Response to Reviewer #1

GENERAL COMMENTS

This paper describes the changes in the physical climate system as well as the biochemical responses in climate projections with CESM2 extended to 2500 under SSP3-7.0. In this extended scenario, CO_2 emissions increase until 2100, then follow a path of CO_2 emission reductions until 2250 when net-zero emissions of CO_2 are reached. The simulations reach a warming approaching 12°C by ~2300 and stabilise at that temperature by 2500.

The paper is very well written and nicely laid out, and the results are interesting and a nice addition to the literature on multi-century climate projections. It is in some places quite dense to get through, but overall, I recommend publication after minor revisions. The geochemistry sections in particular are a bit difficult to understand in some places for an interdisciplinary / non-specialist readership.

One point that I would like to see briefly commented on, is some context on the relevance of this scenario for future projections and its implications. In e.g. the section on rainfall seasonality changes in megacities, L299 states "potentially resulting in substantial social and economic losses". While this is of course true, I think this is a vast understatement of the situation/problem at +12C and we can no longer talk about "potential losses and impacts" in such a hugely different simulated future. Without looking up an exact definition, and while this is of course subjective and not an exact science, I think people usually consider projected changes >3-4°C as "catastrophic" (if not sooner). 12°C is far beyond that and would likely include fundamental changes to the climate system. How is the reader meant to interpret those projections? A bit of context here would be welcome.

A: We would like to thank the reviewer for their thoughtful evaluation of our manuscript, as well as for their constructive comments and suggestions. We have carefully revised the manuscript to incorporate the suggested improvements. Additionally, we have made every effort to present the content in a clear and accessible manner for readers. As the reviewer notes, most individuals would consider a warming of over 3-4°C to be catastrophic. Our simulations reflect a climate state that has never been experienced by humans, making it challenging to discuss specific impacts and losses. However, we believe our simulations still serve as an important illustration of a potential future that we should strive to avoid. The promotion of assessments of the Earth system evolution under such changes over these timescales is also likely to become one of the CMIP7 protocols, in recognition of the high value of such assessments for informing policy and awareness of the risks and consequences of weak mitigation. Therefore, exploring the potential climate changes and impacts of such a scenario is both useful and necessary as a warning. We also included this point in the revised manuscript.

Our detailed point-by-point replies (in black) to reviewer's comments (in blue) are given below.

SPECIFIC COMMENTS

I include specific comments and requests for clarifications below.

1. L227 "the weakening of the AMOC is related to the southward shift of the ITCZ (references)": the sentence here reads as if the ITCZ shift causes the AMOC weakening, but surely that is not what you mean? Is it the other way around? Do you have any evidence for this other than the references? Please rephrase this sentence to include more details, and perhaps something like "studies have linked this change to …" to indicate this is not something that you have shown here.

A: We thank the reviewer for this comment. Following the reviewer's suggestion, we have rephrased the text in the revised manuscript:

"Additionally, our simulations project a southward shift of the climatological Intertropical Convergence Zone (ITCZ), as part of the coupled climate system response to the AMOC slowdown as indicated by previous studies (e.g., Bellomo et al., 2021; Vellinga and Wood, 2008; Zhang and Delworth, 2005), resulting in substantial precipitation increase along the equator and merging of two tropical precipitation bands. As a result, tropical precipitation zones are projected to become narrower (Lau and Kim, 2015) and the dry regions between the two tropical convergence zones are likely to experience wetter conditions in the post-2100 (Fig. S2a-c, Fig. 3d-f)"

2. L235-236 "In addition to the weakening of the easterlies […], our simulations project a substantial reduction of the trade winds in the extended future […]": isn't a weakening in the easterlies the same as a reduction in the trade winds, so you are repeating the same thing twice? Or is there a difference?

A. We thank the reviewer for pointing this out. We have rephrased the text to clarify the description as follows:

"Our simulations project an overall weakening of the easterlies in the Pacific and Atlantic, spanning approximately 30°S to 30°N, with a substantial reduction along the equator in the Pacific in the extended future. This also reflects the weakening of Walker circulation. These changes are projected to become even more pronounced in the deep future (Fig. 3k, l)."

3. L257, "disappearance of the SPCZ": I think this statement is too strong without further evidence, but the Supplementary Material supports this statement. Can you include a reference to the SI? Figure 3e and f) alone are not enough, as they show the difference relative to the reference climatology, not a new climatology for the later periods.

