlines into account, since an underlying variational principle is solved only on a finite-element mesh that covers the sea. This prevents the exchange of information across boundaries such as land bridges, peninsulas or islands, which might produce artificial mixing between, for example, Pacific and Atlantic water masses across the Panama isthmus. In solving the variational principle, it not only takes into account the distance between analysis and data, but also imposes a smoothness constraint and, if desired, an advection constraint, and moreover, it provides an uncertainty estimate.
- Regarding the method employed to create the CLIMAP climatology: As described in detail by Broccoli and Marciniak (1996; see also Manabe and Broccoli, 2020), CLIMAP used a subjective analysis procedure (i.e. contouring by hand) to yield the paleoisotherm maps (CLIMAP Project Members, 1976, 1981), which were then digitized on a regular grid.

- With respect to the GLAMAP climatology, different methods were applied: Contouring of the paleotemperature maps was also by hand, and the isotherms were derived by means of visual triangulation from strictly linear interpolation between the SST reconstructions at the irregularly distributed neighbor sites (Sarnthein et al., 2003; Pflaumann et al., 2003). For gridding, either the digitized isotherms (Paul and Schäfer-Neth, 2003) or the SST reconstructions at the sediment core positions (Schäfer-Neth and Paul, 2004) were objectively interpolated using variogram analysis and kriging in spherical coordinates; and the resulting gridded fields were compared (Schäfer-Neth and Paul, 2004, Fig. 5). The seasonal cycle was constructed in the same way as for the GLOMAP climatology: Following the PMIP (1993) guidelines, a sinusoidal cycle was fitted to the glacial-to-modern anomalies and then the modern monthly SST (taken as 10 m data from the WOA, 1998) was added.

- The variogram analysis and kriging cannot deal easily with coastlines, for example, it may take into account data points separated by a land bridge or an island. This was one motivation to apply the DIVA method (Troupin et al., 2012), which employs a finite-element mesh derived from a given topography.

Data availability: it would be useful for the reader to have the direct URL to avoid searching within the PANGEA database. I searched using "GLOMAP" as keyword (https://www.pangaea.de/?q=GLOMAP) but that request did not return any result, so I guess the data will be published once the paper is published. What is the format of the climatology?

Indeed, the final version of the data will be published in the PANGEA database once the paper is published. The format of the climatology is Network Common Data Format (netCDF).

Some parts of the processing workflow (Section 2) were not totally clear to me, for example lines 89-109: why are the two steps necessary, and why not use all the data at the same time for the monthly interpolations?

We took two steps in order to make use of the diatom and radiolarian data from the Southern Ocean. Because in this region the biogenic particle flux to the sea floor is restricted to austral summer, even in areas unaffected by sea-ice cover (Abelmann and Gersonde, 1991; Gersonde and Zielinski, 2000; Fischer et al., 2002), only Southern Hemisphere summer (JFM) SST has been estimated by Gersonde et al. (2005). Therefore, in the first step, we only used the foraminiferal and dinoflagellate data for JAS and JFM. In the second step, we included the diatom and radiolarian data available for JFM and filled in the missing data for JAS by taking the results from the first step at the grid points where diatom and radiolaria data for JFM exist. In this way we were able to create monthly data at all grid points where data exist and repeat the DIVA analysis.

lines 94-94: To each sea-ice covered data point we assigned an error of 2°C $\longrightarrow$ does this mean that measurements taken where it is supposed to be sea ice are used for the gridding? From line 80, it seems that the finite-element mesh is based on a coastline from a glacial topography, so the measurements on ice would not influence the analysis.

Indeed, we used a glacial topography to generate the coastlines, however, these coastlines do not reflect the sea-ice edges. Therefore the finite-element mesh extended to the sea-ice covered regions. To utilze the information on past sea-ice coverage, we digitized the sea-ice edges, created monthly sea-ice masks and included the sea-ice covered data points in the DIVA analysis. A relatively large error of 2 °C was assigned to each sea-ice covered data point to reflect the uncertainty in the LGM sea-ice extent reconstructions.

Could you add the figure of the coastline and the finite-element mesh in the Appendix?

Yes, we can certainly do that, thank you for this suggestion!

Minor comments and typos

39: This method allows to take ⟶ allows one to take

Corrected

39: the uncertainty on the reconstruction ⟶ the authors probably means the uncertainties on the observations (instrumental errors, representativeness errors etc).

Indeed, we mean the paleo-data. Because these are not direct observations as instrumental data, but indirect estimates derived from fossil faunal assemblages using a transfer function technique, we often use the term “reconstruction”, which may be confusing. Hence in the sentence in question we will replace “reconstruction” by “paleo-data”.

