Revised Southern Ocean sea surface temperatures: Penultimate glacial & last interglacial

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TiPACCs
Tipping Points in Antarctic Climate Components

BJERKNES CENTRE
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Past glacial-interglacial cycles

Why study Quaternary glacials and interglacials - and in particular the last interglacial (LIG)?

- LIG sea level estimated as a few metres higher than present.
- What was the Antarctic Ice Sheet contribution to that higher sea level?
- LIG Antarctic Ice Sheet air temperature and Southern Ocean SST were likely just a few degrees warmer than present.

(*Petit et al., 1999; Kopp et al., 2009; Capron et al., 2014; Dutton et al., 2015; Düsterhus, 2016; Turney et al., 2020,… and many others*)

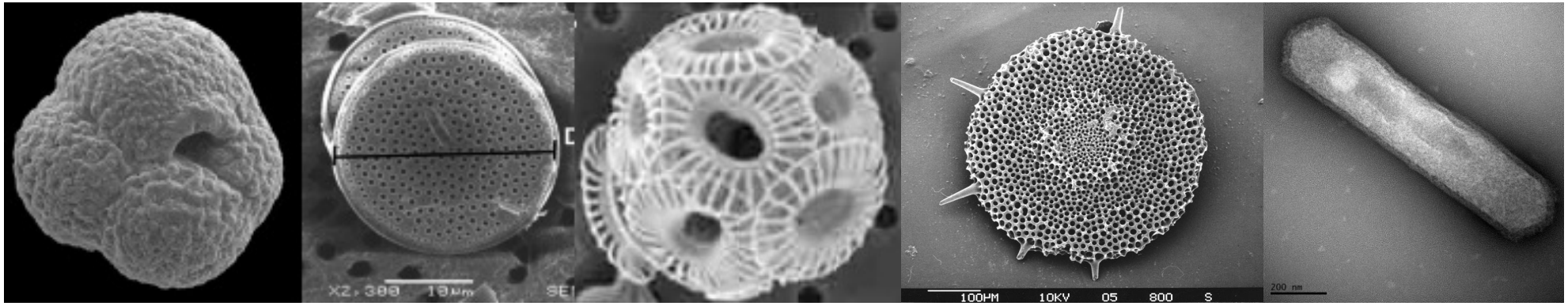
→ Southern Ocean / Antarctic Ice Sheet response to LIG warming could help us understand how the ice sheet and its sea level contribution will respond to near-future climate warming.

This study focuses on Southern Ocean SST during the LIG and penultimate glacial.

Last interglacial /penultimate glacial Southern Ocean SST

Southern Ocean SST is reconstructed from plankton fossils or geochemical signatures preserved in marine sediment cores.

- Alkenones }
- GDGTs (algal cell membrane lipids) } Geochemical proxies
- Foraminifera shell Mg/Ca ratio }
- Diatoms }
- Dinocysts }
- Foraminifera } Assemblages (modern analogue technique or similar)
- Radiolarians }