A: We thank the reviewer for this comment. We have added a reference to the relevant text as well as for Fig. S2b and c regarding future changes in the SPCZ. Additionally, given the issue of model-dependency of SPCZ changes in future projections (Narsey et al., 2022), we have modified the text in the revised manuscript as follows and have made efforts to avoid making overly strong or forceful statements without sufficient evidence:

"One notable feature of the tropical precipitation changes in our extended simulations is the retreat or disappearance of the climatological South Pacific Convergence Zone (SPCZ), which is characterized by a northward shift with loss of its diagonal orientation towards the subtropics relative to the historical climatology (Fig. S2b, c). A comparison between 50-year periods (1950-99 and 2050-99) reveals that several CMIP5 and CMIP6 models show a northward shift of the SPCZ in the future, consistent with our model projections, while others predict a southward shift (Narsey et al., 2022). The equatorward shift and the projected changes in the zonal structure of the SPCZ can be linked to the SST response in the central equatorial Pacific (Cai et al., 2012). Additionally, our simulations project a southward shift of the climatological Intertropical Convergence Zone (ITCZ), as part of the coupled climate system response to the AMOC slowdown as indicated by previous studies (e.g., Bellomo et al., 2021; Vellinga and Wood, 2008; Zhang and Delworth, 2005), resulting in substantial precipitation increase along the equator and merging of two tropical precipitation bands. As a result, tropical precipitation zones are projected to become narrower (Lau and Kim, 2015) and the dry regions between the two tropical convergence zones are likely to experience wetter conditions in the post-2100 (Fig. S2a-c, Fig. 3d-f)."

4. Figure 4h: Title should be precipitation instead of Nino3.4 SST variability (it is the same title as panel d).

A: We have modified the title in the manuscript.

5. E.g. Figure 10: "Fractional changes" typically refer to changes relative to a reference period, e.g. (Extended future – historical)/historical, rather than just a ratio between two periods. Perhaps rephrase to "ratio between Period2/Period1? Also, fractional changes are normally unitless.

A: We thank the reviewer for pointing this out. We have modified the text and the figure caption accordingly in the revised manuscript, as shown here:

