Point to point response to reviewers' comments

The comments are in blue, and our responses are in black.

Response to Reviewer 1:

Comments from Reviewer 1

This paper is a contribution to the special issue dedicated to PLIOMIP2. The authors describe the core simulations performed by 2 different versions of NORESM model.

The paper is well written and illustrated.

It fits the goal of the PLIOMIP2 special issue which is to describe the different model simulations. This manuscript is devoted to the comparison of two different versions of NorESM GCM in the common framework of PLIOMIP2 boundary conditions. In addition, for one of the model versions only, the authors provide the comparison between PLIOMIP1&2 configurations.

My general conclusion is that the study is appropriate for publication in Climate of the Past special issue after the authors answer some comments I raised below. More importantly, the authors have to clarify the inconsistency between numbers in the text and Table 3 and Fig. 1 of the paper concerning SAT. The latter mainly concern the description of what they expect from the comparison of both versions within the PLIOMIP2 framework and a more detailed discussion over northern hemisphere responses of both model versions.

We apologize for the confusion of Northern and Southern hemispheres in the text. The numbers in tables 3 and 5 are right. We have corrected the related numbers in the text in the revised version. Further, we modified the description of the statistics in table 3 and 5 with order from the Northern pole to the Southern pole.

We thank the reviewer for the thorough assessment and constructive comments on our manuscript. We respond to the reviewer's comments below.

Specific comments

- Abstract

1 The results concerning SAT and SST anomalies between mid-Pliocene and preindustrial depict a very large warming of more than 3 ° on the continents at global scale. Here the terrestrial warming is nearly twice as large as the ocean one. The authors should maybe emphasize on this large contrast between continent and ocean. Is this sensitivity of the warming between oceans and continents consistent with IPCCRCP simulations using NorESM versions results for ocean and land contrast?

Revised. We emphasized the warming contrast between continent and ocean in both abstract and result. In the revised manuscript, we added text of "with a greater warming over land than over ocean" in the abstract (Page 1, Line 23–24 in the manuscript with the revisions marked).

We also added sentences in Section 4.1: "Both NorESM1-F and NorESM-L simulate stronger warming over land than over ocean. Relative to the pre-industrial period, the simulated Pliocene global mean surface air temperature (SAT) over land increases by 2.3 °C with NorESM-L and 2.0 °C with NorESM1-F, which is notably larger than the warming over ocean (2.0 °C and 1.6 °C for the NorESM-L and the NorESM1-F, respectively). This stronger warming over land is a common feature in most the PlioMIP2 simulations. However, the simulated zonal mean SAT over land is nearly twice as large as in the ocean at the northern high latitudes (Fig. S1).".