Foraminifera *Mikis et al. (2019)*

Diatoms *Nair et al. (2020)*

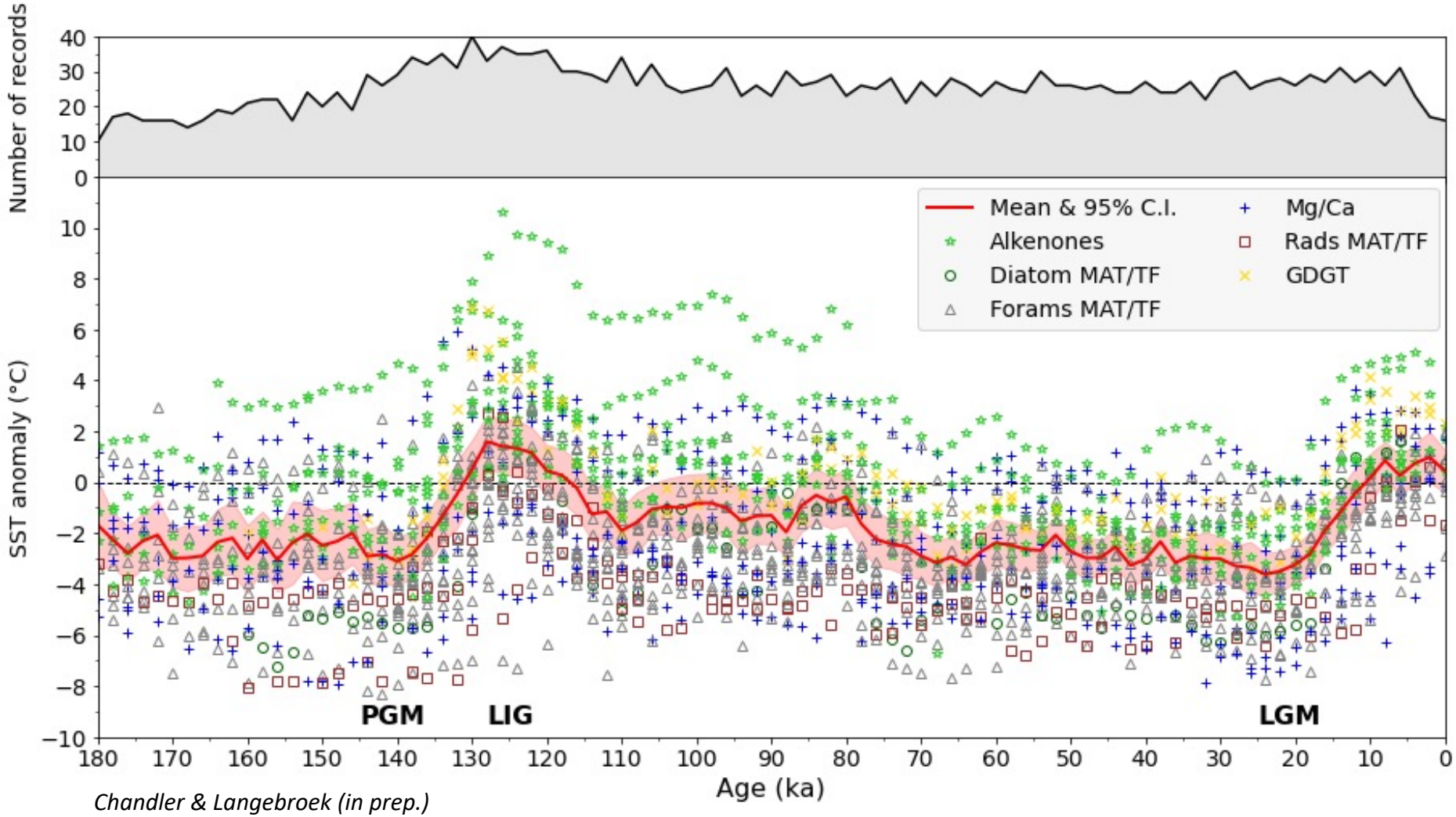
Coccolithophores *Young et al. (2003)*

Radiolarians *Grobe (1980)*

Thaumarchaeota *Hickey (2015)*

Last interglacial /penultimate glacial Southern Ocean SST

Many reconstructions are available for LIG SST … but variance is very high.



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Sites south of 40°S

Original annual SST reconstructions

Resampled to 2 ka.

Original calibration

Original chronology

Anomalies relative to World Ocean Atlas (*Locarnini et al. 2018*)

Only selected records which include the LIG.

Last interglacial /penultimate glacial Southern Ocean SST

Many reasons for high variance…

Besides the differences between proxy types:

- **Different calibrations (geochem) or transfer functions (assemblages).**
- **Horizontal advection as organisms sink through water column.**
- **Representative seasonality & depth? (spring/summer/annual…. surface / thermocline).**
- **Non-thermal factors: salinity, nutrients, food webs, …**
- Different chronologies & dating strategies.
- Poor resolution in some cases.
- Changes to taxonomy / reporting of taxa.
- Selective preservation of particular species in assemblage.
- Sediment reworking.

Last interglacial /penultimate glacial Southern Ocean SST

Three main objectives:

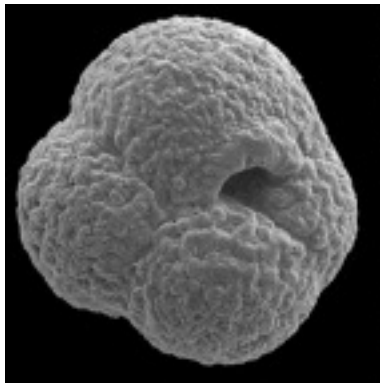
1. Review available calibrations, and recalculate SST with consistent calibrations / training data (reduces some methodological variance). Takes advantage of recent core-top databases.
   Tierney and Tingley, 2015; Haddam et al., 2016; Tierney and Tingley, 2018; Saenger and Evans, 2019; Tierney et al.,2019.

2. Select the proxies which are most reliable in this region.

3. Revise LIG & penultimate glacial SST anomalies based on these recommended calibrations and proxies.

Last interglacial /penultimate glacial Southern Ocean SST

Example: the questions of seasonality and depth…



Suppose this foram has a Mg/Ca ratio of 1.23 mmol/mol.
Does that represent water temperature in spring? or summer?
At the surface or 150 m depth?
Some weighted average of all of these?

Few observations available to confidently constrain the representative seasonality of geochemical proxies in the Southern Ocean, compared to (for example) the N. Atlantic.