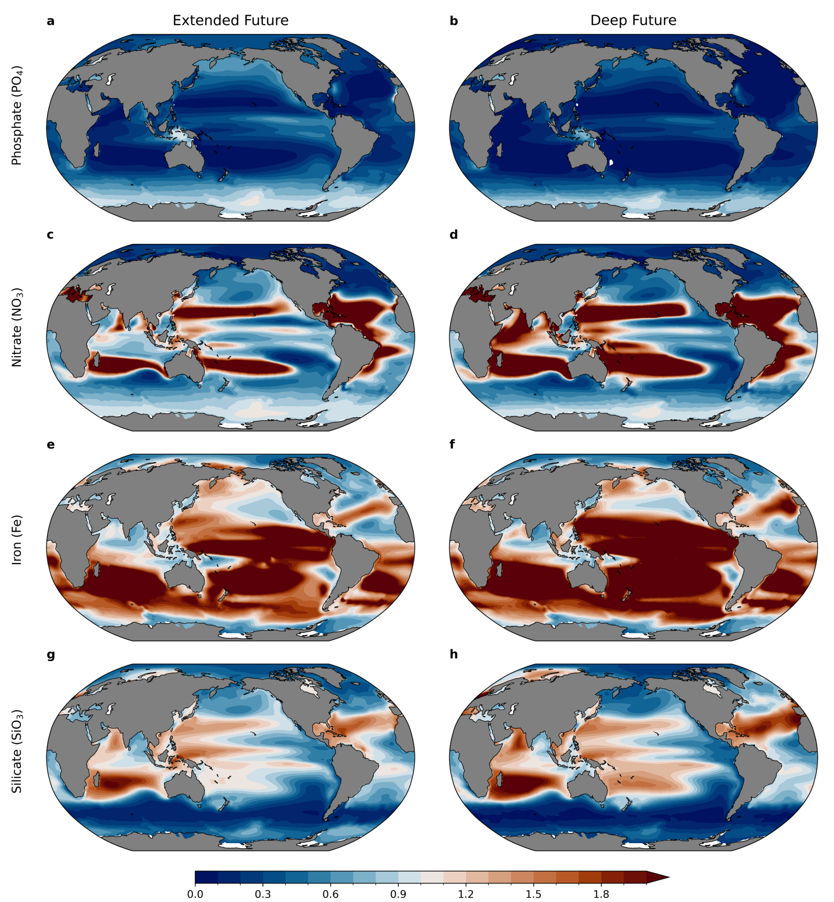

Figure 10: The changes in the future period 2150-2249 (first column) and period 2401-2500 (second column) relative to the historical period 1850-1949. (a, b) PO_4 (mmol m^{-3}), (c, d) NO_3 (mmol m^{-3}), (e, f) Fe (mmol m^{-3}), and (g, h) SiO_3 (mmol m^{-3}). The changes were calculated as the ratio of future to historical period. Blue (<1.0) and red (>1.0) indicate future decreases and increases, respectively, relative to the historical period. All values are averaged over the upper 100 m depth.

6. L339: this should be "availability of food" or "food security", not both.

A: We thank the reviewer for pointing this out, and we have modified the manuscript accordingly ('security' has been deleted).

7. L389-390: I was wondering up to this point whether the simulations were concentration or emissions-driven. Please also include this information in the section describing the simulations.

A: Our simulations are concentration-driven simulations, thus the greenhouse gas concentrations (defined as dry air mole fractions) from historical observations and the SSP3-7.0 scenario were prescribed over the entire simulation period (e.g., regarding CO_2, atmospheric CO_2 mole fraction is specified directly from 1850 to 2500). We have clarified this point in Section 2:

"Meinshausen et al. (2020) provided greenhouse gas concentrations, defined as dry air mole fractions, for both standard and extended SSP scenarios. They used the reduced-complexity climate-carbon-cycle model MAGICC7.0 ('Model for the Assessment of Greenhouse Gas Induced Climate Change') to produce future greenhouse gas concentrations driven by harmonized SSP greenhouse gas emissions (Gidden et al., 2019) and extended emissions beyond 2100. To extend the CESM2-LE from 2101 to 2500, we followed the extended SSP3-7.0 protocol, a concentration-driven configuration. In this extended scenario, fossil and industrial CO_2 emissions are effectively ramped down to zero by 2250 (Meinshausen et al., 2020), as shown in Fig. 1a. Figure 1b presents the time evolution of global mean greenhouse gas mole fractions (CO_2, CH_4, N_2O, and CFCs) which are prescribed in these simulations under the historical (1850-2014), standard SSP3-7.0 (2015-2100) and extended SSP3-7.0 (2101-2500) scenario forcings. The global mean atmospheric CO_2 mole fraction at the end of the 25th century provided by the extended SSP3-7.0 scenario is approximately 1371 ppm."

8. L414: Please be more explicit about the link between NPP and POC export for non-biochemistry specialists. Does export imply a direction (vertical downwards)?

A: We thank the reviewer for pointing out the need to improve the clarity of our explanation in order to be accessible to non-specialists.

"Next, we revisit the approximately 15 % drop in globally integrated marine NPP shown in Fig. 2e. As a substantial fraction of newly produced organic matter is vertically exported below the surface and remineralized into inorganic matter in the ocean's interior - a process known as the biological pump - NPP changes within the euphotic zone propagate into changes in particulate organic carbon (POC) fluxes throughout the water column. In other words, export represents a net downward transport of organic material (typically expressed in carbon mass units) across a depth horizon, with this component of the flux being primarily sustained through gravitational sinking. Primary production is the rate at which organic material is produced from inorganic compounds and does not have a directional component. Given the predominance of recycling within the sunlit surface layers of the ocean, primary production is almost always larger than export. Regionally, ocean NPP increases by up to ~80 % in the Southern Ocean and decreases by up to 50 % in the mid-latitudes of the North Atlantic in the extended future (Fig. 9b). The spatial patterns of NPP change are qualitatively similar to the changes in POC export at a depth of 100 m (Fig. 9e), ….."

9. L453-454 "thermocline PO_4 concentrations": do you mean concentrations above the thermocline? Suggest adding a line highlighting the position of the thermocline to Figure 11.

