Review for the manuscript

Asymmetric changes of temperature in the Arctic during the Holocene based on a transient run with the CESM

by Hongyue Zhang et al.

Submitted for publication in Climate of the Past

**General**

The manuscript investigates Arctic temperature changes in an accelerated earth system model (ESM) simulation for the Holocene with CESM. The authors present asymmetric temperature changes between the Pacific and Atlantic parts of the Arctic and attribute those changes to varying pattern of atmospheric circulation and sea ice concentrations. Moreover, authors suggest that those asymmetric changes are especially pronounced in a simulation that is only driven with changes in orbital forcings.

The manuscript is unfortunately not representing the state-of-the-art literature and more important, lacks of simulations that are currently available for the Holocene in a transient sense. Accelerated simulations for the Holocene were expedient because of a lack of computing capacities some 20 years ago. Therefore according conclusions, especially on long term changes such as ocean-related sea ice processes can be afflicted with high uncertainties, also in the context of the interpretation with proxy data.

As such I cannot suggest publication of the manuscript in the present form. Below I list a number of suggestions and more recent studies including non-accelerated simulations that can be used for a substantially revised version of the manuscript.

**Specific**

In the following I will just point to the main concerns and how authors might extent and update their investigations taking into account more recent studies and adapting their hypothesis to more ESM/GCM-relevant questions.

Reply: We appreciate you for your precious time in reviewing our paper and providing valuable and insightful comments. We have carefully considered the comments and tried our best to address every one of them.

Introduction:

The introduction lacks at least one paragraph motivating recent modeling studies over the Holocene, the challenges and implications e.g. of accelerated simulations vs. non-accelerated and the uncertainties involved in reconstructing external drivers (specifically solar and volcanic) for decadal-to-multi- decadal variability (cf. also studies listed as additional references below)

Reply: Thank you for pointing out the potential caveats of the acceleration and uncertainties in our results that were not fully discussed in the previous manuscript. Indeed, it is important to have more discussions on the recent modeling studies and comparisons between accelerated and non-accelerated simulations. For instance, Varma et al. (2012) compared the simulation results with 10 times acceleration and non-acceleration, and found that there is no significant difference in the characteristics of global surface climate change. Timm and Timmermann (2007) used the ECBilt-CLIO model to simulate the climate since the Last Glacial Maximum (LGM) by 10 times acceleration, and compared the simulation results without acceleration and found that the simulation results with 10 times acceleration reproduced well the large-scale trend of atmospheric temperature in the Holocene. Lu et al. (2019) found that the acceleration leads to suppressed and delayed responses mainly in the deep sea and has less robust effect on the surface and subsurface. Jing et al. (2022) compared the temperature and precipitation changes in NNU-Holocene simulation and Trace-21k non-acceleration simulation, and in terms of overall trend and distribution, the temperature and precipitation distribution patterns of NNU and Trace are similar. These and the uncertainties of reconstructing external drivers will give the reader a more complete understanding of the motivation of our study. It should be pointed out that we have focused more on the long-term climate change (linear trend) rather than decadal to multi-decadal timescale changes. Thank you for the additional references. We will add these descriptions in the introduction section.