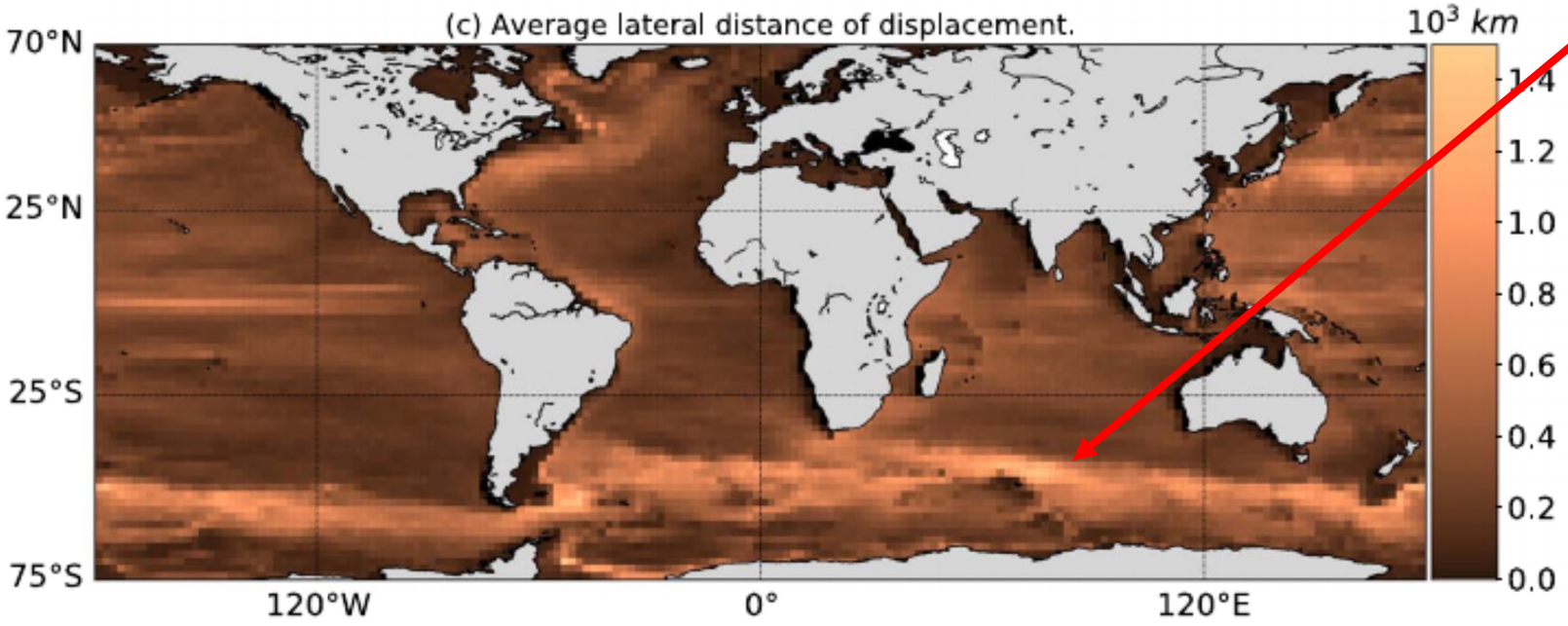
Could assemblage-based proxies be more reliable in this respect?

Were the representative seasonality and depth different under past climates?