40: or for assessing the data-analysis mismatch. ⟶ independently of the interpolation technique, the data-analysis mismatch is not always a relevant metrics: one can obtain a very small mismatch by forcing the analysis to be close to the observation. This would result in a "noisy" or "patchy" interpolated field, which may not represent what a climatology should be.

This is certainly true, thank you for pointing this out. Figures 3 and 4 show that the interpolated fields are neither “noisy” or “patchy”, something we will take up in the discussion of our results.

line 49: "we digitized sea-ice edges" ⟶ can you explicit what is the process to digitize? For Xiao et al. (2015, Fig. 7a), the panel a of their figure did not display any coordinates, how was that solved? Does this also means that no other publication provides the sea-ice edges in digital format?

It is indeed true that none of the publications provides the sea-ice edges in digital format. Therefore we had to digitize the curves from the published maps to obtain their location in geographic coordinates. In case of Xiao et al. (2015, Fig. 7a), neither the projection nor the coordinates are given, hence we used the few indicated topographic features (islands) and the sediment core locations to take into account a summer ice edge north of the Barents Sea in our sea-ice mask.

65 is associate with ⟶ associated with

Corrected

72-73 the magnitude of the data (anomalies) themselves as well as on the gradients, the variability and data-analysis misfits

Rewritten as follows: the magnitude of the data (anomalies) themselves as well as on the gradients, the variability and data-analysis misfits

82 We fitted the covariance function to the foraminiferal data ⟶ indicate how many data points were considered for the fit.

There were 444 data points considered for the fit. We will add this number to the revised manuscript.

84 estimates of the correlation length of 9.2° and 10.2° ⟶ is there a physical explanation to this difference, or do you attribute that to numerics?

We attribute this difference to more noise and a longer tail of the data covariance for the July-August-September (JAS) season that results in a slightly larger correlation length of the fitted covariance.

94 To each sea-ice covered data point we assigned an error of 2 °C ⟶ is it necessary, since you defined a coastline and mask using "glacial topography GLAC-1D"

Please see our response to your general comment on lines 94–94.

103: new (artificial) diatom and radiolaria data ⟶ what is the source of these data? (and why "artificial"?)

The diatom and radiolarian data for JAS are "artificial" in the sense that they were generated from the results of the first step of the DIVA analysis at the grid points where diatom and radiolaria data for JFM exist (please see our response to your general comment on lines 89–109).

141 South Alantic ⟶ South Atlantic

Corrected

169-170 DIVA may be used to more accurately estimate the spatial covariances as described by the non-diagonal terms ⟶ Beckers et al. (2014) may be relevant for this aspect Beckers, J.-M.; Barth, A.; Troupin, C. & Alvera-Azcárate, A. Some approximate and efficient methods to assess error fields in spatial gridding with DIVA (Data Interpolating Variational Analysis) (2014). Journal of Atmospheric and Oceanic Technology, 31: 515-530. doi:10.1175/JTECH-D-13-00130.1

Thank you for pointing out this reference to us. We will refer to it in the revised manuscript.

224 may allow to first smooth ⟶ may allow one to first smooth

Corrected

Figure 2:

- *indicate the meaning of the yellow-brownish area close to the Antarctica (rectangles in the attached figure)*

  We apologize for the missing information in the figure caption. The yellow-brownish areas close to Antarctica and in the Arctic ocean indicate the LGM sea-ice masks based on the selected LGM sea-ice reconstructions.

- *Analyzed SST anomalies ⟶ with respect to what reference or background are computed the anomalies? (also in text, line 97).*

  The LGM estimates from the MARGO database are themselves anomalies that are calculated with respect to World Ocean Atlas 1998. We will clarify this in the Methods section of the revised manuscript.

- *the size of the dots representing the data is a little bit to large, so several dots overlap, especially in the northern part of the domain. In Figure 4 the dots are smaller.*

  Thank you for pointing this out to us. We will reduce the size of the dots representing the data and use the same size in all figures.

334 WOA: World Ocean Atlas 1998 ⟶ why not use a more recent version of the World Ocean Atlas?

The main reason for using the 1998 version of the World Ocean Atlas is to be consistent with the MARGO database, because it is this version that was used for calibrating the methods which were used to reconstruct the LGM estimates and served as a reference for the LGM SST anomalies. Furthermore, the majority of the data that entered the 1998 version represents observations that were taken before the intensification of global warming towards the end of the 20$^{\mathrm{th}}$ century, thereby reducing the anthropogenic imprint.

Figures for the monthly fields: having 6 (or maybe 12) sub-figures seems possible and won't cause problem to the readability of the plots.

Thank you fo this suggestion. We will try combining 6 or even 12 sub-plots in one figure and check its readability, especially of the dots representing the data.

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