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

André Paul[1], Stefan Mulitza[1], Ruediger Stein[1, 2], and Martin Werner[2]

[1] MARUM – Center for Marine Environmental Sciences and Department of Geosciences, University of Bremen, Bremen, Germany

[2]Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research (AWI), Bremerhaven, Germany

Response to Anonymous Referee #1

We are very grateful to the referee for sharing her/his expertise with us and bringing up several key points that strengthen our manuscript considerably.

General comments

109-118 These 2 paragraphs are not totally clear to me: I understood that $2°$ *by* $2°$ *averaged data are used, but then it is stated (line 117) that "DIVA method was used to interpolate the sampled points back to the* $2° \times 2°$ *grid". I might miss something, but I would appreciate if you could make it clearer, maybe adding a figure.*

Thank you for pointing this out to us. We admit that our original formulation was indeed not totally clear. To make it clearer, we extended the section in question and added a new figure that details the step of testing the DIVA method. In addition, we extended the caption of Fig. 2 (previously Fig. 1):

«To first test the DIVA method on data that are much sparser than oceanographic observations, we adopted the procedure by Schäfer-Neth et al. (2005). We took the test data from the World Ocean Atlas 1998. According to WOA (1998), the original ocean profile data are first vertically interpolated from observed depth levels to standard depth levels, then the arithmetic means of each variable in each $1°$ and $5°$ square of the World Ocean are calculated. Except for calculating the arithmetic means, these data have not been subject to any other analysis. These global fields are therefore referred to as "unanalyzed" fields. The $1°$ unanalyzed annual-mean temperature at a depth of 10 m had been used to calibrate the MARGO transfer function technique (the original data file name is `t00mn1`; it is also available as `otemp.raw1deg.nc` from psl.noaa.gov).

Schäfer-Neth et al. (2005) further binned these data into a regular grid with a constant resolution of $2°$ using the GMT program `xyz2grd` (Wessel and Smith, 1998). The coverage is nearly complete, except for the central Arctic Ocean and some points off the Antarctic coast (cf. Fig. 1, *top*). Finally, they greatly reduced this coverage by keeping only those $2°$ squares that contain an ocean sediment core site from MARGO Project Members (2009). This is the input data set for testing the DIVA method (cf. Fig. 1, *middle*).

The DIVA method was used to interpolate these sparse test data to a complete regular grid with a constant resolution of 2°. The differences between the interpolated field (Fig. 1, *bottom*) and the "unanalyzed" field (Fig. 1, *top*) were calculated as a measure of the misfit. This allows for a near-global assessment of the result from the interpolation using the DIVA method.»

247 when you indicate "Figures 3 and 5 show that when applied to the paleo data the interpolated fields are neither noisy nor patchy" it would be relevant to be complete and indicate that this is true because of the selected analysis parameters. For instance, working with a very small correlation length ($L \approx 0.2\circ$ for instance) would have led to a noisy fields.

We rephrased that sentence as follows:

«Figures 4 and 6 show that when applied to the paleo data the interpolated fields are neither "noisy" nor "patchy" . Because the paleo data allowed for a large correlation length of 10°, we obtained a smooth climatology, which we take as an indication that the data points were not overfitted.»

In DIVA, one can select different coordinate systems (Section 6.2.3 in the User Manual): could you indicate which one was used (probably icoord=2, cosine projection).

Yes, it is true that we used the parameter `icoordchange = 2` that corresponds to the cosine projection. We now mention this in Subsection 2.3 of the Methods section:

«To apply the DIVA method to the paleo data, we used the glacial topography GLAC-1D at 21,000 years before present (cf. Tarasov et al., 2012; Briggs et al., 2014) to generate glacial coast lines and create a corresponding global finite-element mesh using a cosine projection.»

245 "but thanks to the underlying global finite-element mesh with less complications..." $\longrightarrow$ is there a benefit in terms of computational time that could be mentioned here?

In fact, it is difficult to directly compare the requirement on computing time, but our impression is that overall the method is more efficient and needs less time. Therefore we added a small note as follows:

«We indeed found that the DIVA method was capable of analyzing data that were much sparser than current oceanographic observations, with a skill that was comparable to variogram analysis and kriging, but thanks to the underlying global finite-element mesh with less complications (such as the introduction of communication masks to avoid the pairing of data points that are unlikely to influence each other in the real ocean, cf. Schäfer-Neth et al., 2005, Fig. 2) and overall in less time.»