A: Yes, the text refers to the PO_4 concentrations above the thermocline. We have clarified this in the revised manuscript. In addition, following the reviewer's suggestion, we have added lines representing the depth of the 20°C isotherm averaged over the historical period (1850-1949), the extended future period (2150-2249), and the deep future period (2401-2500) to Fig. 11a in the revised manuscript to represent the position of the thermocline, as shown here:

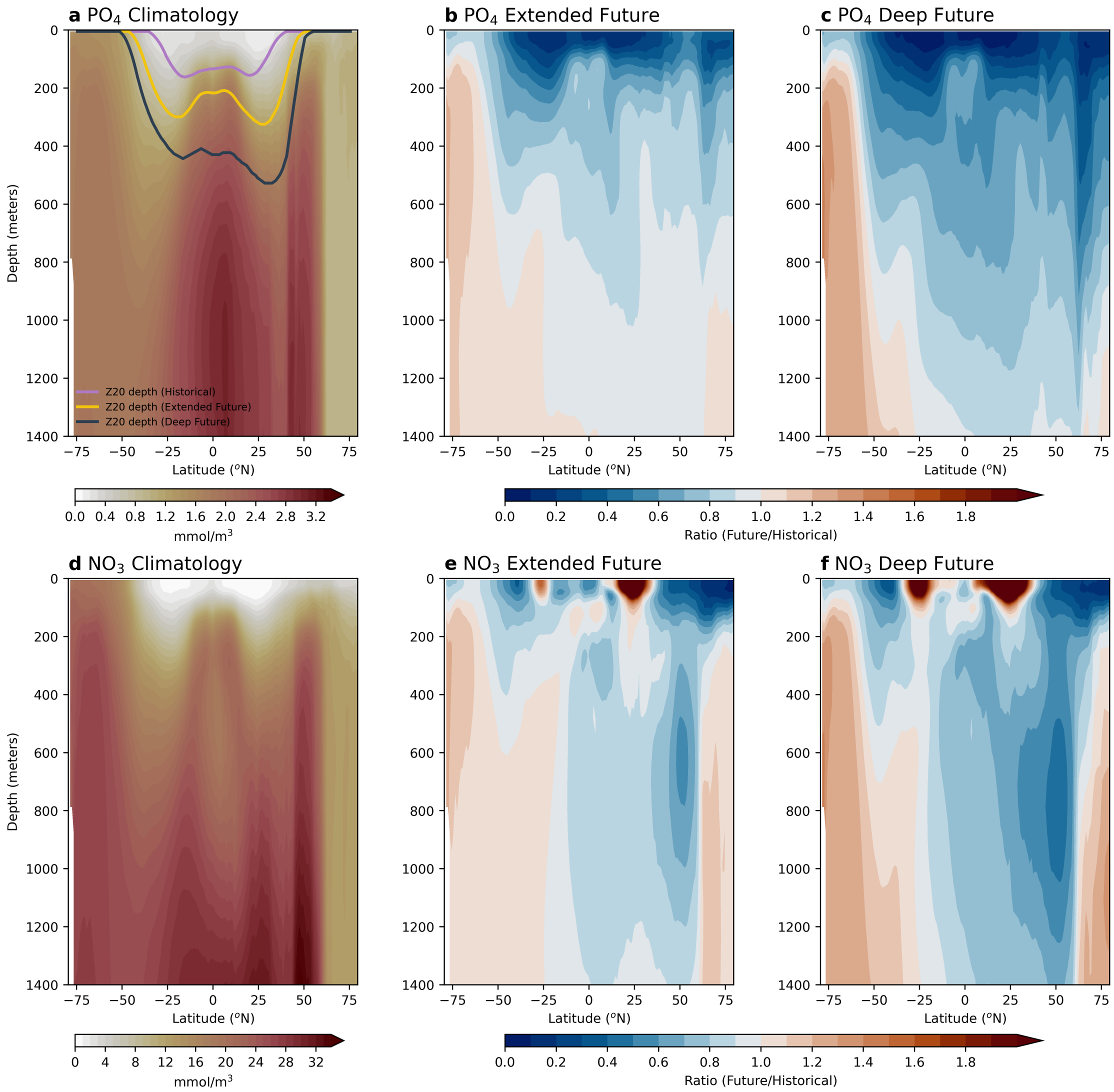

Figure 11: Reference climatology (period 1850-1949) (first column), and changes in the period 2150-2249 (second column) and period 2401-2500 (third column), relative to 1850-1949. (a-c) Zonally averaged PO_4 (mmol m^{-3}) and (d-f) zonally averaged NO_3 (mmol m^{-3}). The changes in b, c, e and f were calculated by dividing the values in the future periods by the values in the period 1850-1949. Blue (<1.0) and red (>1.0) in b, c, e and f indicate future decreases and increases, respectively, relative to the period 1850-1949. In a, pink, yellow, and dark gray lines indicate the depth of 20°C isotherm averaged over the historical period (1850-1949), extended future period (2150-2249), and deep future period (2401-2500), respectively.

