Silicon isotopes in an EMIC's ocean: sensitivity to runoff, iron supply and climate

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November 21, 2022

Abstract

The isotopic composition of Si in biogenic silica (BSi), such as opal buried in the oceans' sediments, has changed over time. Paleo records suggest that the isotopic composition, described in terms of δ^{30}Si, was generally much lower during glacial times than today. There is consensus that this variability is attributable to differing environmental conditions at the respective time of BSi production and sedimentation. The detailed links between environmental conditions and the isotopic composition of BSi in the sediments are, however, controversially discussed in the literature. In this study, we explore the effects of a suite of offset boundary conditions during the LGM on the isotopic composition of BSi archived in sediments in an Earth System Model of intermediate complexity. Our model results suggest that a change in the isotopic composition of Si supply to the glacial ocean is sufficient to explain the observed overall low(er) glacial δ^{30}Si in BSi. All other processes explored triggered model responses of either wrong sign or magnitude, or are inconsistent with a recent estimate of bottom water oxygenation in the Atlantic Sector of the Southern Ocean. Caveats, mainly associated with generic uncertainties in today's pelagic biogeochemical modules, remain.

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$$s\ ms(D\quad S\ i)\quad r\ \ BS\ i\frac{B\quad S\ i}{BS\ i}\quad P\quad ff\ \frac{D\quad S\ i}{DS\ i} \qquad (6)$$

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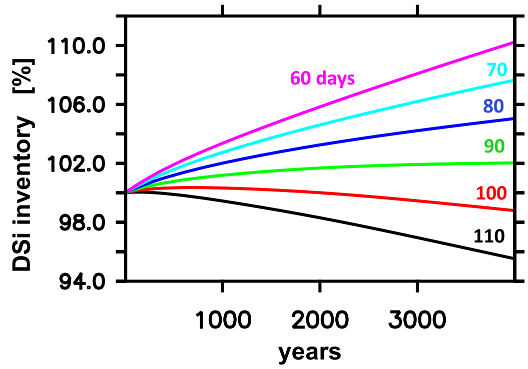

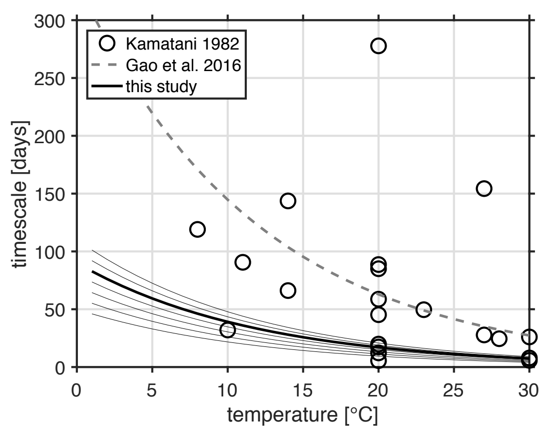

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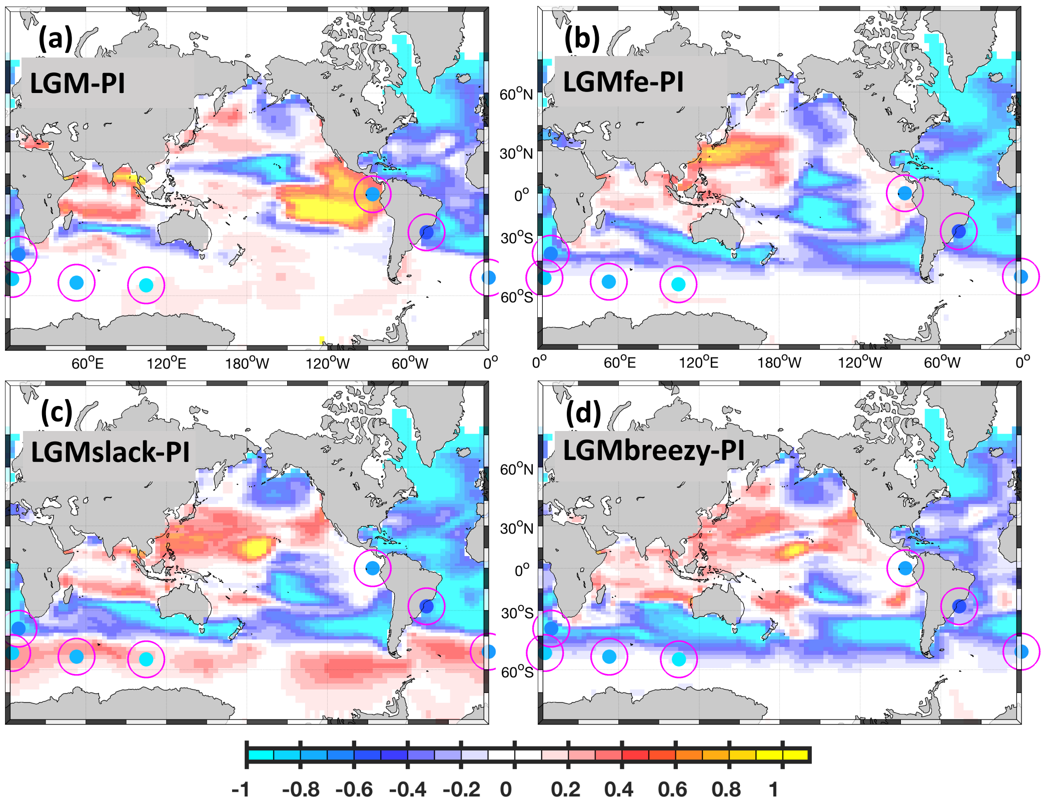