Figure 2. In the workflow, there is a final step not visible there: the analysis itself, performed after the estimation of the analysis parameters.

This is certainly true, accordingly, we added the final step to the workflow to Fig. 3 (previously Fig. 2):

Figure 3: it would be interesting to also have the number of data points for each period.

The foraminiferal and dinoflagellate data for JAS and JFM are comprised of 464 data points. In addition, there are 117 points from the diatom data and 19 points from the radiolarian data for Southern Hemisphere summer (JFM). In total, there are 464 data points for JAS and 600 data points for JFM (without data points that are assumed to be covered by sea ice according to our sea-ice reconstruction).

We added this information to Subsection 2.3 of the Methods section as well as to the caption of Fig. 4 (previously Fig.3):

«Therefore, in the first step, we only used the foraminiferal and dinoflagellate data for JAS and JFM (464 data points). In the second step, we included the diatom data (117 data points) and radiolarian data (19 data points) 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.»

Figure 6: it seems that the GLOMAP product is the only one properly dealing with the Mediterranean Sea: the spatial resolution in Annan and Hargreaves (2013) represents the Mediterranean as two different sub-seas; in Kurahashi-Nakamura et al. (2017) the Mediterranean is absent; in Tierney et al. (2020), it appears homogeneous. I guess this does not impact the result of the studies performed at a local scale, but it might be worth mentioning this difference when comparing the methods, especially if one takes into account that there are available data in the Mediterranean Sea (Figure 1 for example).

To properly deal with this difference between the methods, we first rephrased Secion 2.4 of the Methods section:

«For a a comparison to other reconstructions, we selected the recent studies by Annan and Hargreaves (2013), Kurahashi-Nakamura et al. (2017) and Tierney et al. (2020) as well as the earlier studies by CLIMAP (1981) and GLAMAP (Sarnthein et al., 2003). The horizontal resolution differs among these reconstructions and ranges between 1° and 5°. For analysis and plotting purposes, we interpolated them to the same regular grid with a constant resolution of 1°. We calculated the annual-mean anomalies for the global, tropical and high-latitude oceans from these studies as well as our own results. Because an uncertainty estimate was not available for all studies, we only weighted by area.»

We added the following sentence to the caption of Table 3:

«The NSST results from the multiple linear regression by Annan and Hargreaves (2013) are provided on a regular grid with a constant resolution of 5°.»

We added a new paragraph to the Discussion section:

«Regarding the Mediterranean Sea, in the coarse reconstruction by Annan and Hargreaves (2013) it is represented as two separated "sub-seas", while it is completely missing in the reconstruction by Kurahashi-Nakamura et al. (2017). The "off-line" data assimilation method by Tierney et al. (2020) yields a homogeneous result. It seems that the GLOMAP reconstruction is the only one that can properly present the Mediterranean Sea, in terms of spatial resolution of the underlying finite-element mesh as well as in taking into account the available data (cf. Fig. 4 and Fig. 6)».

General: the term SST is employed frequently, yet it is often referring to the temperature at 10 meters. Is it correct? I believe that in remote-sensing and in operational oceanography, SST refers to the temperature in the first millimeters of the water column. Could you address that definition early in the manuscript?

In response to this valid remark, we now distinguish between sea-surface temperature (SST) and near-sea surface temperature (NSST) and added the following paragraph to the Introduction:

«Following, e.g., Dail and Wunsch (2014), the adjective "near" is used to distinguish these temperatures, which in the case of the GLAMAP and MARGO projects are based on calibrations for the top 10 m of the ocean and depend on phytoplankton and zooplankton that live even deeper, in the top 200 m to 300 m of the ocean, from those used in other communities, in which SST is at the surface itself and can even be a skin temperature that does not reflect the temperature below.»

Minor comments and typos

The sea-ice mask seems to be a time-demanding product itself, is it also made available for re-use?

Yes, we will make the sea-ice mask available along with the NSST reconstruction.

