Responses to Reviewer #2

This is my first review of a paper titled 'A numerical study on melt water feedback in the coupled Arctic Sea ice-ocean system' by Zhang et al. The paper discusses the impact of freshwater from sea ice melt on sea ice growth/melting itself. Using a 1D sea ice - ocean model the authors find that depending on the initial stratification, the melt water has a strong negative feedback on ice melt but depending on stratification can have either a positive or negative impact on the following winter ice growth. The results themselves are interesting, although I do question the linkage to meltwater alone (see below). As such the manuscript lacks some details and could be published with minor revisions, although the results reflect the importance of freshwater in general, not melt water alone. However, I give suggestions to modify their experimental setup to actually attribute their results to sea ice meltwater, or to carry out with their results, but to recast their results in terms of general freshwater perturbations. I encourage the authors to consider the suggested modification to their approach and therefore suggest major revision.

Thank you very much for the comments and suggestions, which help us to improve the quality of the MS. In the following, we provide responses (blue text) to the comments, and revised the MS accordingly ***(black bold italic)***.

Major comments:

1) If I understand correctly, what the authors do here, is that they have one 'control' simulation with full meltwater release and perturbation experiments with scaled down versions of meltwater release. However, although the amount of meltwater release is scaled down the sea ice melt itself stays the same, i.e. some freshwater disappears in the process.

Because the authors also don't take into account any other sources of freshwater, the influence of sea ice meltwater in respect to other freshwater sources remains unclear. To me, the experiments, as they are done now, appear more as traditional freshwater release experiments (albeit with seasonal cycle), rather than experiments that would try to isolate the role of sea ice meltwater. If the authors would want to really isolate the role of sea ice meltwater on the ice melt/growth, then I think one would need to do something like this:

a) Create a simulation that reproduces ITP profiles with other freshwater fluxes included. Based on Figure 4 the authors claim that this is the case already, but the simulations done here are very short and already at the surface mixed layer the salinity differences can be several PSU in some stations. The easiest would be to deduce freshwater convergence from ITPs and remove the (observed) sea ice melt water flux from the convergence, allowing the model to calculate that. It would also be interesting to diagnose the actual sea ice melt water flux from ITPs and for example cross-correlate that with sea ice growth across the different ITP's to see if the authors hypothesis can be identified in the observations.

b) Once the authors have the stable control simulation, they could repeat the experiments, keeping the freshwater convergence the same, but perturbing the sea ice meltwater flux.

Such an experimental setup would answer the question 'what is the importance of sea ice meltwater for sea ice melt/growth?'. In the current setup I would argue that all the authors can truly answer to is 'what is the role of freshwater for sea ice melt/growth (thermodynamic)?'. I do think the identified feedbacks are neat, but in the current form I think the authors would need to rephrase their aim and discuss the caveats of their experimental setup. For example, in their 0% experiment, there is no freshwater source to the surface, which obviously gives a very large signal, but it is not realistic to claim that this signal can be attributed to sea ice meltwater (because there would be other freshwater sources contributing to the stratification). I leave it to the authors to decide on their approach, but I would think modifying their setup would be achievable and would certainly increase the impact of the paper.

Thanks for the comments and experiment suggestions. The aim of this study is to investigate the melt water feedback on sea ice melting, so we remove sea ice melt water in the model directly to disable the feedback mechanism to examine melt water feedback effects by comparing it with the control run. In order to avoid the exaggeration of the meltwater feedback effect, we added other external freshwater forcing in all the experiments in the new MS. We tried to deduce freshwater convergence from an ITP and found it difficult to obtain a real sea ice melt water flux. The suggested experiment design is good to study the role of the sea ice melt water in the sea ice melting/growth but may not be suitable to study the meltwater feedback. Perhaps we did not claim the aim of our study clearly, we revised the MS and clarified our research objective in the **Section 1.**

Lines 47-57: ***Melt water from the sea ice has a comparatively low density and therefore accumulates in the top ocean layer, strengthens the upper ocean stratification. Due to the stabilizing of the cold halocline, the ocean heat flux available to melt sea ice decreases, which in turn hinders sea ice melting. This is a negative sea ice/ocean feedback on sea ice melting (Bintanja et al., 2013), and we call it melt water feedback in this paper. Zhang (2007) and Bintanja et al. (2013) suggest that this negative sea ice/ocean feedback can explain the anomalous increase in Antarctic sea ice extent before 2010s. Many positive feedback processes in the Arctic atmosphere-ocean-ice systems are extensively studied, such as the well-known sea ice albedo feedback (Hall, 2004; Winton, 2000; Pithan and Mauritsen, 2014), water vapor feedback (Gordon et al., 2013; Taylor et al., 2013) and the Cloud-Albedo feedbacks (Zelinka et al., 2012; Bodas-Salcedo et al., 2016). However, there are almost no quantitative studies on this negative melt water feedback on sea ice melting in the Arctic, although many previous studies have investigated the effects of increased freshwater flux by adding freshwater flux to the ocean surface in models to represent increased runoff or precipitation (Nummelin et al., 2015, 2016; Davis et al., 2016a; Pemberton and Nilsson, 2016).***

