Responses to Reviewer 1

Dear Reviewer:

Thank you very much for your review and comments. Based on your comments, we will modify the paper accordingly, and here is a summary of the modifications and responses.

1. Fichefet and Maqueda (1997) carried out a similar study in an uncoupled setup. Which results in the current study go beyond these results?

Fichefet and Maqueda (1997) investigate the sensitivity of a sea ice model to many physical processes, among which the relevant one to our paper is the lateral change of sea ice. We compare their work with ours in terms of the following aspects:

a) Fichefet and Maqueda (1997) use a sea ice model coupled to a 1-D ocean mixed layer, while the model used in our work is a high-resolution global climate model, which contains the feedback between sea ice and other components (i.e. atmosphere and ocean).
b) They perform a no-lead experiment, with the sea ice concentration being 100% whenever ice exists, while our sensitivity experiment allow the evolution of sea ice concentration.
c) Their simulations show reduced ice volume in response to the absence of leads, identically, our results indicate increased mean ice thickness due to the extension of open water. Besides, we also show the feedback among the sea ice, ocean and surface air temperature. In addition, we vary the lateral-vertical growth ratio of sea ice by applying a different reduction factor (c* in our paper) in a simple idealized model, which further gives us a more comprehensive view of the effect of open-water ice growth.

Finally, based on the reviewer's comment, we will add the following content in the discussion section of the revised paper:

<u>“There are studies trying to explore the sensitivity of sea ice model to the absence of leads. Fichefet and Maqueda (1997), for example, conduct a no-lead experiment and reveal a decrease in the Arctic mean ice thickness due to suppressed oceanic heat loss in winter, which coincides with our results from a different aspect.”</u>

2. Mauritsen et al. (2012, doi: 10.1029/2012MS000154) and Notz et al. (2013, doi: 10.1002/jame.20016) describe the impact of tuning the lead-closing parameter in MPI-ESM in some detail. Which results in the current study go beyond these results?

The purpose of Mauritsen et al. (2012, doi: 10.1029/2012MS000154) and Notz et al. (2013, doi:10.1002/jame.20016) is to have the simulated annual mean Arctic ice volume close to observational estimate. One of the tuning method is to vary the vertical-lateral ice growth ratio (Cfreeze). By increasing/decreasing Cfreeze, more/less open ocean areas persist during freeze-up, thereby enhancing/weakening oceanic heat loss and sea-ice formation. This is in good agreement with our work.

What we offer beyond their results, is that we also show the spatial distribution of Arctic and Southern Ocean sea ice change. Besides, we as well investigate the response of ocean circulation and the climate to the changing sea ice parameter. In addition, the model used in our study has a high resolution in the polar regions (20-50 km). Therefore, it is more suitable for simulating sea ice evolution and its feedbacks.

Finally, based on the reviewer's comment, we will add the following content in the discussion section of the revised paper:

"Mauritsen et al. (2012, doi: 10.1029/2012MS000154) and Notz et al. (2013, doi:10.1002/jame.20016) test the sensitivity of the climate model MPI-ESM to vertical-lateral ice growth ratio (Cfreeze). By increasing/decreasing Cfreeze, more/less open ocean persists during freeze-up, thereby enhancing/weakening oceanic heat loss and sea ice formation. This is in good agreement with our work."

3. A number of studies have examined the impact of changes in sea-ice volume on atmospheric circulation, most recently regarding the possible impact on mid-latitude weather systems. Which results in the current study go beyond these results?

Based on the reviewer's comment, we will add the following content in the discussion section of the revised paper:

"There are a number of studies aiming at investigating the responses of climate to changes of the Arctic sea ice. For example, Magnusdottir et al. (2004) used an atmosphere general circulation model CCM3 to investigate the impact of sea ice change on the atmosphere and found significant changes in the North Atlantic storm track. Chiang and Bitz (2005) found that imposed ice can induce a rapid cooling and drying of the air and surface over the entire mid- and high latitudes, simulated by the Community Climate Model version 3 coupled to a 50-m slab ocean. More recently, Semmler et al. (2012) who forced the model EC-EARTH-IFS with reduced ice cover found negative sea level pressure anomalies over the western Arctic and positive anomalies over Siberia, affecting surface temperatures over Europe. Liu et al. (2012) found that the declining autumn Arctic sea ice is linked to the negative phase of the winter Arctic oscillation, resulting in increased cold surges over large parts of the northern continents. Our work is different from former studies from the following aspects:

a) Unlike other studies mentioned above, our sensitivity experiment aims at changing the horizontal-to-vertical growth ratio of newborn ice on open water as shown in Fig. 1, and is not for simulating the climate changes. This study is motivated by the uncertainties in the parameterizations distributing the new ice volume between growth in area and thickness, which is due to our lack of fundamental understanding and a proper representation of processes in coupled simulations.
b) In our work, the changes of sea ice thickness and sea ice concentration are not identical, as sea ice becomes much thicker, but ice concentration significantly decreases over large parts of the polar regions especially in winter. In contrast, sea ice change in former studies indicates a similar pattern for thickness and concentration, and the response of climate is due to the combined effect of the two elements.
c) Our simulations indicate a positive feedback between the Arctic sea ice, the surface temperature and the strength of AMOC, which is beyond the scope of former results."

4. What is the experimental setup of the experiments conducted here? How long was the model run?

As we describe in Section 3.3, the control experiments FE-CTR is a 350 years' pre-industrial simulation, the sensitivity experiment FE80 is initialized from the 300th year of the control simulation, and integrated for another 50 years. The average of the last 20 model years is analyzed.

Every simulation performed by SIM is integrated for 50 years. The average of the last 20 model years is analyzed.

Is it in equilibrium?

The model has run into quasi-equilibrium with trends in global mean sea surface temperature being less than 0.05 °C/century (0.00048 °C/year and 0.00037 °C/year for FE-CTR and FE80 over the last 20 model years, respectively). The trends of all variables in SIM is 0 for the last 20 model years. We will add the above points into the revised paper.

How significant are any of the results found? Could the differences between the two simulations simply be caused by internal variability?

According to the reviewer's comment, we calculate the standard deviations of sea ice thickness, sea ice concentration, thermodynamic sea ice growth, ocean temperature, ocean salinity, AMOC stream function, surface air temperature (SAT), and sea level pressure, based on the last 150 model years of the control simulation. Then we compare the anomalies of those variables mentioned above to their respective standard deviations. In terms of the anomaly figures in the paper, we marked the areas of significant changes with black dots (see the end of this letter).

Figure 1 and 2 show the anomalies of sea ice thickness and concentration respectively. Areas marked with black dots represent that the difference over that region is significant. As can be seen, sea ice changes in the central Arctic, Fram Strait, and the North Atlantic subpolar region are significant.

Furthermore, even though the Arctic SST has only a slight decrease, such little cooling is significant (Fig. 3a), and the pronounced cooling and freshening over the North Atlantic are both beyond the standard deviations (Fig. 3a,b). We also observe a significant change of thermodynamic ice growth over the North Atlantic subpolar gyre (Fig. 4). In terms of the zonal ocean profile (Fig. 5a,b), the change of temperature and salinity are significant over the Arctic surface and subsurface, and over the region of 0-100 m, 45°-65°N. The AMOC stream function is significantly weakened (Fig. 5c). Unfortunately, it appears that the warming over Europe and North America, and the sea level pressure (SLP) anomaly over the Northern Hemisphere, do not exceed their respective standard deviation (Fig. 6). We will discuss this in the discussion, saying that the SAT and SLP changes are not robust.

5. The description of the ice-concentration evolution in section 2 follows closely Hibler (1979). I think this should be made explicit, and only the modifications to the original scheme should be discussed in more detail.

FESOM-ECHAM6 calculates ice concentration evolution according to the approach of Dorn (2009) who improved the simulation of Arctic sea ice cover by modifying parameterizations of sea ice change as described in Hibler (1979). Therefore, the basic equation governing the sea ice evolution is based on Hibler (1979), and there is some modifications based on Dorn (2009).

Based on the reviewer's comment, we will improve the description of the ice-concentration parameterization in section 2 in the revised paper as follows:

The parameterization of ice-concentration evolution used in FESOM-ECHAM6 follows Hibler (1979) closely. Here, only details on the improved equations and more sophisticated schemes by Dorn et al. (2009) are given.

When new ice is formed on open water, the ice concentration increases at a rate given by:

$$\dot{A}_{ow} = \frac{1}{h_0} max(\dot{h}_{ow}, 0)$$

where h_{ow}, the effective ice production rate at open water area, is calculated based on the open water energy budget.