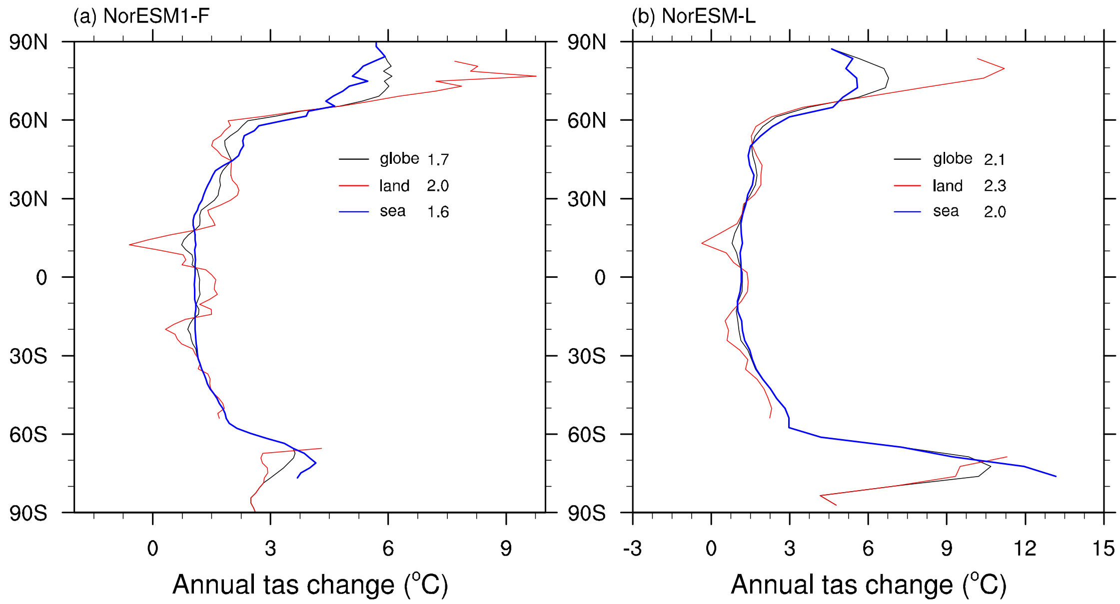

Fig. S1. The zonal mean of the difference in climatological annual mean surface air temperatures (units: °C) between Pliocene and pre-industrial experiments according to NorESM1-F (left panel) and NorESM-L (right panel). The black, red, and blue lines represent values over globe, land, and ocean, respectively.

The warming sensitivity between the oceans and the continents in the Pliocene simulation is consistent with that found in RCP2.6 and RCP8.5 simulations with NorESM1-M (see Figure 8 in Iversen et al., 2013).

2 The authors should if possible give the major differences between both versions to better understand the large sensitivity to the AMOC.

Revised.

We added the following sentences in the abstract: "NorESM1-M is the version of NorESM that contributed to the Coupled Model Intercomparison Project Phase 5 (CMIP5). NorESM-L is the low-resolution of NorESM1-M, whereas NorESM1-F is a computationally efficient version of NorESM1-M, with similar resolutions and updated physics. Relative to NorESM1-M, there are notable improvements in simulating the strength of the AMOC and the distribution of sea ice in NorESM1-F, partly due to the updated ocean physics.” (Page 1, Line 18–22 in the manuscript with the revisions marked.)

3 The intensification of the water cycle in a warmer climate (Clausius-Clapeyron relationship for global scale) is expected but more importantly, we would like to know whether regional patterns of precipitations are similar or not.

Revised.

We added and re-organized some sentences in the abstract: “The simulated precipitation for the Pliocene increases by 0.14 mm day^{-1} globally in both model versions, with large increases in the tropics and especially in the monsoon regions and only minor changes, or even slight decreases, in subtropical regions. The intertropical convergence zone (ITCZ) shifts northward in the Atlantic and Africa in boreal summer.” (Page 1, Line 26–28 and Page 2, Line 1–2 in the manuscript with the revisions marked.)

The abstract should briefly clarify these points.

Revised. Thanks for these suggestions.

- Section 1: Introduction

The introduction is excellent for me, summarizing the evolution of the PLIOMIP project and the contribution of the NORESM group.

We thank the reviewer for the positive remarks.

- Section 2: Model description

This section needs some improvements so that the reader may understand better the results section.

1. We need to know a bit deeper in the main text which modifications have been done in version 1-F and if they provided improvements for the preindustrial control run. Are they related with a better spatial resolution or related to the hydrologic cycle simulations?

2. What do the authors expect using the version 1-F for PLIOMIP2 with respect to what they already obtained in the previous standard (L) version? I agree that the authors referred to the paper by Guo et al (2019) for a detailed description, but we need a minimum of details for better understanding of the results described in the next section.

We add some more details about NorESM1-F in section 2 in the revised manuscript.

Compared to NorESM1-M, NorESM1-F takes some measures to improve computational performance, employs several physical updates and parameterization modifications in ocean and atmosphere components.

Paleoclimate simulations with coupled model, e.g., NorESM-L, often require thousands of years’ integration to reach equilibrium, usually at the expense of resolution to save computational resources. Compared to NorESM-L, NorESM1-F has several advantages in paleoclimate modelling, such as the higher resolution, faster running speed, and several improvements, such as more realistic AMOC, sea ice distribution and hydrological cycle.

Section 3: Experimental design

Why the spin up procedure is different for version 1-F?

Before we ran the Pliocene experiment with NorESM1-F, there was one previous simulation with atmosphere CO_2 set at 400 ppmv spin-up for 2000 years using NorESM1-F (Figure Sketch). In this spin-up experiment, the topography was not changed to the PlioMIP2 conditions. Initialized from this experiment, the Pliocene experiment with NorESM1-F is integrated for another 500 years long. 500-year is the minimum integration length for PlioMIP2 simulation (Haywood et al., 2016).

We added the details about the initialization of ocean model in Table 2 in the revised manuscript.