30 (MARGO) (Kucera et al., 2005a). ⟶ (MARGO, Kucera et al., 2005a). using the () command in latex

35 (see also Broccoli and Marciniak (1996 and Manabe and Broccoli, 2020). ⟶ missing parenthesis

110 We used the annual-mean temperature for 10 m depth ⟶ at 10 m depth

126 we fixed the correlation length at average value of 10◦ ⟶ at an average value of

All done

153 SH ⟶ please define (Southern Hemisphere I guess)

Now we use “Southern Hemisphere” throughout instead.

167 from the modern topography ⟶ indicate which topography was employed (including the version number)

We employed the bottom depth assigned to each 1° square of the World Ocean Atlas 2018 as topography, and we modified the paragraph (as well as the caption of Figure A1) accordingly:

«Figure A1 shows the coastlines that were generated from the modern topography (based on the bottom depth assigned to each 1° square by Garcia et al., 2019) for testing the DIVA method on the WOA (1998) data sampled at the MARGO core locations, as well as from the LGM topography (GLAC-1D, cf. Tarasov et al., 2012; Briggs et al., 2014) for our application of the DIVA method to the LGM NSST reconstruction.»

179 the impact of advection by the western boundary currents, which is missing in our application of DIVA ⟶ the other methods don't use the advection neither in the interpolation scheme, so the difference should not come

This is correct, hence we dropped the last half-sentence from the manuscript.

187 There was even an 1 °C ⟶ There was even a 1 °C

Done

227 Eq (5): what is the denominator u^2? Also, the sum should be written $\sum^{N_{\mathrm{data}}}$

We rewrote Eq. 5 as follows:

$$J_{\mathrm{misfit}} = \frac{1}{N_{\mathrm{data}}} \sum_{i=1}^{N_{\mathrm{data}}} \frac{\left(T_i^{\mathrm{gridded}} - T_i^{\mathrm{data}}\right)^2}{e_i^2} \,. \tag{1}$$

In this equation, e_i is the average uncertainty of the data in the ith grid cell. We now use the symbol e_i to distinguish it from u_i, which is the uncertainty of the analyzed field in the ith grid cell.

318 has no anlogs, ⟶ analogs

Done

394 than assimilationg ⟶ than assimilation

Done

References

Annan, J. D. and Hargreaves, J. C.: A new global reconstruction of temperature changes at the Last Glacial Maximum, Climate of the Past, 9, 367–376, https://doi.org/10.5194/cp-9-367-2013, 2013.

Briggs, R. D., Pollard, D., and Tarasov, L.: A data-constrained large ensemble analysis of Antarctic evolution since the Eemian, Quaternary Science Reviews, 103, 91–115, https://doi.org/10.1016/j.quascirev.2014.09.003, 2014.

CLIMAP Project Members: Seasonal reconstructions of the Earth's surface at the Last Glacial Maximum, Geological Society of America, Map and Chart Series, MC-36, 1–18, 1981.

Dail, H. and Wunsch, C.: Dynamical Reconstruction of Upper-Ocean Conditions in the Last Glacial Maximum Atlantic, Journal of Climate, 27, 807–823, https://doi.org/10.1175/JCLI-D-13-00211.1, 2014.

Garcia, H., Boyer, T., Baranova, O., Locarnini, R., Mishonov, A., Grodsky, A., Paver, C., Weathers, K., Smolyar, I., Reagan, J., Seidov, D., and Zweng, M.: World Ocean Atlas 2018: Product Documentation, Tech. rep., Ocean Climate Laboratory, NCEI/NESDIS/NOAA, Silver Spring, MD, 2019.

Kurahashi-Nakamura, T., Paul, A., and Losch, M.: Dynamical reconstruction of the global ocean state during the Last Glacial Maximum, Paleoceanography, 32, 326–350, https://doi.org/10.1002/2016PA003001, 2017.

MARGO Project Members: Constraints on the magnitude and patterns of ocean cooling at the Last Glacial Maximum, Nature Geoscience, 2, 127–132, https://doi.org/doi:10.1039/NGEO411, 2009.

Sarnthein, M., Gersonde, R., Niebler, S., Pflaumann, U., Spielhagen, R., Thiede, J., Wefer, G., and Weinelt, M.: Overview of Glacial Atlantic Ocean Mapping (GLAMAP 2000), Paleoceanography, 18, doi:10.1029/2002PA00 769, 2003.