We originally intended to conduct experiments using the suggested experimental design. We calculated the freshwater convergence of the ITPs (Fig.1 below). However, the actual amount of ice melt corresponding to each ITP data point is unknown, which makes it difficult to accurately calculate the proportion of melt water in the freshwater convergence. Furthermore, ITPs is continuously moving. Advection and other external forcing processes have a significant impact on the vertical temperature and salinity, which leads to large fluctuations in the calculated freshwater flux value (black solid line in Fig.1 below). In the coupled ice-ocean model, the calculation of melt water flux for each time step depends on the sea ice melting, and the removal of a portion of freshwater flux based on the freshwater convergence calculated from ITP will lead to an inaccurate assessment of the melt water feedback in the coupled model.

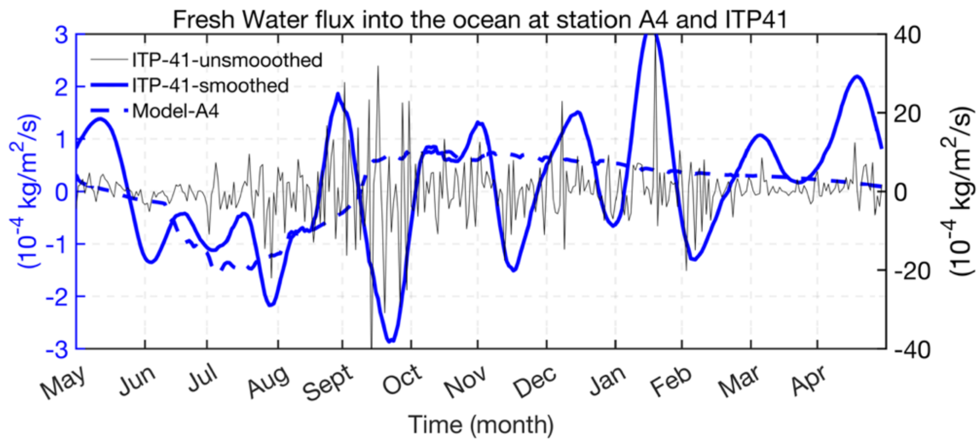

Figure 1. The time series of freshwater flux calculated for station A4 and ITP41. The black solid line represents the unsmoothed freshwater flux values of ITP41, while the blue dotted line shows the 30-day moving average of ITP41. The blue solid line represents the simulated freshwater flux values at station A4.

We acknowledge that the signal of the melt water feedback is to be exaggerated if the other external freshwater forcings were ignored. So, we re-run all experiments with incorporating other fresh water sources. According to Haline et al. (2015)'s research on the freshwater balance of the Arctic Ocean, the main sources of freshwater input in the Arctic Ocean are river runoff, Bering Strait inflow, and net precipitation, with a total input of approximately 9400±490 km^3yr^{-1}. Meanwhile, freshwater output occurs through the Davis Strait, the Fram Strait, and the Canadian Archipelago, with a total output of approximately 8200±550 km^3yr^{-1}. The net input of freshwater into the Arctic Ocean is approximately 1200 km^3yr^{-1}. We added this part of the freshwater as other freshwater sources into the model.

With the addition of the external freshwater input, the effect of melt water feedback decreased slightly compared to the old experiments without other external freshwater sources. However, it has little impact on the conclusions. We added some sentences in **section 1** and **section 2.3** to illustrate the existence of external freshwater forcing in the model.