The lead closing parameter h0 in the equation is computed by:

$$h_0 = max({h_0}^{min}, min({h_0}^{max}, h))$$

Here h0min and h0max are thresholds of demarcation ice thickness. Different from the fixed-value approach by Hibler (1979) used in the standard ice growth scheme, FESOM-ECHAM6 uses a special case with h0min and h0max being 0.5 m and 1.5 m respectively.

When melting of sea ice occurs, the decrease in ice concentration is based on the assumptions of Hibler (1979) that the sea ice thickness is uniformly distributed between 0 and two times actual sea ice thickness.

For further information on the ice concentration evolution in the model, it is referred to Hibler (1979).

6. The description of the simple idealized model in section 3 follows closely the PhD thesis Notz (2005). In particular, all approximations for atmospheric fluxes were apparently directly copied from that thesis without any reference. This should be changed.

Thank you. We will refer to Notz (2006) in Section 3.2 in the revised paper, and we will also mention that on the basis of Notz (2006), we additionally apply the ice-concentration evolution parameterizations described in Section 2. Furthermore, there are two main differences between the 1-D model in Notz (2006) and the one used in our work:

a) The radiation fluxes forcings used in this paper closely follow the simplicity empirical estimation by Maykut and Untersteiner (1971), while Notz (2006) uses higher albedo to offset the radiation fluxes during polar night period.
b) We initialed the model with 0.5 m sea ice in the beginning of the model year, while in Notz (2006), the model starts at August with no sea ice cover.

7. The relevance of any of these findings depends on the complexity of the ice-thickness distribution in any given model. It should be discussed if these results have any relevance to modern sea-ice models that usually have more complex distribution schemes of sea-ice thickness than the one given by Hibler, 1979.

Based on the reviewer's comment, we will improve part of the contents relating to the ice-thickness distribution in the discussion section of the revised paper:

Partitioning of lateral versus vertical growth of sea ice is most realistically simulated in models that explicitly include a sub-scale distribution of ice thickness (Hibler, 1979; Bitz et al., 2001). In such models, lateral melting can roughly be represented by the disappearance of the thinnest sea-ice classes and the accompanying expansion of open water. However, in a multi ice-thickness distribution model, the lateral-vertical aspect ratio controlling the open-water ice growth would still need to be determined empirically. Therefore, using a modern sea ice model with multi ice-thickness categories will probably lead to similar results.

Another realistic approach of lateral versus vertical melting is based on the ratio of bottom area versus edge area of the ice pack. However, the relationship between the ice floe size and many external factors, for example, ice age, ice thickness and weather condition (Dumont et al., 2011) is not yet sufficiently implemented in sea ice models.

8. Units in Figure 10 are confusing: a mass transport usually does not have units m2/s.

Thank you. The unit should be kg/s. We will correct this in the revised paper.

Furthermore, we also notice a typing error in the paper at Table 2, page 28. The content “80f” should be “80%”. We will correct this in the revised paper.

Finally, we are grateful to the comments of the anonymous reviewer which have helped to improve the paper.

Figure Captions

Figure 1. Sea ice thickness for FE-CTR, units are m. Area marked with black dots represent that the difference over that region is significant.

Figure 2. As in Fig. 1, but for sea ice concentration, units are %.