Last interglacial /penultimate glacial Southern Ocean SST

Another example: lateral advection

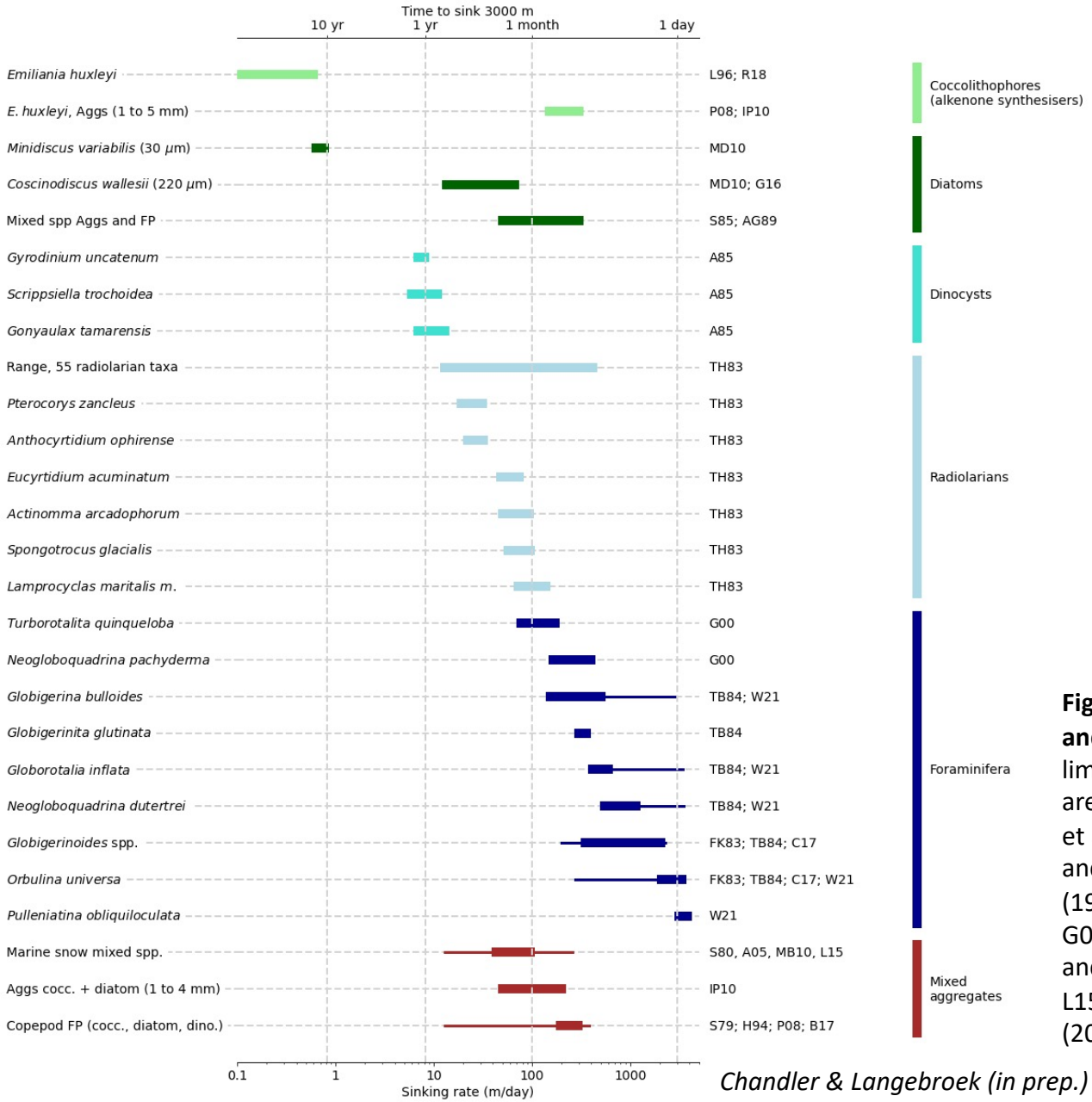
Organisms sampled in Southern Ocean sediments may have travelled **>1000 km from their original habitat.** Lateral advection has a diffusion component which might not be corrected by back-trajectory modelling *(Popova, 1986; Batchelder, 2006; van Sebille et al., 2015; Nooteboom et al., 2019)*.



Nooteboom et al. (2019): horizontal distance travelled by "typical" slow-sinking particles, e.g. dinocysts.

The magnitdue of the problem depends on how fast the organisms sink…

Last interglacial /penultimate glacial Southern Ocean SST



Foraminifera: fast sinkers, small problem.

Radiolarians: diverse mix of fast & slow sinkers, potentially large problem for an assemblage-based proxy (both the provenance and the assemblage are altered).

Cocclithophores, Diatoms, Dinocysts?? Complicated by aggregation & grazing.

GDGT synthesisers??? Are there any data?

Fig: Observed sinking rates of planktic organisms, as individuals or as aggregates (Aggs) and faecal pellets (FP). Thick lines show the 'likely' range and thin lines the upper and lower limits based on qualitative assessments of the cited observations. Sinking times (top axis) are estimated assuming a steady sinking rate in water 3000 m deep. References: S79 Small et al. (1979), S80 Shanks and Trent (1980), FK83 Fok-Pun and Komar (1983), TH83 Takahashi and Honjo (1983), TB84 Takahashi and Be (1984), A85 Anderson et al. (1985), S85 Smetacek (1985), AG89 Alldredge and Gotschalk (1989), H94 Harris (1994), L96 Lecourt et al. (1996), G00 Gyldenfeldt et al. (2000), A05 Ashjian et al. (2005), P08 Ploug et al. (2008), IP10 Iversen and Ploug (2010), MB10 McDonnell and Buesseler (2010), MD10 Miklasz and Denny (2010), L15 Laurenceau-Cornec et al. (2015), G16 Gemmell et al. (2016), R18 Rosas-Navarro et al. (2018), B17 Belcher et al. (2017), C17 Caromel et al. (2014), W21 Walker et al. (2021).

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Last interglacial /penultimate glacial Southern Ocean SST

How do we reduce reconstruction errors?

We have carefully reviewed the available proxies for Southern Ocean SST reconstructions.

At present, for reconstructions at glacial-interglacial times scales we would recommend…

Foraminifera assemblages and alkenones as the most reliable proxies in this region.
Diatoms and *G. bulloides* Mg/Ca as 'moderately reliable' in this region.
Dinocyst & radiolarian assemblages, and *N. pachyderma* Mg/Ca as least reliable in this region.