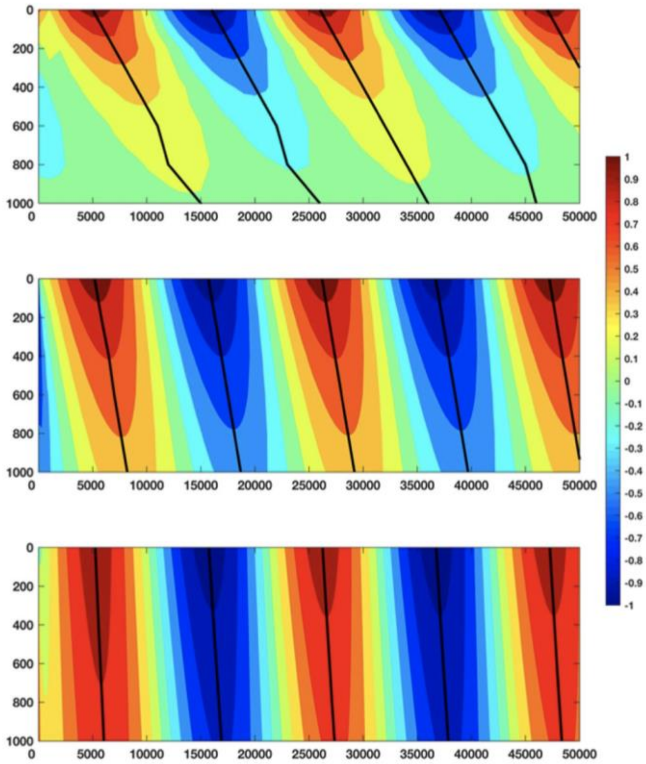


Fig. 12 Time sequence of the vertical temperature profile in a simple diffusion model under three acceleration scenarios: (upper panel) 100-fold acceleration, (middle panel) tenfold acceleration and (bottom panel) non-acceleration. (from Lu et al. 2019)

Another crucial and yet missing part is on the potential drivers giving rise to an asymmetric temperature response. Some mechanisms such as changes in equator-to-pole temperature gradient and/or changes in overall sea ice concentrations are presented. But no hypothesis or guiding question in how those general changes should result in regionally different responses are discussed.

Reply: Thank you for pointing this out. We will add some detailed discussion of the mechanisms on how these potential drivers might lead to the regionally different responses.

2 Method and data

2.1 The CESM model and the transient simulations

ll. 106 ff: The authors describe their acceleration technique, also using changes in solar and volcanic output. I was wondering how those changes, reconstructed on yearly time scales can be implemented in a simulation with an acceleration factor of 10. (e.g. typically more than 2 volcanic eruptions happen per decade). How is this temporal discrepancy between annual reconstructions for accelerated simulations accounted for, also considering the post-volcanic effects on the simulated climate.

Reply: Thank you for your important comments. We aggregate the solar forcing to annual timescale, and then do a 10-year average as the time series of solar forcing used in the simulation is shown in Figure below (Wan et al. 2020). For the volcanic forcing, the volcanic events during the 10-year period were integrated into one volcanic eruption event. On the basis of this assumption, the horizontal diffusion of lower stratospheric aerosols was calculated using the stratospheric transport parameters. Based on the stratospheric-tropospheric folding and BD (Brewer Dobson) circulation theory latitude- and time-dependent functions to describe aerosol production and deposition (Grieser J et al.1999; Holton J et al. 1995). The details of the modelling methods will be added to the revised manuscript. Because we focus on long-time-scale changes, and volcanic eruptions are found to have a smaller impact on climate than orbital forcing. Therefore, we mainly investigate the orbital forcing effects in All forcing simulation and ORB simulation.