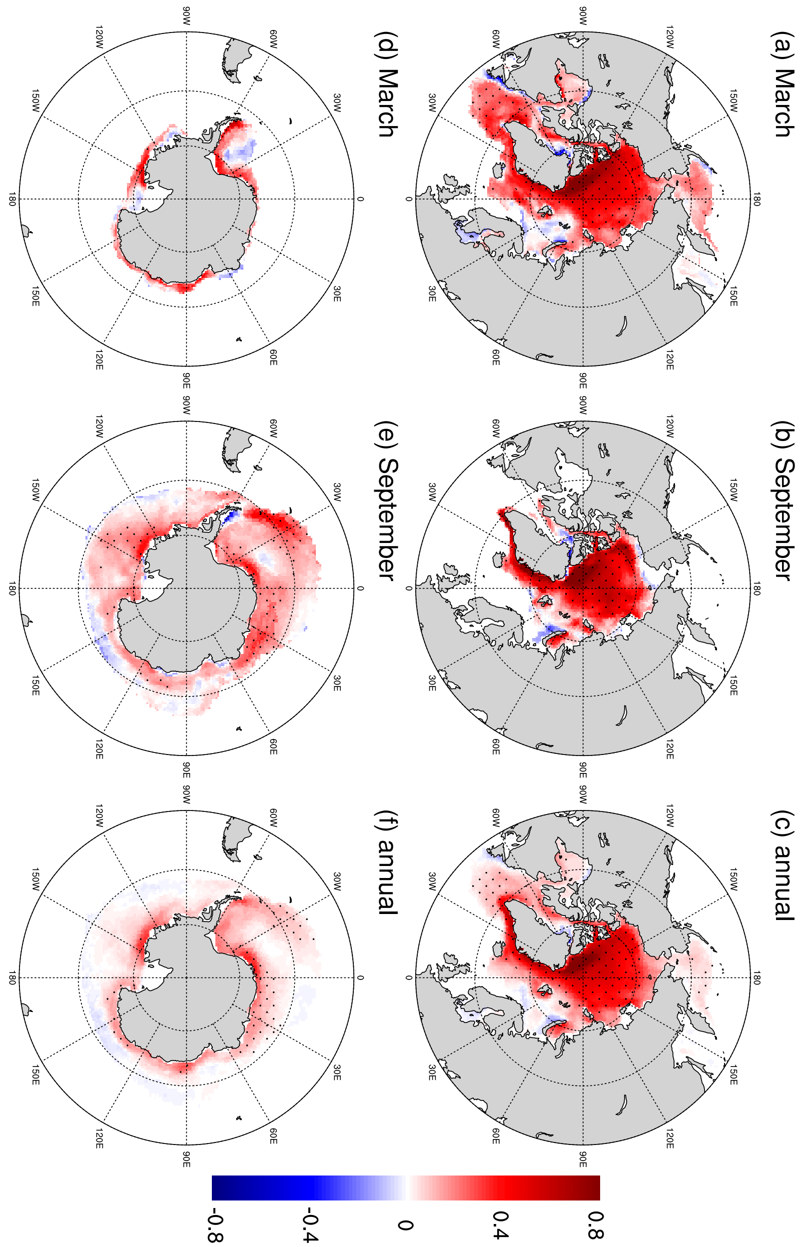
Figure 3. Difference of annual mean (a) the sea surface temperature and (b) the sea surface salinity between experiments FE80 and FE-CTR (FE80 minus FE-CTR).

Figure 4. Difference of annual mean thermodynamic growth rate of grid-cell mean ice thickness between experiments FE80 and FE-CTR (FE80 minus FE-CTR).

Figure 5. Difference of (a) zonal mean ocean temperature, (b) zonal mean ocean salinity and (c) AMOC between experiments FE80 and FE-CTR (FE80 minus FE-CTR) for the Atlantic region.

Figure 6. Difference of (a) surface air temperature and (b) sea level pressure in boreal winter between experiments FE80 and FE-CTR (FE80 minus FE-CTR). Units are $^{\circ}C$ and hPa.