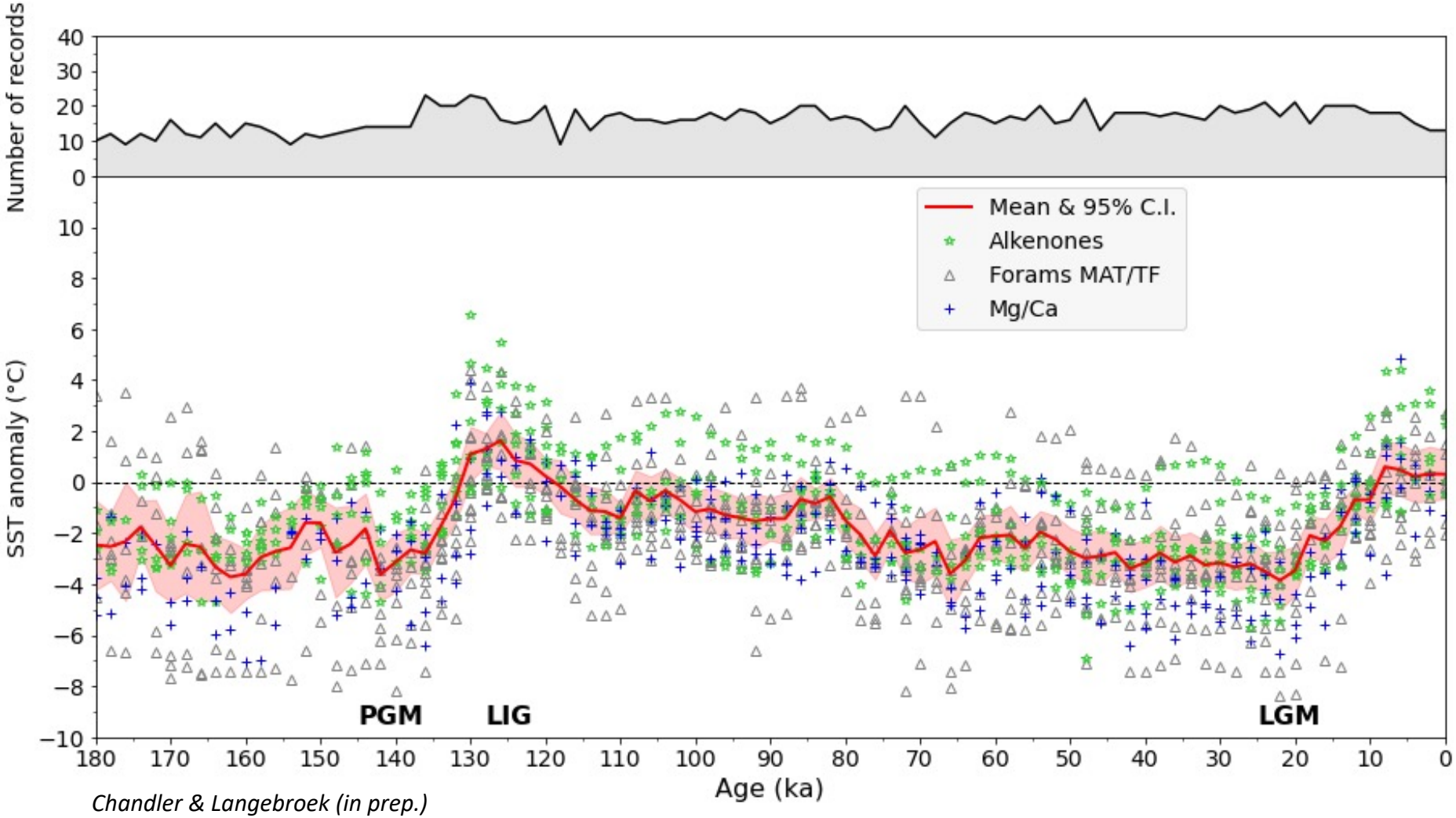
These 'less reliable' proxies suffer from weak calibrations or are likely to be susceptible to strong advection bias in the Southern Ocean. But of course these proxies can be great to use elsewhere at other locations / time periods!

Overall, considering the many uncertainites with all these proxies in the Southern Ocean….

A multi-proxy regional average should be much more robust than records from single sites.

Last interglacial /penultimate glacial Southern Ocean SST – Revised estimate

Reduced variance.
More strongly reflects geographic variability with less influence of reconstruction errors.



Chandler & Langebroek (in prep.)

Sites south of 40°S

Recalibrated annual SST reconstructions

Resampled to 2 ka.