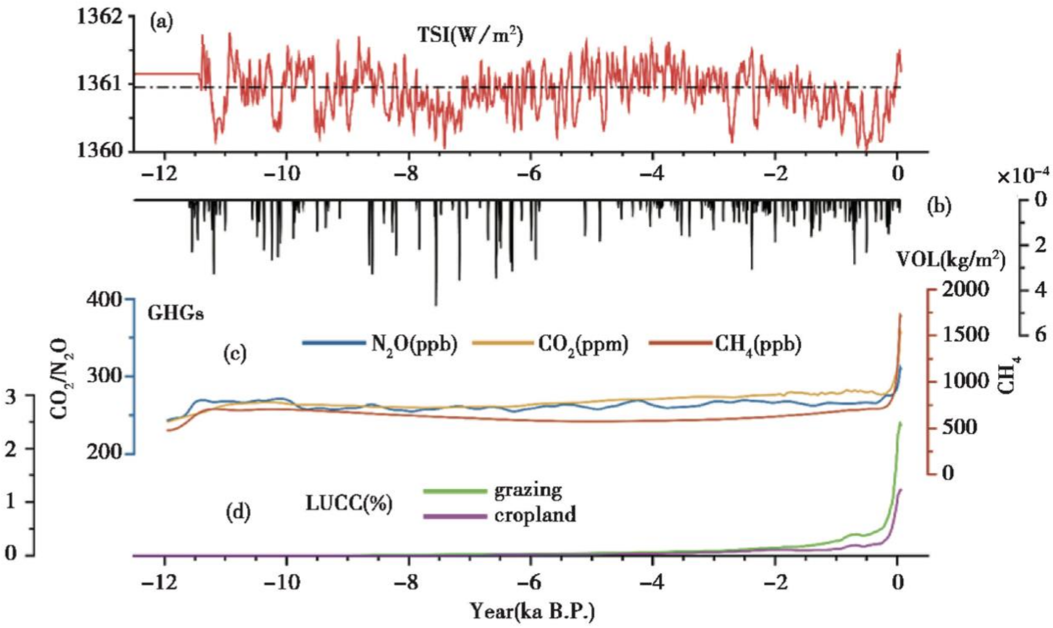



Fig. 1 The external forcing timeseries used in the NNU-Hol simulation. The TSI VOL, GHG and LUCC are a b c and d respectively (Wan et al.2020)

ll. 116 ff: There are new, and non-accelerated comprehensive Earth System model simulations available (cf. references) that should be used as additional source of information to back-up results based on the accelerated simulations with CESM.

Reply: Thank you for your comments and suggestions. We found that similar temperature asymmetry changes also exists in the Arctic region based on the results of Trace-21k non-acceleration simulation. We will consider to add the Trace results to the manuscript.

Another general comment relates to the questions why the authors did not at least use an ensemble approach for their simulations to estimate the amount of long-term (centennial-to-millennial scale) climate variability.

Reply: Thank you for your comments and suggestions. Unfortunately, the main restriction is because of limited computing resources. For our long-term (12ka) climate simulations, with multiple forcings applied, we employ the acceleration technique, and each simulation has only one member.

2.2 Reconstructing Paleo Proxy data

This paragraph just lists the proxy data sets used for comparison without any information on potential uncertainties involved in the reconstructions, e.g. related to the uncertainties in the proxy archives towards their meteorological/climate variables, dating uncertainties, regional sparseness of proxy data, especially in the Arctic domain.

Reply: Thank you for your comments and suggestions. We will revise the manuscript to add a part of the uncertainty description. It should be noted that the uncertainty of the reconstruction has already been discussed in Kaufman et al. (2020). Since this is not the main focus of our study, we did not discuss the uncertainties in the proxy results in details.

Since the authors investigate changes in ocean-related sea ice variability, also a paragraph on proxies representing changes in sea-ice concentrations including their uncertainties would be helpful.

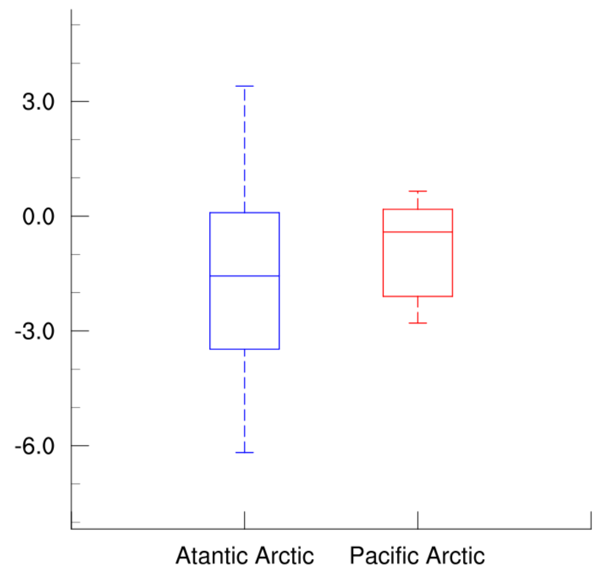
Reply: Thank you for your comments and suggestions. We haven't included the proxies of sea ice yet. It's a good suggestion, we will look for some relevant sea ice reconstructions and compare with our model results.

3. Result

3.1 Arctic temperature change

ll. 152 ff: How robust are the temperature changes? Are they statistically significantly different to internal changes. Therefore, applying a statistical test is helpful to estimate the amount of internal variability between the two different periods, preferentially taking into account the serial correlations within the proxy-based estimations of temperature variability.