Figures



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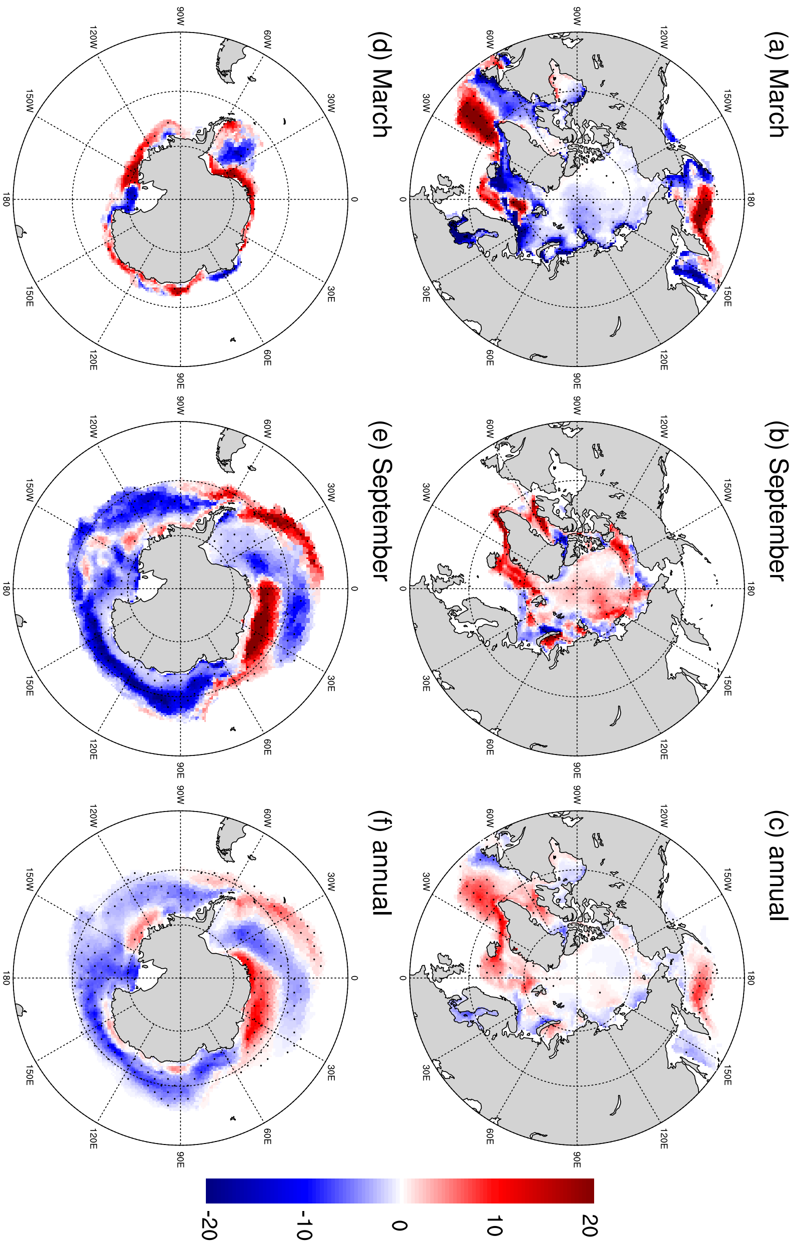
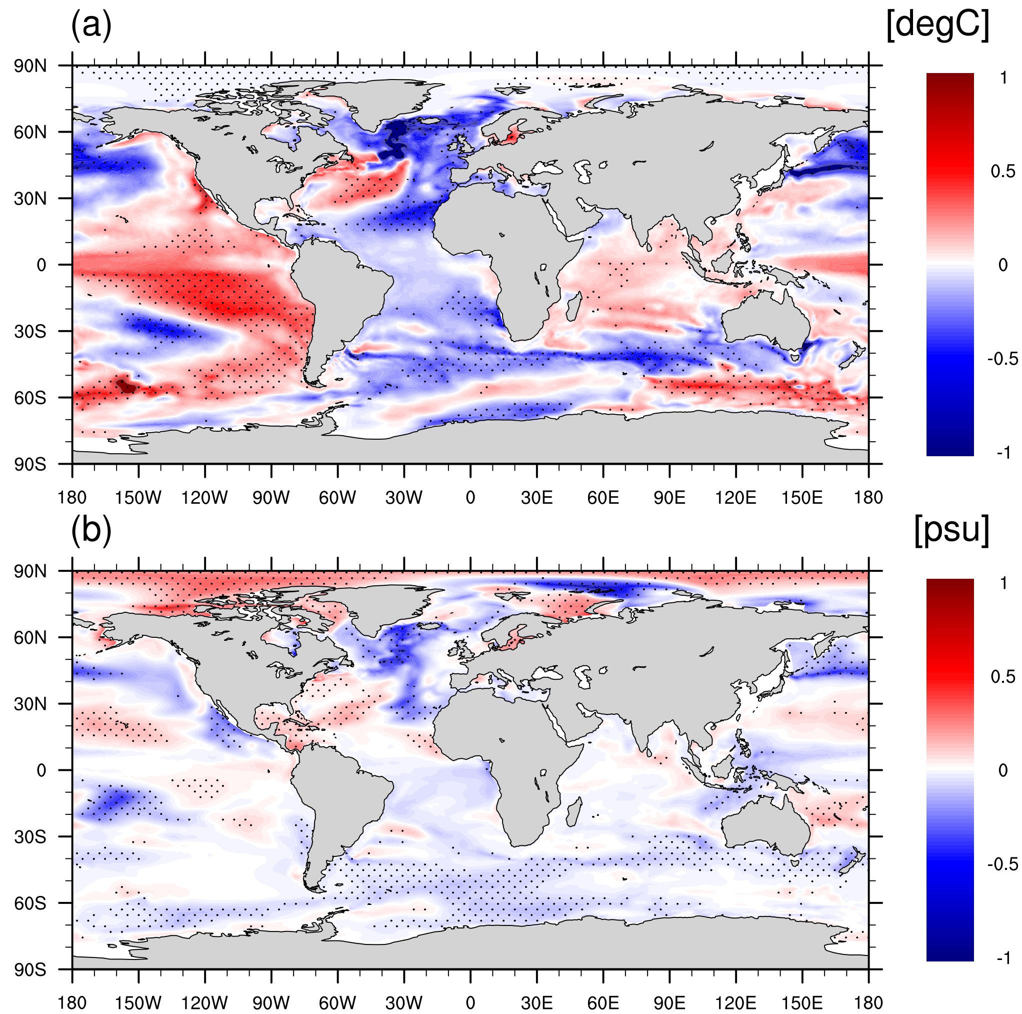