Schäfer-Neth, C., Paul, A., and Mulitza, S.: Perspectives on mapping the MARGO reconstructions by variogram analysis/kriging and objective analysis, Quaternary Science Reviews, 23, 1083–1093, doi:10.1016/j.quascirev.2004.06.017, 2005.

Tarasov, L., Dyke, A. S., Neal, R. M., and Peltier, W. R.: A data-calibrated distribution of deglacial chronologies for the North American ice complex from glaciological modeling, EPSL, 315-316, 30–40, https://doi.org/10.1016/j.epsl.2011.09.010, 2012.

Tierney, J. E., Zhu, J., King, J., Malevich, S. B., Hakim, G. J., and Poulsen, C. J.: Glacial cooling and climate sensitivity revisited, Nature, 584, 569–573, https://doi.org/10.1038/s41586-020-2617-x, 2020.

Troupin, C., Barth, A., Sirjacobs, D., Ouberdous, M., Brankart, J.-M., Brasseur, P., Rixen, M., Alvera-Azcárate, A., Belounis, M., Capet, A., Lenartz, F., Toussaint, M.-E., and Beckers, J.-M.: Generation of analysis and consistent error fields using the Data Interpolating Variational Analysis (DIVA), Ocean Modelling, 52-53, 90–101, https://doi.org/10.1016/j.ocemod.2012.05.002, http://modb.oce.ulg.ac.be, 2012.

Wessel, P. and Smith, W. H. F.: New, improved version of Generic Mapping Tools released, EOS Transactions of the American Geophysical Union, 79, 579, 1998.

WOA: World Ocean Atlas 1998, Tech. rep., National Oceanographic Data Center, Silver Spring, Maryland, 1998.