Reply: Thank you for your comments and suggestions. We used box figure (see below) as well as t-tests to help estimate the amount of internal variability between the two different periods. Due to the small sample size of the Pacific Arctic reconstruction data, the temperature changes are only showing significance ($p<0.10$) on t-test.



ll. 172 ff: How significant are the changes between the Arctic and the Pacific region ? (i.e. -0.67 vs. +0.09.) Especially the Pacific trend seems to be statistically indistinguishable from a zero trend).

Reply: Thank you for your comments and suggestions. The t-test suggests the temperature changes in two region are significant ($p<0.01$). For winter temperature change it seems to be statistically indistinguishable from a zero trend, but for annual average or summer, there is a significant cooling.

ll. 191 ff: Also for the model-based differences of the sea ice a local statistical test on the spatial pattern including the effect of serial correlation is important to test the robustness and statistical significance of the according changes.

Reply: Thank you for your comments and suggestions. We will modify the figure and perform spatial significance test for the figure of sea ice change.

ll. 202 ff: Changes in atmospheric circulation are also influenced to a high degree to internal variability – as such it is very important to use additional model simulations to back-up those changes, resulting from the CESM accelerated simulation. Moreover, why are the results of the orbital simulation are "more significant" than the one for the all forcings ? On Holocene time scales changes in orbital forcing on seasonal time scales exert a larger impact than the decadal-and sub-decadal changes caused by solar and volcanic activity. Therefore it is important to describe in greater detail how changes in solar and volcanic forcings are implemented into the accelerated CESM simulation.

Reply: Thank you for your comments and suggestions. As mentioned above, the difference between acceleration and non-acceleration simulation is the dampened and delayed response to external forcings in the deep ocean for the latter. There should be no big differences for the atmospheric circulation and surface climate response. We will consider to add some results of other non-accelerated simulations (e.g. Trace-21k). Orbital forcing as the most obvious driver of long-term trend changes during the Holocene. Volcanic and TSI forcing have less impacts on long-term trends, and their role is more dominant on shorter timescales such as decadal and multi- decadal scale. However, the aim of our study is not to focus on these shorter timescales, so our analyses focus on orbital forcing and All forcing simulations.

3.3 EOF of SLP and UV wind regression and 3.4 The connection between Arctic dipole pattern and PDO

The whole sections lack a more thorough motivation on i) how the statistical concepts are used/defined and the ii) the robustness and statistical significance of the according regression patterns between the PCs and the underlying wind/sea ice fields. For instance, the PCs presented in Fig. 6 are (obviously) filtered with a low-pass filter. This should be accounted for when discussing and presenting the results.

Reply: Thank you for your comments and suggestions. We will add more statistical tests. As the PCs presented in Fig. 6, you're right, it's filtered. We will clarify the filter we used in the revised manuscript.

Further, in addition to the UV regression, a Canonical correlation analysis would be better suited for this kind of investigation in section 3.3, since the rationale is to compare the common behavior of patterns (in this case the spatially resolved SLP and wind/sea ice fields.)

Reply: Thank you for your comments and suggestions. We will try the Canonical correlation analysis methods to compare with that.

A last point is again on the validity and model-dependence of the results based only on the accelerated simulation with CESM. This is in my opinion the weakest but most crucial point of the study.

Reply: Thank you for your comments and suggestions. As mentioned before, we will add some describing the validation of CESM simulations and analyze some results of unaccelerated simulations, but the main focus will remain on the CESM results.

4. Discussion

l. 291: Authors should formulate more nuanced that in this very version of the manuscript, results only apply to their few accelerated simulations with CESM that need to be compared with more recent, non-accelerated studies.

Reply: Thank you for your comments and suggestions. We will add a comparison with more recent, non-accelerated studies.

l. 293: How should GHG changes, only changing very moderately in the pre-industrial period of the Holocene counteract any changes in orbital forcing ? If any, volcanic (and maybe in parts) negative periods of solar activity could counteract the negative trend in orbital forcing during the JJA season over the Arctic.