10. L462 "Viewed this way": what way? This is unclear – the previous sentence states that the change in the transfer efficiency is modest, yet here you state the changes in the remineralisation source are substantial. Please clarify.

A: We apologize for any confusion. We have added an additional short paragraph:

"For both carbon and PO_4, the transfer efficiency changes only slightly by the end of the 25th

century, stabilizing with a modest increase to a global value of approximately 14 %. The modest simulated increases in transfer efficiency result from decreases in oxygen concentrations within the mesopelagic domain, which reduce the respiration rates of sinking organic particles. Meanwhile, the mesopelagic remineralization source, calculated as the difference between the fluxes at 100 m and 1000 m (rather than their ratio), shows substantial changes in the deep future. By the 2490s, decreases are projected to be 28.4 % for carbon and 36.0 % for PO_4 (Table 2). The substantial decrease in PO_4 is largely due to the increased carbon-to-phosphorus ratios of sinking organic particles under PO_4-depleted future conditions (Kwon et al., 2022), leading to disproportionately larger reductions in sinking particulate organic phosphorus than in sinking particulate organic carbon (Table 2). To understand how the PO_4 budget for the mesopelagic domain evolves, it is important to consider that this largely reflects the cumulative (multi-century) impact of changes in remineralization rates, modulated by perturbations to boundary fluxes across the faces of the low-latitude mesopelagic domain. Although it is beyond the scope of the current study to fully close the budget, the closed budgets presented in Rodgers et al. (2024) for a steady-state case with a different state-of-the-art model suggest that the rates of material exchange of properties (mixing and advection) between the deep ocean and the mesopelagic domain within the tropics can also contribute to modulating low-latitude mesopelagic PO_4 inventories."

11. L468: Are there any explanations for this partial buffering in the case of carbon?

A: In response to the reviewer's comment, we have added an explanation for the partial buffering effect in the revised manuscript:

"Second, the fractional loss in PO_4 remineralization is greater than that for DIC. This characteristic of the plastic stoichiometric relationship between carbon and phosphate in MARBL indicates that the forced changes identified for PO_4 are partially buffered in the case of carbon. The partial buffering effect indicates the way in which the decrease in PO_4 remineralization does not fully translate into a proportional decrease in carbon remineralization. This suggests that while the remineralization of these two elements within the mesopelagic domain is related, it does not follow with a fixed elemental ratio. In other words, the system buffers or dampens the expected changes in carbon fluxes that would have resulted from adherence to a fixed carbon-to-phosphorus ratio (Redfield et al., 1963), mitigating the overall impact of changes in phosphorus fluxes. Third, despite warming of the mesopelagic domain for these simulations, …..”

12. L548: “unprecedented”: there are a handful of studies looking at very long future projections at different global warming levels with fully coupled models, though the experimental design is different. Not a criticism, just mentioning for awareness.

A: We thank the reviewer for their comment. We have rephrased this sentence as follows:

“Our fully coupled simulations, among the most comprehensive in scope for future projections, provide insights into changes in the mean state and variability for key fields across the atmosphere, ocean, sea ice, land, and ecosystems on multi-centennial time scales from 1850 to 2500.”

13. L572-573 “. the stoichiometric plasticity mechanism identified by Kwon et al. (2022) provides only moderate modulation into the deep future.” What is the mechanism identified by Kwon et al.? Moderate modulation of what?

A: We have included a detailed explanation in Section 3.3 and made revisions to the text in Section 4 of the revised manuscript:

- Line 422 in the submitted version:

“The NPP reductions in oligotrophic gyres are also driven by surface nutrient depletion, suggesting that nutrient uptake plasticity – an adaptive strategy used by phytoplankton to reduce nutrient uptake while maintaining carbon fixation (i.e., increasing carbon-to-phosphorus ratios in phytoplankton cells or communities) when surface nutrients are scarce - is less effective beyond the 21st century. This strategy, which plays a key role in sustaining ocean NPP until the 21^{st} century (Kwon et al., 2022), loses its effectiveness in later periods.”