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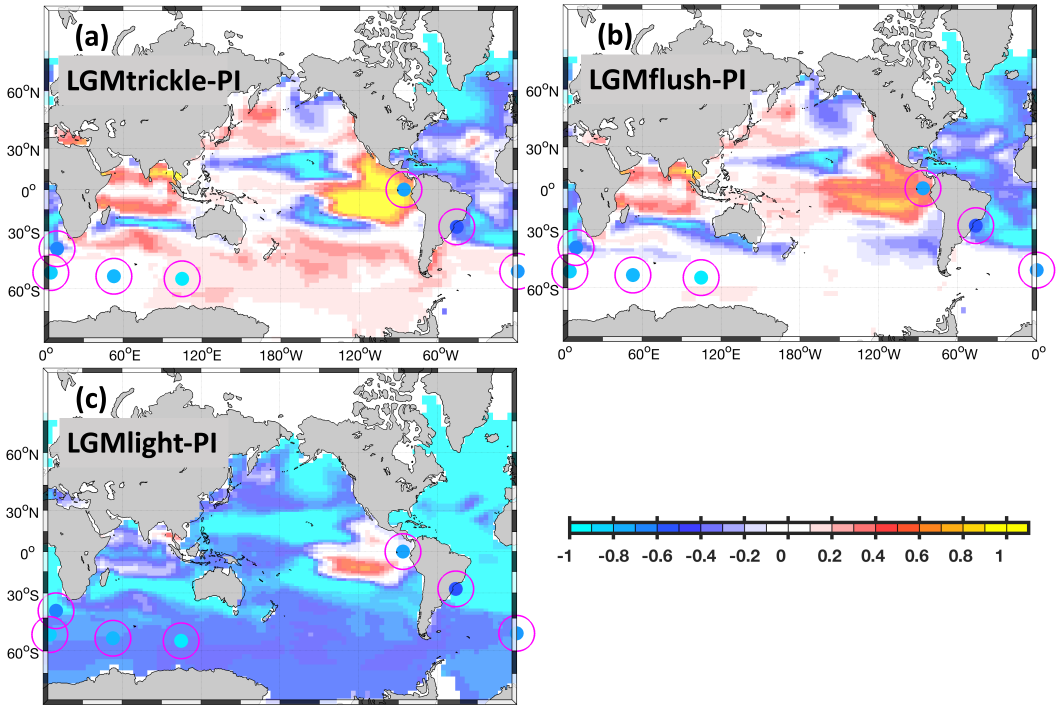
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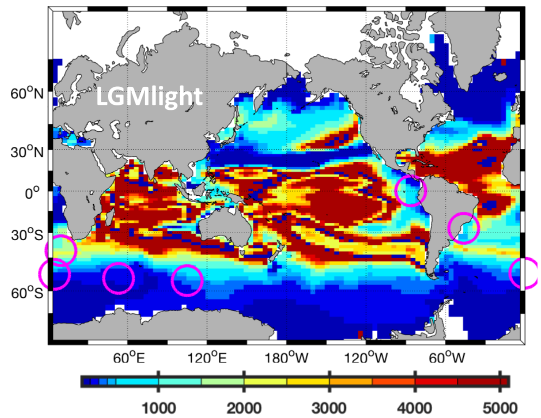

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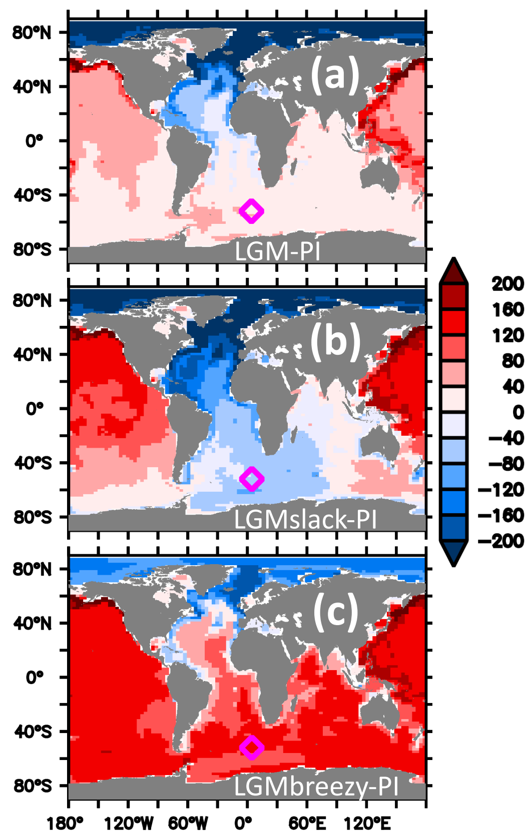