Figure 2. As in Fig. 1, but for sea ice concentration, units are %.



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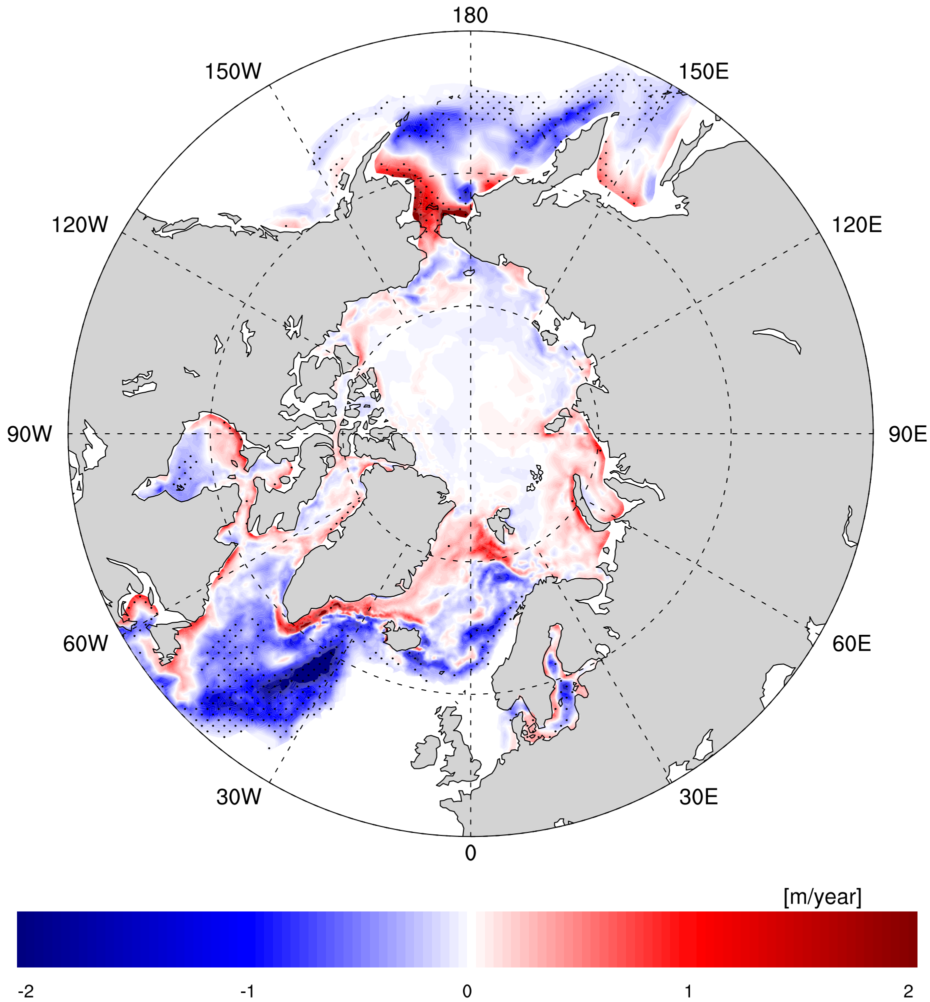