New calibrations

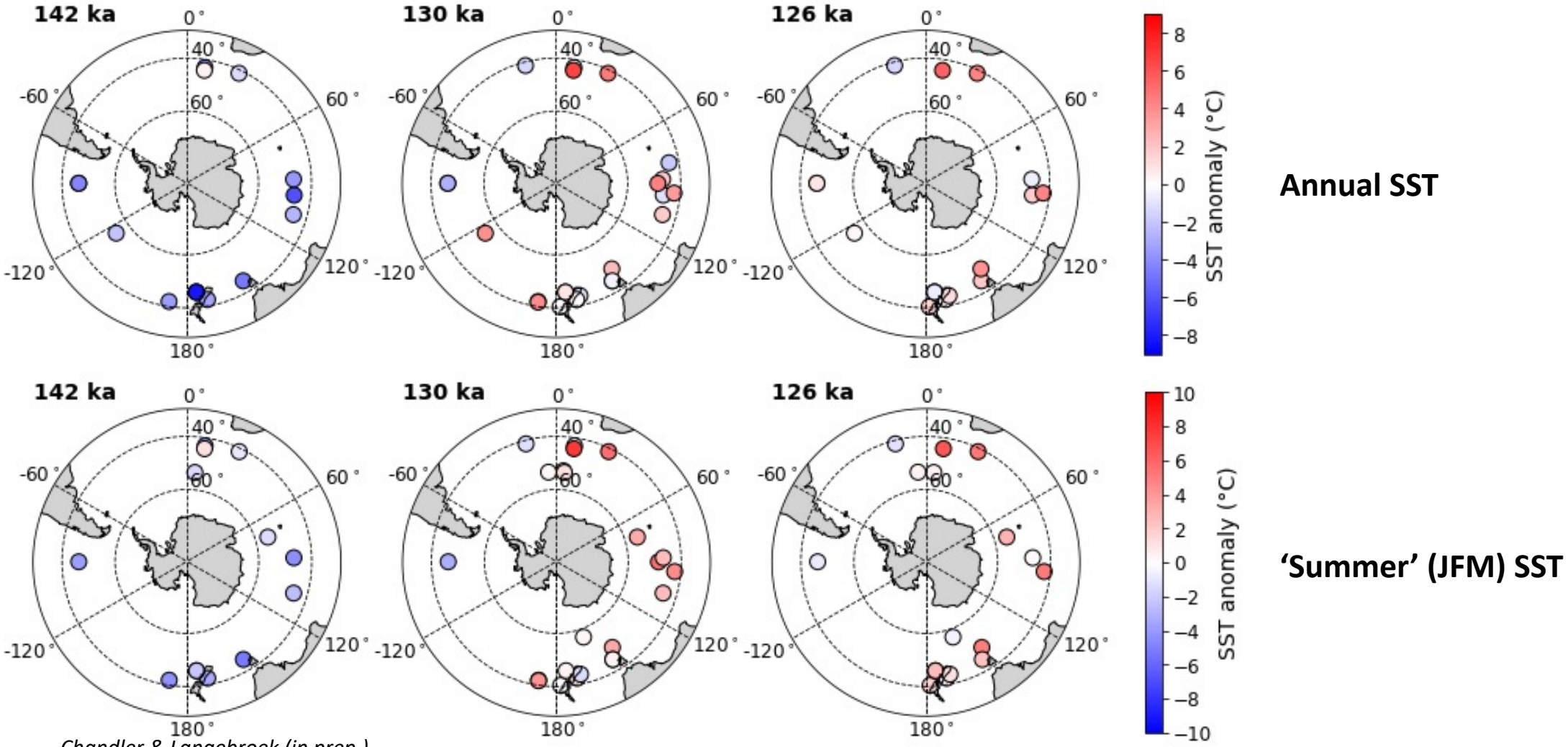
LS16 chronology

Anomalies relative to World Ocean Atlas (*Locarnini et al. 2018*)

Again, only selected records which include the LIG.

Last interglacial /penultimate glacial Southern Ocean SST – Revised estimate

Spatial distribution of reconstructions



Annual SST

‘Summer’ (JFM) SST

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Last interglacial /penultimate glacial Southern Ocean SST – Revised estimate

Conclusions

1. We have recommended the optimal calibrations and proxies for Southern Ocean SST at Quaternary glacial/interglacial time scales.

2. Regional mean anomalies using our recommended proxies/calibrations are:
   - LIG (peak) +1.6 ± 1.1ºC (annual) +1.9 ± 1.3ºC (summer) at 126 ka
   - PGM –3.6 ± 1.0ºC (annual) –4.0 ± 1.2ºC (summer) at 142 ka