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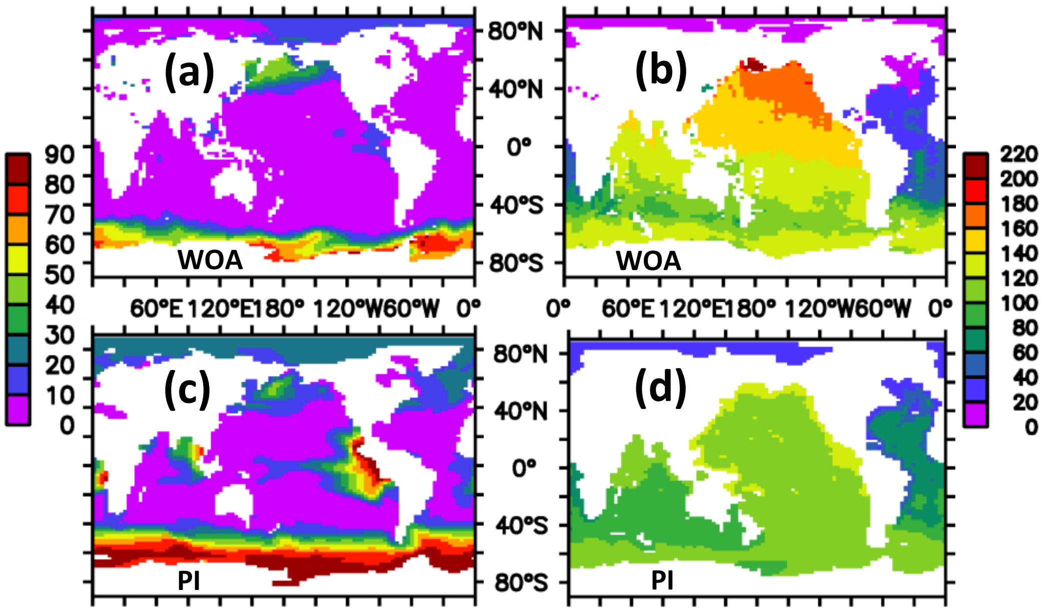

(a)
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WOA
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PI
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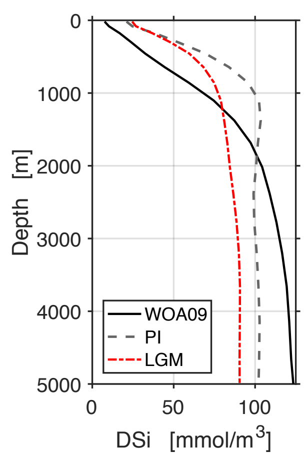