Reply: Thank you for your comments and suggestions. We will revise this statement. We mean that the orbital simulation shows stronger asymmetric changes compare to the All forcing simulation. This implies that the combined effect of other forcings (solar irradiance, volcanic eruptions, greenhouse gases, and land use/land cover) and internal climate variability is offsetting this asymmetric changes (as opposite to the orital forcing). The contribution of different forcings is what we will need to study in the future. The reason why we mention "e.g. GHG" is that in future climate change, the GHG is an important factor that cannot be ignored. We will revise this paragraph to make it more clearly.

l. 284: The authors state that additional simulations should be used for investigations. Since those simulations are yet available authors should use them as an integral part of their revised study and thoroughly test their hypotheses with non-accelerated simulations and those carried out with different CMIP4-types of models.

Reply: Thank you for your comments and suggestions. We will add a comparison with more recent, non-accelerated studies.

Figures:

Fig 3.1: How does the Proxy (z-score) and the Model (°C) compare on the same axis ? In my opinion it would be necessary to show both on the same scale for an appropriate comparison.

Reply: Thank you for your comments and suggestions. We've modified it.

Fig. 5: Please use units of hPa when presenting changes of sea level pressure fields.

Reply: Thank you for your comments and suggestions. We've modified it.

Fig 6, 9a and 10a: In this form of the presentation, the EOF pattern seem to carry normalized values (i.e. z-scores). In order to re-normalize the EOFs (i.e. eigenvectors), the patterns should be multiplied with the square root of their eigenvalue. Then the EOF patterns carry the units (in this case Pa(hPa) for SLP and K for SSTs, respectively). Eventually the according (original) PCs should be divided by the square root of the eigenvalue in order to show consistent patterns between EOFs and PCs. In addition, the temporal filtering should be indicated for the time series.

Reply: Thank you for your comments and suggestions. We will modified it.

Additional references / State-of-the art Holocene ESM simulations:

Transient Holocene simulation (6ka BP - 2ka BP) with interactive vegetation and phenology: https://vesg.ipsl.upmc.fr/thredds/catalog/work/p86mart/IPSLCM6/PROD/Holocene/TR6AV-Sr02/catalog.html

Braconnot, P., Zhu, D., Marti, O. and Servonnat, J.: Strengths and challenges for transient Mid- to Late Holocene simulations with dynamical vegetation, Clim. Past, 15(3), 997–1024, doi:10.5194/cp-15-997-2019, 2019

Braconnot, P., Marti, O., Crétat, J., Zhu, D., Sanogo, S., Balkanski, Y., Caubel, A., Cozic, A., Foujols, M.-A. and Servonnat, J.: Transient simulations of the last 6000 years with the IPSL model, in PMIP Workshop group P2FVAR., 2019.

Bader, J., Jungclaus, J., Krivova, N., Lorenz, S., Maycock, A., Raddatz, T., Schmidt, H., Toohey, M., Wu, C.-J. & Claussen, M., 2020: Global temperature modes shed light on the Holocene temperature conundrum. Nature Communications, 11: 4726. doi:10.1038/s41467-020-18478-6.

Dallmeyer, A., Claussen, M., Lorenz, S. J., Sigl, M., Toohey, M., and Herzschuh, U.: Holocene vegetation transitions and their climatic drivers in MPI-ESM1.2, Clim. Past Discuss. Clim. Past, 17, 2481–2513, https://doi.org/10.5194/cp-17-2481-2021, 2021.

New References:

Varma V, Prange M, Merkel U, et al. Holocene evolution of the Southern Hemisphere westerly winds in transient simulations with global climate models[J]. Climate of the Past, 2012, 8(2): 391-402.

Timm O, Timmerman A (2007) Simulation fo the last 21000 years using accelerated transient boundary conditions*. J Clim 20(17):4377–4401

Lu, Z., Liu, Z. Orbital modulation of ENSO seasonal phase locking. Clim Dyn 52, 4329–4350 (2019). https://doi.org/10.1007/s00382-018-4382-1

Jing Y, Liu J, Wan L. Comparison of climate responses to orbital forcing at different latitudes during the Holocene[J]. Quaternary International, 2022, 622: 65-76.

Holton J R, Haynes P H, McIntyre M E, et al. Stratosphere-troposphere exchange[J]. Reviews of geophysics, 1995, 33(4): 403-439.

GRIESER J, SCHONWIESE C D. Parameterization of spatio-temporal patterns of volcanic aerosol induced stratospheric optical depth and its climate radiative forcing[J]. Atmósfera, 1999, 12(2).