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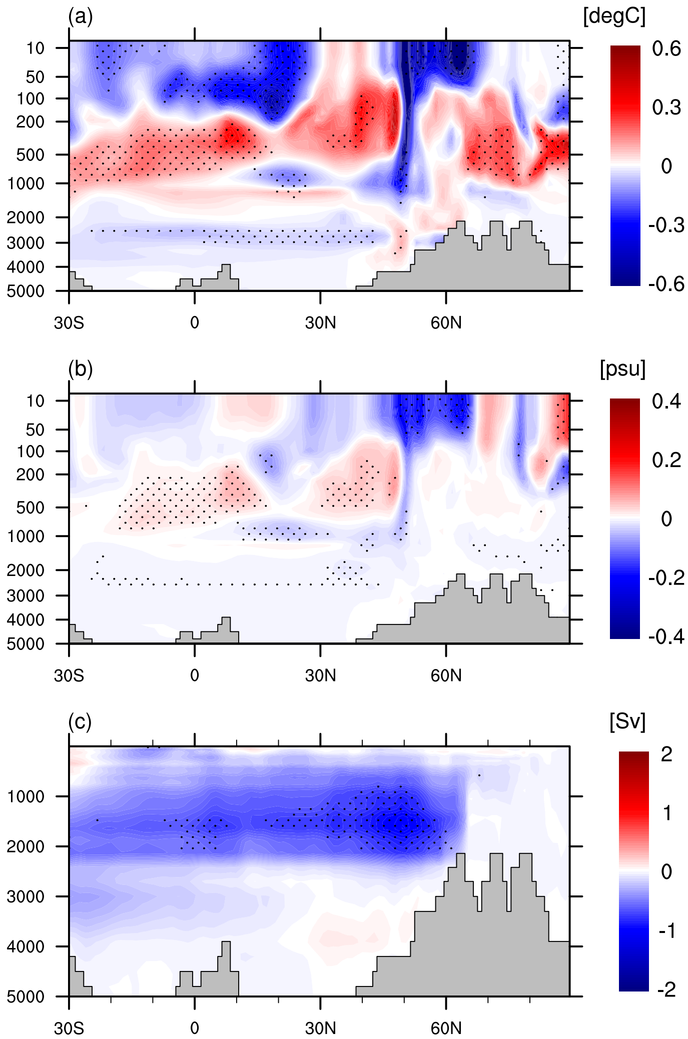

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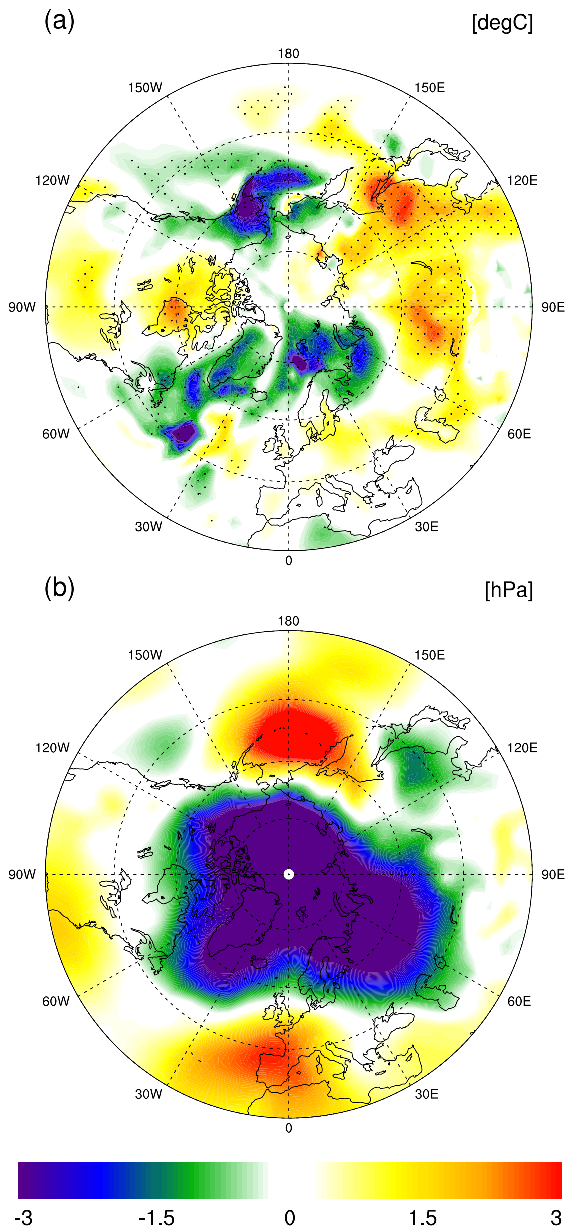

Figure 6. Difference of (a) surface air temperature and (b) sea level pressure in boreal winter between experiments FE80 and FE-CTR (FE80 minus FE-CTR). Units are $^{\circ}C$ and hPa.