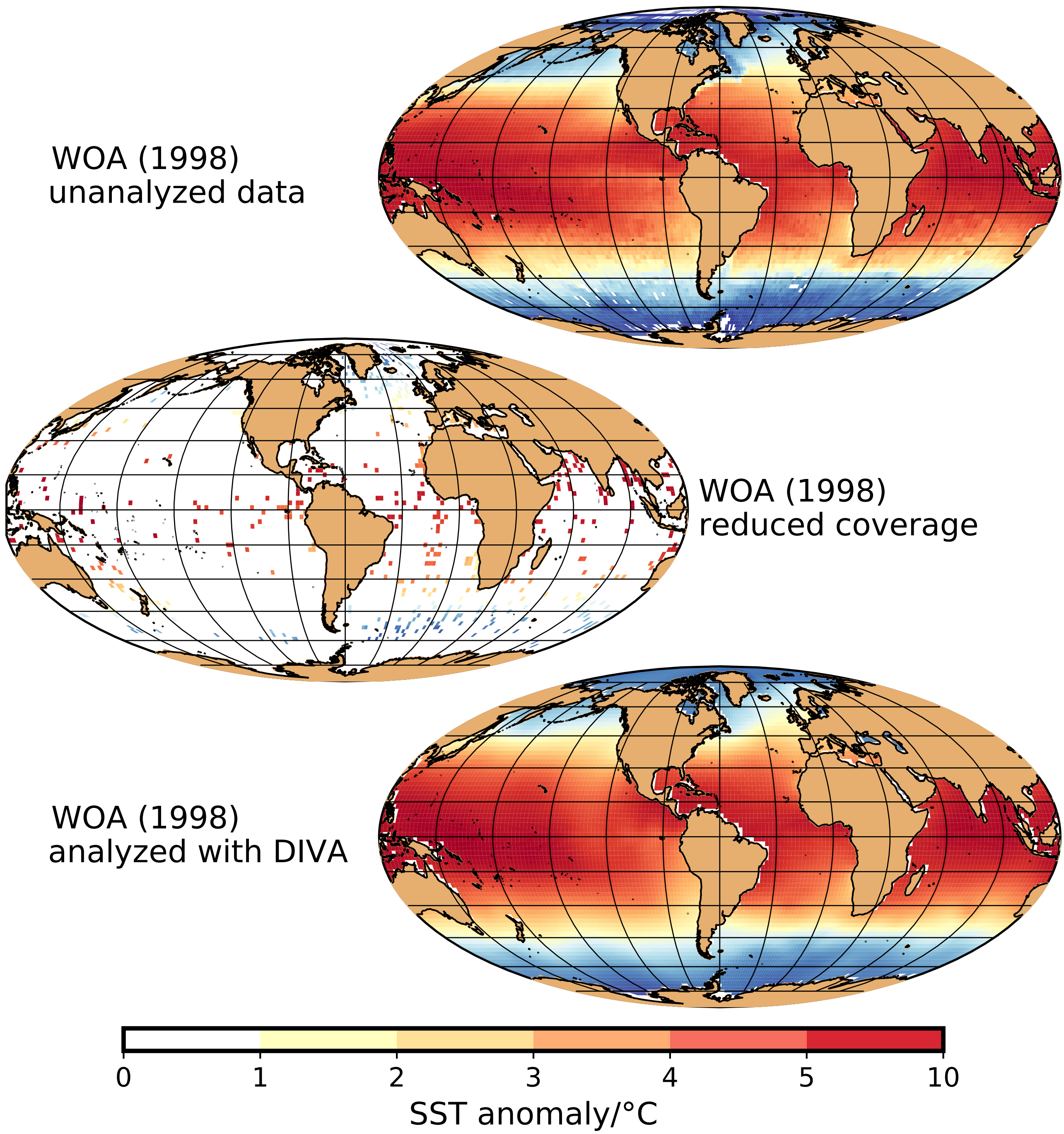

Figure 1. *Top:* Unanalyzed annual-mean temperature at a depth of 10 m from the World Ocean Atlas 1998 (WOA, 1998), binned into a regular grid with a constant resolution of 2° using the GMT program xyz2grd (Wessel and Smith, 1998). *Middle:* The same data, but after greatly reducing the coverage by keeping only those 2° squares that contain an ocean sediment core site from MARGO Project Members (2009). This is the input data set for testing the DIVA method (Troupin et al., 2012). *Bottom:* The result of using the DIVA method to interpolate the sparse test data to a complete regular grid with a constant resolution of 2°.

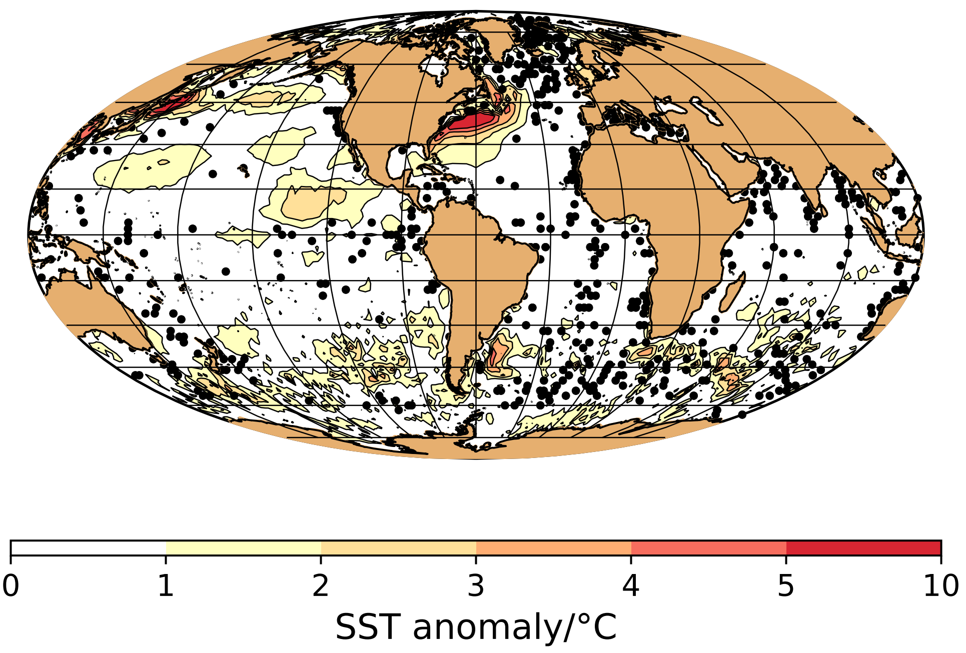

Figure 2. Absolute difference between the analyzed (using the DIVA method, Troupin et al., 2012) and unanalyzed (from the World Ocean Atlas 1998, WOA, 1998) annual-mean temperature at a depth of 10 m, shown as contour lines (for the contour intervals, see the color bar). In addition, the MARGO ocean sediment core sites are depicted as black circles (MARGO Project Members, 2009).