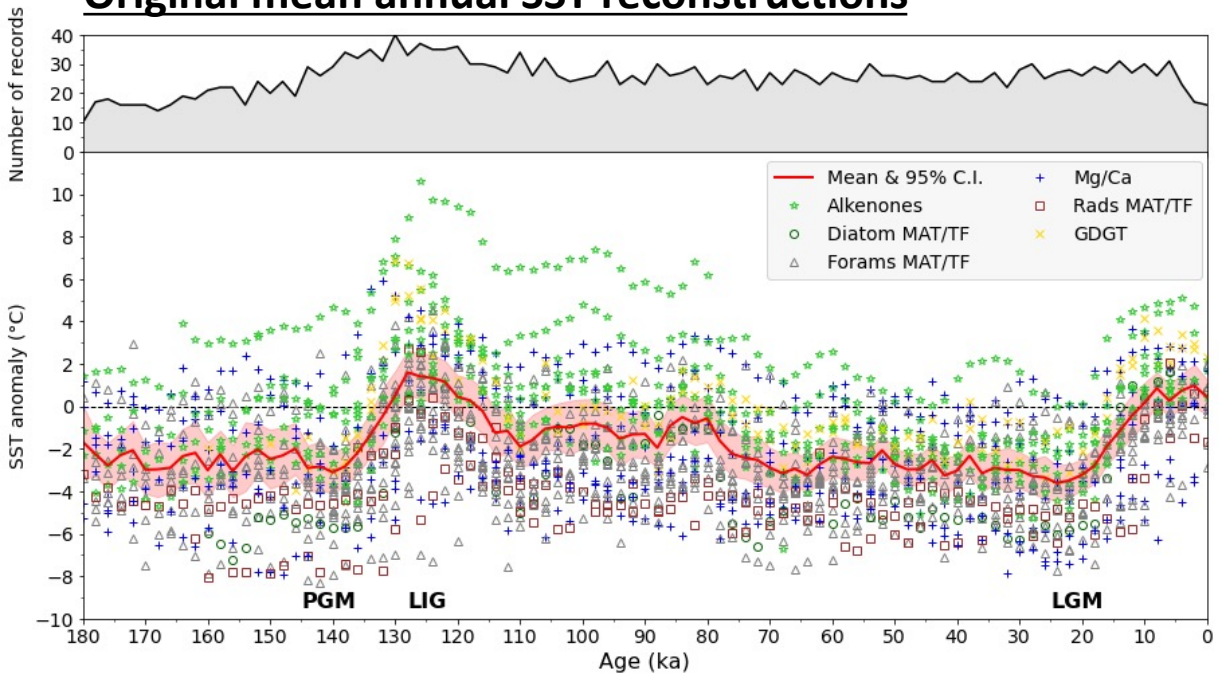
3. Compared to past estimates, the mean & variance better reflect geographic variability (less influence of individual reconstruction errors – although these are still important).

4. Advection/dispersion, and reprentative depth/seasonality really need better constraints in Southern Ocean. Poorly known at present, let alone in the past!

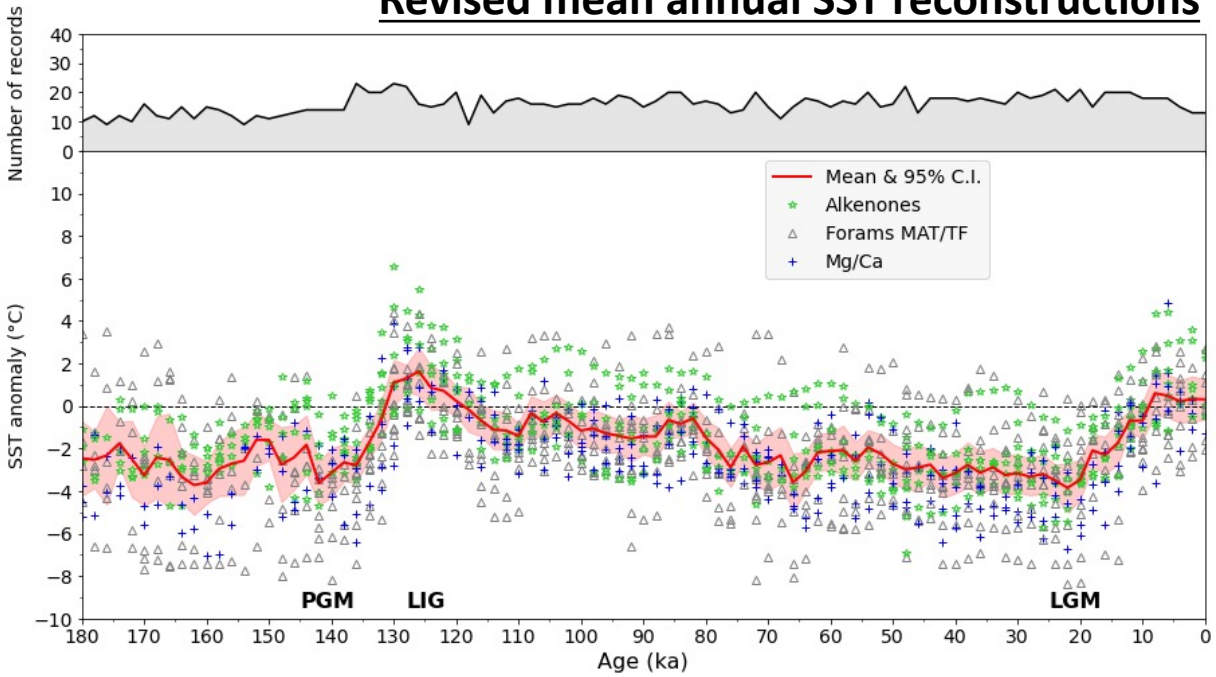
Last interglacial /penultimate glacial Southern Ocean SST – Revised estimate