- Line 571 in the submitted version:

“This decrease in PO_4 remineralization leads to substantial surface PO_4 depletion and reduced NPP in subtropical gyres from the 22^{nd} century onward. The projected future changes in nutrient dynamics could affect primary productivity, food webs, and biodiversity in marine ecosystems.”

References

Bellomo, K., Angeloni, M., Corti, S., and von Hardenberg, J.: Future climate change shaped by inter-model differences in Atlantic meridional overturning circulation response, Nature Communications, 12, 3659, 10.1038/s41467-021-24015-w, 2021.

Cai, W., Lengaigne, M., Borlace, S., Collins, M., Cowan, T., McPhaden, M. J., Timmermann, A., Power, S., Brown, J., and Menkes, C.: More extreme swings of the South Pacific convergence zone due to greenhouse warming, Nature, 488, 365-369, 2012.

Gidden, M. J., Riahi, K., Smith, S. J., Fujimori, S., Luderer, G., Kriegler, E., van Vuuren, D. P., van den Berg, M., Feng, L., Klein, D., Calvin, K., Doelman, J. C., Frank, S., Fricko, O., Harmsen, M., Hasegawa, T., Havlik, P., Hilaire, J., Hoesly, R., Horing, J., Popp, A., Stehfest, E., and Takahashi, K.: Global emissions pathways under different socioeconomic scenarios for use in CMIP6: a dataset of harmonized emissions trajectories through the end of the century, Geosci. Model Dev., 12, 1443-1475, 10.5194/gmd-12-1443-2019, 2019.

Kwon, E. Y., Sreeush, M. G., Timmermann, A., Karl, D. M., Church, M. J., Lee, S.-S., and Yamaguchi, R.: Nutrient uptake plasticity in phytoplankton sustains future ocean net primary production, Science Advances, 8, eadd2475, doi:10.1126/sciadv.add2475, 2022.

Lau, W. K. M. and Kim, K.-M.: Robust Hadley Circulation changes and increasing global dryness due to CO₂ warming from CMIP5 model projections, Proceedings of the National Academy of Sciences, 112, 3630-3635, doi:10.1073/pnas.1418682112, 2015.

Meinshausen, M., Nicholls, Z. R. J., Lewis, J., Gidden, M. J., Vogel, E., Freund, M., Beyerle, U., Gessner, C., Nauels, A., Bauer, N., Canadell, J. G., Daniel, J. S., John, A., Krummel, P. B., Luderer, G., Meinshausen, N., Montzka, S. A., Rayner, P. J., Reimann, S., Smith, S. J., van den Berg, M., Velders, G. J. M., Vollmer, M. K., and Wang, R. H. J.: The shared socio-economic pathway (SSP) greenhouse gas concentrations and their extensions to 2500, Geosci. Model Dev., 13, 3571-3605, 10.5194/gmd-13-3571-2020, 2020.

Narsey, S., Brown, J. R., Delage, F., Boschat, G., Grose, M., Colman, R., and Power, S.: Storylines of South Pacific Convergence Zone Changes in a Warmer World, Journal of Climate, 35, 6549-6567, https://doi.org/10.1175/JCLI-D-21-0433.1, 2022.

Redfield, A. C., Ketchum, B. H., and Richards, F. A.: The influence of organisms on the composition of seawater, The sea, 2, 26-77, 1963.

Rodgers, K. B., Aumont, O., Toyama, K., Resplandy, L., Ishii, M., Nakano, T., Sasano, D., Bianchi, D., and Yamaguchi, R.: Low-latitude mesopelagic nutrient recycling controls productivity and export, Nature, 632, 802-807, 10.1038/s41586-024-07779-1, 2024.

Vellinga, M. and Wood, R. A.: Impacts of thermohaline circulation shutdown in the twenty-first century, Climatic Change, 91, 43-63, 2008.

Zhang, R. and Delworth, T. L.: Simulated Tropical Response to a Substantial Weakening of the Atlantic Thermohaline Circulation, Journal of Climate, 18, 1853-1860, https://doi.org/10.1175/JCLI3460.1, 2005.