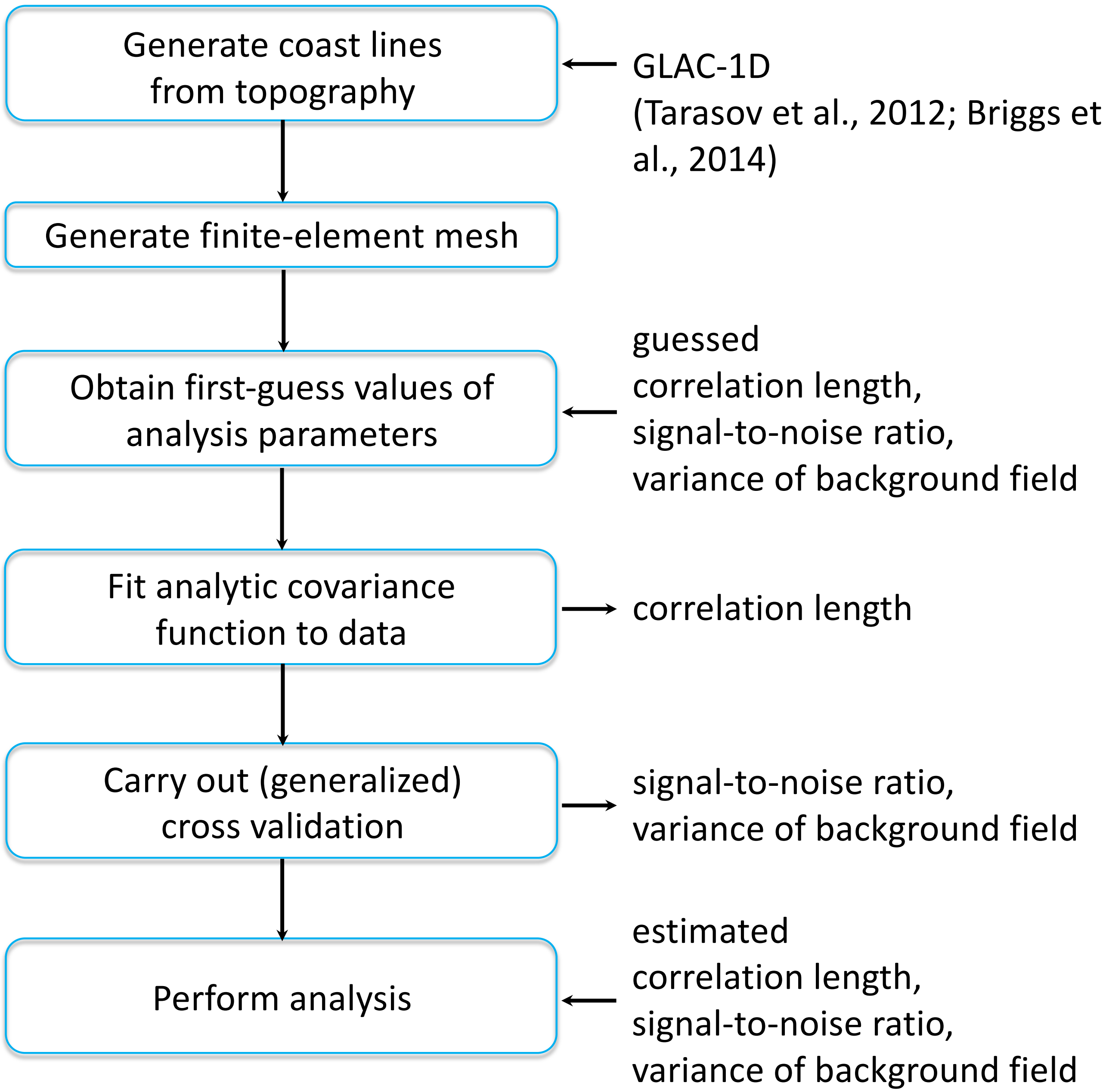

Figure 3. General workflow of DIVA (Data-Interpolating Variational Analysis, Troupin et al., 2012).