Summary

Original mean annual SST reconstructions



Revised mean annual SST reconstructions



Detailed review helped by recent databases

High variance

Inconsistent calibrations / training data / dating

Uncertain seasonality, depth, non-thermal influences

Some proxies susceptible to lateral advection

Geographic variability

Reduced variance

Consistent calibrations / training data / dating

Uncertain seasonality, depth, non-thermal influences

Reduced errors from lateral advection

Geographic variability

Last interglacial /penultimate glacial Southern Ocean SST

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Core-top sediment datasets:

Haddam et al. (2016) https://doi.org/10.1002/2016PA002946. Saenger & Evans (2019) https://doi.org/10.1029/2018PA003507. Tierney & Tingley (2014) https://doi.org/10.1016/j.gca.2013.11.026. Tierney & Tingley (2015) https://doi.org/10.1038/sdata.2015.29. Tierney & Tingley (2018) https://doi.org/10.1002/2017PA003201. Tierney et al. (2019) https://doi.org/10.1029/2019PA003744.

Original temperature reconstructions:

Barrows et al. (2007) https://doi.org/10.1029/2006PA001328. Becquey & Gersonde (2003) https://doi.org/10.1029/2000PA000576. Bianchi & Gersonde (2002) https://doi.org/10.1016/S0031-0182(02)00516-3. CLIMAP (1984) https://doi.org/10.1016/0033-5894(84)90098-X. Cortese et al. (2007) https://doi.org/10.1029/2007PA001457. Cortese et al. (2013) https://doi.org/10.1002/palo.20052. Crosta et al. (2004) https://doi.org/10.1016/S0377-8398(03)00072-0. Crosta et al. (2020) https://doi.org/10.1594/PANGAEA.913534. De Deckker et al. (2019) https://doi.org/10.1080/08120099.2018.1495101. Esper & Gersonde (2014) http://dx.doi.org/10.1016/j.palaeo.2014.08.008. Govin et al. (2009) https://doi.org/10.1029/2008PA001603. Hasenfratz et al. (2019) https://doi.org/10.1126/science.aat7067. Hayes et al. (2014) https://doi.org/10.1126/science.1256620. Hays et al. (1976) http://www.jstor.org/stable/1743620. Hayward et al. (2008) https://doi.org/10.1016/j.gloplacha.2008.07.003. Hayward et al. (2012) http://dx.doi.org/10.1016/j.marmicro.2011.10.003. Ho et al. (2012) https://doi.org/10.1029/2012PA002317. Howard and Prell (1992) https://doi.org/10.1029/91PA02994. Ikehara et al. (1997). https://doi.org/10.1029/97GL00429. Labeyrie et al. (1996) https://doi.org/10.1029/95PA02255. Lüer et al. (2009) http://dx.doi.org/10.1016/j.marmicro.2008.12.002. Martinez-Garcia et al. (2010) https://doi.org/10.1126/Science.1184480. Mashiotta et al. (1999) https://doi.org/10.1016/S0012-821X(99)00116-8. McClymont et al. (2016) https://10.1002/2016PA002954. Nürnberg & Groenveld (2006) https://doi.org/10.1029/2005GC000984. Pahnke et al. (2003) https://doi.org/10.1126/science.1084451. Pahnke & Sachs (2006) https://doi.org/10.1029/2005PA001191. Panitz et al. (2015) https://doi.org/10.1016/j.marmicro.2014.12.003. Pelejero et al. (2004) https://doi.org/10.1016/j.margeo.2006.04.004. Pichon et al. (1992) https://doi.org/10.1029/92PA00709. Rickaby & Elderfield (1999) https://doi.org/10.1029/1999PA900007. Romero et al. (2015) https://doi.org/10.1002/2014PA002636. Schaefer et al. (2005). Marine Micro., https://doi.org/10.1016/j.marmicro.2004.12.001. Sowers et al. (1993) https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/93PA02328. Tapia et al. (2015) http://dx.doi.org/10.1016/j.epsl.2014.11.031. Thöle et al. (2019) https://doi.org/10.1016/j.epsl.2019.115716. Weaver et al. (1998) https://doi.org/10.1029/97PA02982. Zielinski et al. (1998) https://doi.org/10.1029/98PA01320.

Age models & chronology:

Original reconstructions are plotted simply using the published age models and chronology. Revised reconstructions use age models aligned by foraminiferal $d^{18}O$ (Lisiecki & Raymo, https://doi.org/10.1002/2016PA003002).