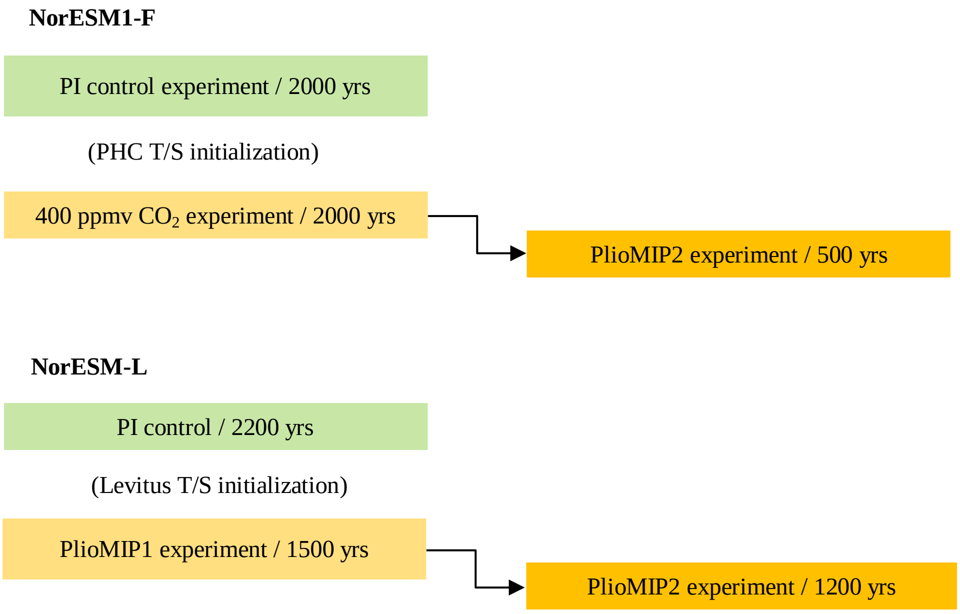

Figure Sketch for NorESM1-F and NorESM-L experiments flow.

Section 4: Results

- Section 4.1 Temperature

Superimposed to a zonal description, it would be interesting to discuss the result in terms of land/ocean.

Revised. Please see our previous response to the reviewer's specific comment regarding the warming contrast between continent and ocean.

The authors write: "The simulated Pliocene annual mean SAT increases by 3.2°C (NorESM1-F) and 7.6°C (NorESM-L) at the northern high latitudes and by 5.2°C (NorESM1-F) and 4.9°C (NorESM-L) at the Southern high latitudes."

This is totally inconsistent with fig. 1 and Table 3. It may be possible that the authors confused Norther and Southern hemisphere in the text. Anyway, it is crucial to clarify this point. If you believe the text, there is a large warming over the NH for both versions, but the enhancement is much larger especially for NorESM L. It should be discussed as well as the enhanced seasonal cycle which is certainly largely responsible for the seasonal sea ice behavior in the warmer L version.

We apologize for the confusion of Northern and Southern hemispheres in the text. The numbers in tables 3 and 5 are right. We have corrected the related numbers in the text in the revised version. Further, we modified the description of the statistics in table 3 and 5 with order from the Northern pole to the Southern pole, following the other reviewer's suggestion.

We add the discussion on the seasonal warming and sea ice reduction in section 5.1. We have re-organized the related sentences as: "On the one hand, the larger seasonal warming in the Southern Ocean favors less sea ice extent in the Pliocene experiment simulated with NorESM-L. On the other hand, the presence of less sea ice, leads to a reduction in albedo and to a more active ocean-atmosphere interaction, and contributes to the higher levels of Southern Ocean warming in the Pliocene experiment simulated with NorESM-L." (Page 9, Line 13–17 in the manuscript with the revisions marked).

- Section 4.3 :SST

The version 1-F depicts a smaller global warming, but a larger one at high latitude of northern hemisphere compared to the L version. It would be interesting superimposed to the analysis which is already provided for the southern Hemisphere to add as a new section in part 5 a similar discussion concerning northern hemisphere to investigate why 1-F version is depicting a weaker response most over the globe except over mid to high latitudes of northern hemisphere. The different behavior of the two versions in north and south hemispheres should be emphasized.

We added one paragraph to discuss the warming dissimilarities of the two NorESM versions at the northern middle and high latitudes in section 5.1. Please see Section 5.1 in revised manuscript.