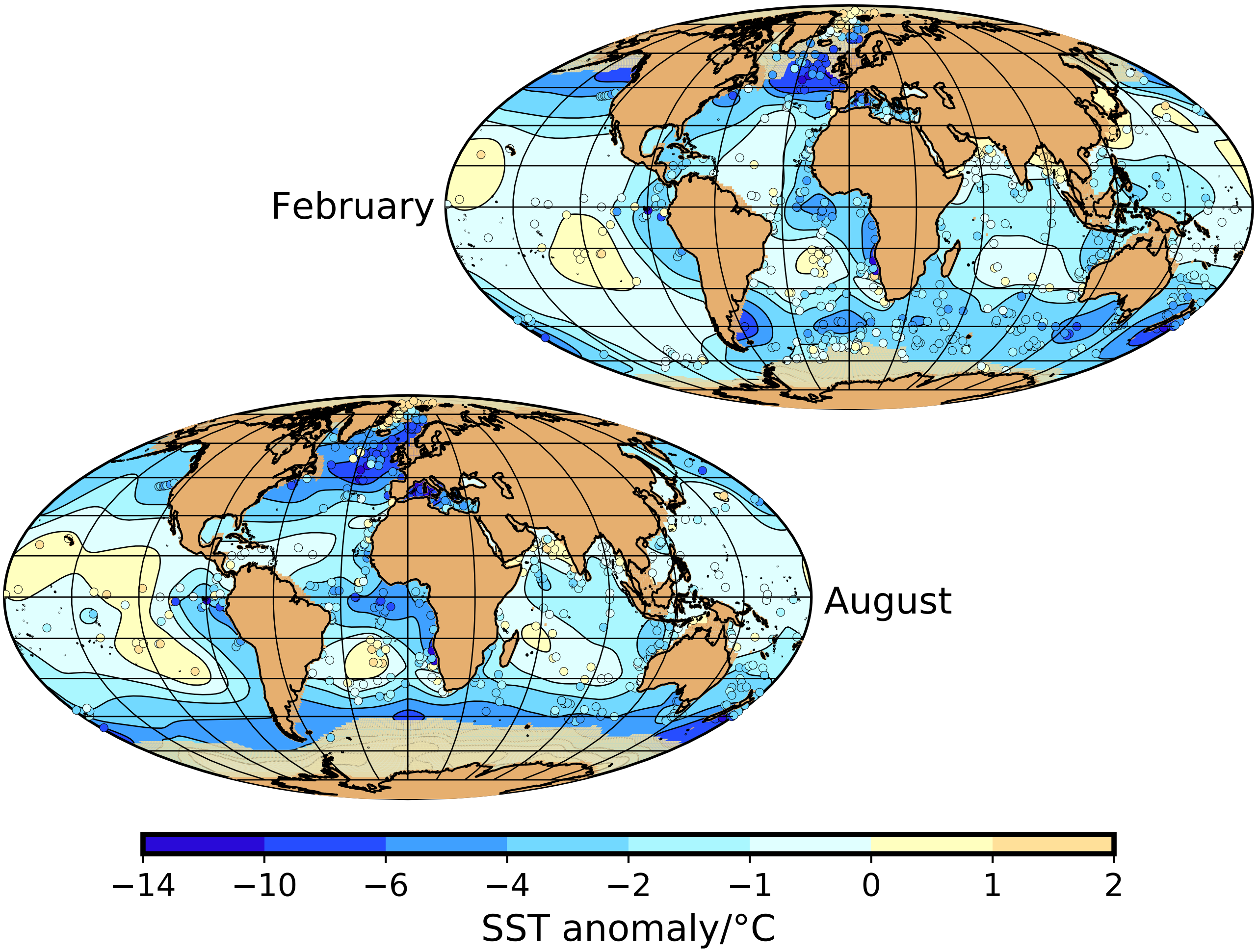

Figure 4. Analyzed LGM NSST anomalies for February and August (contour map) and data points (colored circles). In total, there are 600 data points for February and 464 data points for August (without the data points that are assumed to be covered by sea ice). The anomalies are relative to WOA (1998). The yellow-brownish areas close to Antarctica and in the Arctic indicate the LGM sea-ice masks based on the selected LGM sea-ice reconstructions.