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DSi [mmol/m^3]
WOA09
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LGM
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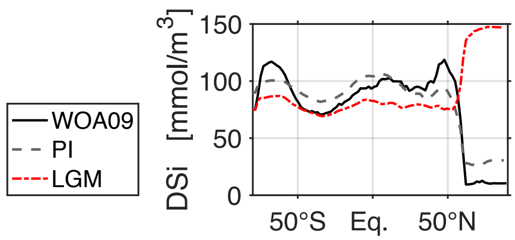
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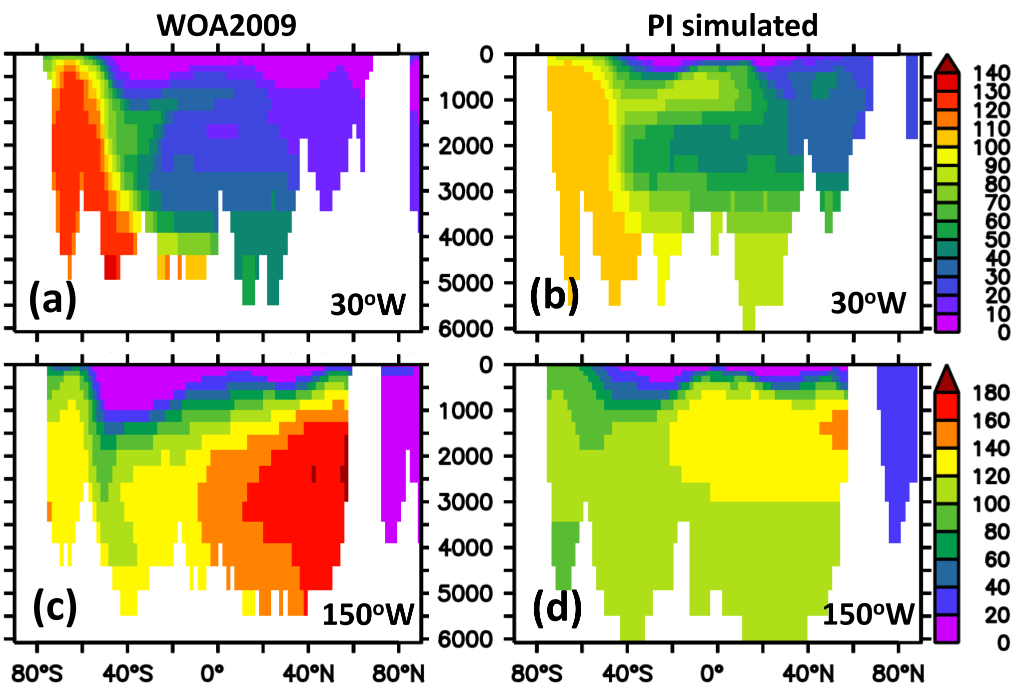
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Figure A.5. Meridional sections over depth (in m) of PO_4 in units mmol Si m^{-3}. Panel (a) and (c) refer to observations (Garcia et al., 2010) and panel (b) and (d) to the preindustrial simulation.

nutrient biased low it seems unlikely that a deficient circulation is the cause for these biases (although this can not be ruled out). This suggests that the SO nutrient trapping relates strongly to the biogeochemical model parameters. One conclusion from this may be that the biogeochemical model is better tuned with respect to phosphate than to DSi. This is to be expected because of the wider use of the phosphate-based biogeochemical model and the much shorter equilibration time scales for phosphate which facilitate the respective tuning to observations. In the Pacific, however, the situation differs, and subsurface maxima in the northern hemisphere (except the Arctic) are too low for both phosphate and DSi. Following our reasoning above this may be indicative for flaws in the ocean circulation module. Please note, however, that the attribution of flaws in model behavior to respective processes is challenging and may even be impossible given the current set of observations (e.g. Löptien and Dietze, 2019).

Table A.1 provides a quantitative estimate of how our DSi/BSi module compares against the underlying biogeochemical and ocean circulation module of Brennan et al. (2012). The simulated temperature variance is overestimated by 3% and the temperature bias is 0.6 K, corresponding to 9% relative to the standard deviation in the observations. The respective bias to standard deviation of salinity is with 0.03 even smaller (5% relative to the standard deviation in the observations). Simulated phosphate concentrations are, surprisingly, even closer to observations than simulated salinities: the bias to standard deviation ratio is smaller (4%) and the simulated variance covers 86% of observed levels (versus 70% for salinity). Given that the salinity distribution directly affects ocean circulation via density driven pressure gradients, it is remarkable that the misfit in this active physical property can be much larger than the misfit of the rather passive (in terms of their effect on circulation) phosphate whose distribution is directly shaped by oceanic circulation. This may be an indication that the biogeochemical mod-

References

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22 25, [illegible] 01010 [illegible] 6 (2005).
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[illegible]
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[illegible]
[illegible] (201) [illegible]

during the Last Glacial Maximum: model-data comparison. Quaternary Science Reviews, 64, 104{120, doi:10.1016/j.quascirev.2012.12.008.

Stoll, H., (2020). 30 years of the iron hypothesis of ice ages. Nature, 578, 370{371, doi:10.1038/d41586-020-00393-x.

Treguer, P., Nelson, D. N., Van Bennekom, A. J., DeMaster, D. J., Leynaert, A., and Queguiner, B., (1995). The Silica Balance in the World Ocean: A Reestimate. Science, 268, 5209, 375{379, doi:10.1126/science.268.5209.375 .

Weaver, A. J., Eby, M., Wiebe, E. C., Bitz, C. M., Du y, P. B., Ewen, T. L., Fanning, A. F., Holland, M. M., Macfadyen, A., Matthews, H. D., Meissner, K. J., Saenko, O., Schmittner, A., Wang, H., and Yoshimori, M., (2001). The UVic Earth System Climate Model: Model description, climatology, and applications to past, present and future climates. Atmosphere-Ocean, 39, 361{428, doi:10.1080/07055900.2001.9649686.

Wischmeyer, A. G., De La Rocha, C., Maier-Reimer, E., and Wolf-Gladrow, D. A., (2003). Control mechanisms for the oceanic distribution of silicon isotopes. Global Biogeochemical Cycles, 17, 3, 1083, doi:10.1029/2002GB002022.