- Section 4.4 Salinity

Large differences on salinity are depicted between both versions. This result needs to be analyzed and understood at global scale and not only for the southern hemisphere. This also points towards a new subsection in the discussion focused on Northern hemisphere.

In our experimental flow (Figure Sketch), there are divergent responses in global mean sea surface salinity (SSS) in PlioMIP2 experiment with NorESM1-F and NorESM-L. There is a slight positive shift in global mean SSS in the NorESM-L simulation, and a negative shift in global mean SSS in the NorESM1-F simulation (Note the mean value in Fig. 4). The divergent responses are likely associated with the different vertical redistribution of salt in the two models, due to differences in e.g. surface layer mixing, ocean ventilation, convection and circulation. The two models have different vertical resolutions and horizontal/vertical mixing schemes, which makes it difficult to disentangle the factors causing the contrasting salinity responses.

However, when the shift in global mean SSS is removed, NorESM-L and NorESM1-F show similar regional anomalies. Both versions show that the Both versions show that the SSS contrast among the Indian Ocean, the Arctic and the rest of the oceans is intensified in the Pliocene experiment (Fig. S2). We added those in Section 4.4 in the manuscript with the revisions marked.

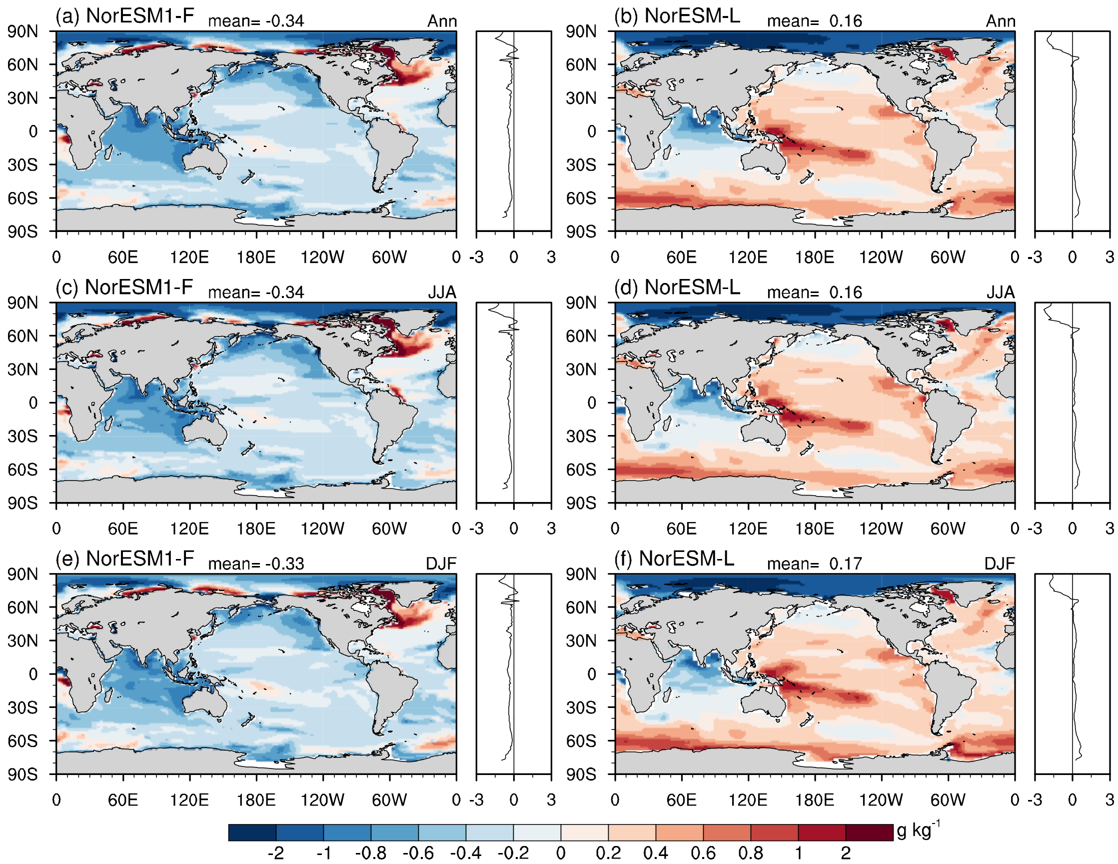

Fig. 4. The difference in climatological sea surface salinity (units: g kg^{-1}) between Pliocene and pre-industrial experiments according to NorESM1-F (left panel) and NorESM-L (right panel) for the annual mean (a and b), boreal summer (c and d), and boreal winter (e and f). The zonal mean is shown to the right of each plot.

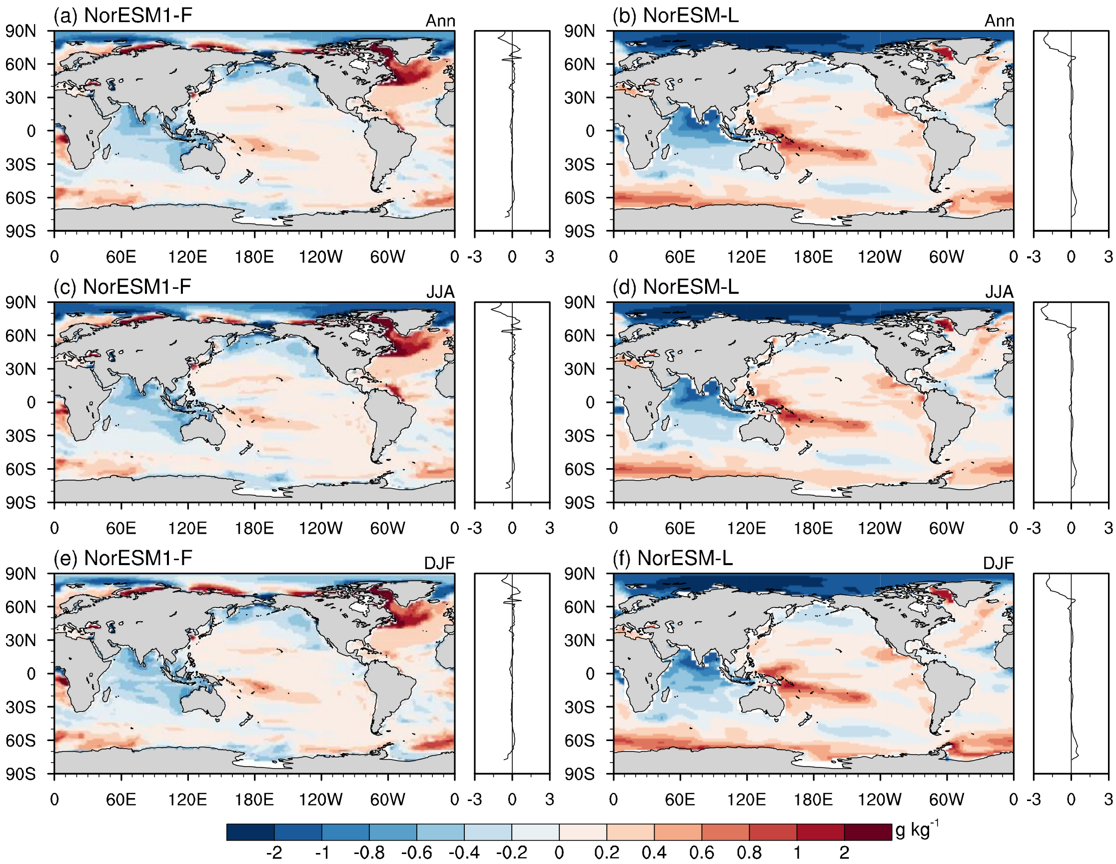

Fig. S2. Same as Figure 1, but for each grid, the global mean shift is excluded to emphasize the response of the sea surface salinity contrast between ocean basins in the Pliocene experiment.

Apparently, the sea surface salinity increase in the Atlantic is larger with NorESM1-F than in NorESM-L. We added sentences in Section 5.1: "In associated with the larger salinity increase in the northern North Atlantic (Fig. 4), the enhancement of AMOC is larger with NorESM1-F than with NorESM-L (~15% vs. ~9%), which favors the larger responses in the Pliocene northward ocean heat transport to the Atlantic with NorESM1-F (Figs. 6 and 7)." (Page 10, Line 12–15 in manuscript with the revisions marked).

- Section 4.5: Sea ice

An important result concerns the summer arctic sea ice especially with regard to future climate. It could be interesting, in the discussion, to add more details on the causes of these differences.

We added the discussion about sea ice in the Section 5.1.

For instance we re-organized some sentences in Section 5.1: "Simulated Pliocene southward ocean heat transport to the Southern Ocean is reduced according to NorESM1-F, but increased according to NorESM-L (Fig. 7), which partly explains the reduction in the Southern Ocean sea ice extent being more pronounced for NorESM-L than it is according to NorESM1-F (Fig. 5) (Page 9, Line 12–15 in the manuscript with the revisions marked)."

We also added the following sentences in Section 5.1: “The stronger Pliocene warming at the northern high latitudes is most likely related to the mechanism responsible for the larger responses in sea ice reduction with NorESM1-F, since the clear sky albedo, particularly in sea ice regions, dominates the high latitudes warming in Pliocene (Hill et al., 2014). In associated with the larger salinity increase in the northern North Atlantic (Fig. 4), the enhancement of AMOC is larger with NorESM1-F than with NorESM-L (~15% vs. ~9%), which favors the larger increase in the Pliocene northward ocean heat transport to the Atlantic with NorESM1-F (Figs. 6 and 7). Correspondingly, the less sea ice simulated in the Pliocene experiment contributes to a larger warming at the high latitudes with NorESM1-F than with NorESM-L through the ice-albedo feedback (Figs. 1 and 3).” (Page 10, Line 5–13 in the manuscript with the revisions marked).

- Section 5: Discussion

This part includes 2 sections. The first one could be improved and enlarged because it deals mainly with the Southern Hemisphere.

In the discussion section, the part concerning south hemisphere salinity difference and its relation with ocean dynamics and sea ice is appropriate but we expect a bit more discussion on topics I raised above, especially on differences between both versions on NH high latitudes for land and sea thermal contrast and arctic sea ice and AMOC/PMOC responses.

In Section 5.1, we added a discussion about the difference in the simulated Pliocene warming at the northern middle and high latitudes. Here, we discussed the ocean heat transport, sea ice, AMOC, and salinity change. Please see Section 5.1 in the manuscript with the revisions marked.

The land sea thermal contrast is not discussed here since both versions simulate similar land/sea thermal contrasts in terms of zonal means (Fig. S1). We already added a related description of the land sea thermal contrast in Section 4.1. Please see Page 6, Line 14–20 in the manuscript with the revisions marked.

The second part of the discussion raises an important point on sensitivity of different models to the closure of seaways and the authors should point out also in their conclusions that these new results, because they are different from the previous synthesis provided by Shang for PLIOMIP1, could certainly be an important focus of the future intercomparison within PLIOMIP2 project.

Revised. In the conclusions, we added the following sentence: “The model–dependent sensitivity to the closure of the ocean gateways in the northern high latitudes will be an interesting question that is worth further attention within the PlioMIP2 community.”. (Page 12, Line 5–7 in the manuscript with the revisions marked).

Figures and Tables: The numbers in Table 3 are compatible with Fig. 1, but the text is not constituent with them. Concerning Table 3 and section 4.3 (SST), it is difficult to know from the table if the numbers in the text are correct.

We confused the Northern and Southern hemispheres in the text. The numbers in tables 3 and 5 are right. In the revised version, we modified the description of the statistics in table 3 and 5 with order from the Northern pole to the Southern pole.

Revised. Please see Tables 3 and 5.

Referrences

Guo, C., Bentsen, M., Bethke, I., Ilicak, M., Tjiputra, J., Toniazzo, T., Schwinger, J., and Otterå, O.H.: Description and evaluation of NorESM1-F: a fast version of the Norwegian Earth System Model (NorESM). Geosci. Model Dev. 12, 343–362, 2019.

Haywood, A.M., Dowsett, H.J., Dolan, A.M., Rowley, D., Abe-Ouchi, A., Otto-Bliesner, B., Chandler, M.A., Hunter, S.J., Lunt, D.J., Pound, M., and Salzmann, U.: The Pliocene Model Intercomparison Project (PlioMIP) Phase 2: scientific objectives and experimental design. Clim. Past 12, 663–675, 2016.

Iversen, T., Bentsen, M., Bethke, I., Debernard, J. B., Kirkevåg, A., Seland, Ø., Drange, H., Kristjansson, J. E., Medhaug, I., Sand, M., and Seierstad, I. A.: The Norwegian Earth System Model, NorESM1-M – Part 2: Climate response and scenario projections, Geosci. Model Dev., 6, 389–415, 2013.