Section 1, lines 38-43: ***The volume of net input freshwater that comes to the Arctic Ocean from external sources is roughly 1200±730 km^3 annually, with an inflow of 9400 ± 490 km^{3}yr^{-1} and an outflow of 8250 ± 550 km^{3}yr^{-1}, while approximately 11300 km^3 freshwater enter the ocean in summer through melting. The volume of melt water in the Arctic Ocean is approximately 10 times greater than that of net freshwater input, leading to an increase of 1.2 m in the Arctic Ocean's surface freshwater layer (Haine et al., 2015), which separate the surface ML from the near-surface temperature maximum (NSTM).***

Section 2.3, lines 152-157: ***Although the focus of this study is on the melt water feedback in the coupled ocean-sea ice system, freshwater fluxes due to runoff inflow, precipitation minus evaporation, and input or output from straits also contribute to the stratification changes of the Arctic Ocean. The signal of the melt water feedback is to be exaggerated if those external freshwater forcings were ignored. So, we also consider the external freshwater forcing in the experiments. Haine et al. (2015) reported that the annual net inflow of freshwater to the Arctic Ocean is approximately 1200 km^{3}yr^{-1}, and we add this net freshwater inflow to our model on a daily average to represent various freshwater sources other than the melt water.***

We revised the values of the experimental results in **Abstract.**

Line 12: ***… by 16.6% by strengthening ocean stratification.***

Lines 14-15: ***… by 12.3% during the winter, while it decreased by more than 40% in areas with weak stratification.***

We also made changes to other similar values in the new MS, but since these changes are scattered throughout in the MS, we are not list them here.

We would like to clarify that this study is based on ideal one-dimensional model experiments where each experiment uses identical atmospheric and external freshwater forcing fields. So, we do not aim to perfectly replicate the variability of the ITP profiles in the control experiments. The comparison between the observations and simulations shown in Figure 4 of the first MS (but it is Figure 5 in the new MS) is to demonstrate that the seasonal changes of ocean temperature and salinity simulated by our one-dimensional model are qualitatively consistent with the observed data. This is to verify that our experimental results are not deviating from reality. Such a model validation method has also been used in some previous studies of Arctic Ocean stratification using 1D models (such as Linders and Björk, 2013; Toole et al., 2010). We added a figure (below, fig. 2, but it is figure. 4 in the new MS) in the new MS to compare the time series of simulated and observed temperature and salinity. This figure aims to illustrate the temperature and salinity changes simulated by the model in detail and further demonstrate that our model results are reliable.

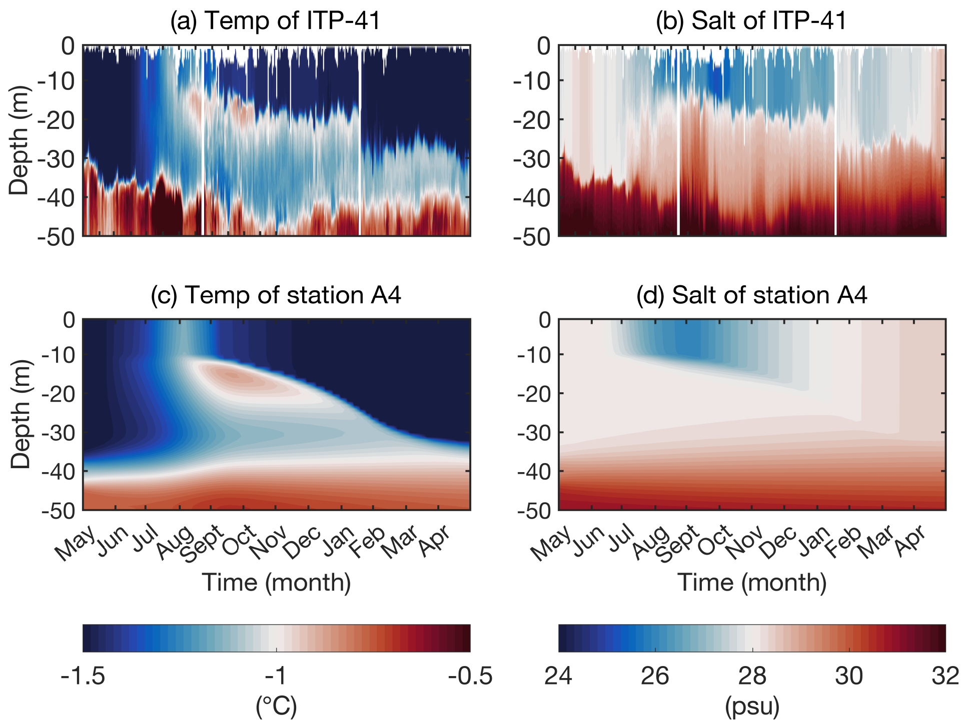

Figure 2 (Figure 4 in the new MS): The time series of temperature (left) and salinity (right) for the upper 50 meters were derived from (a), (b): ITP41 observations and (c), (d): simulated values at station A4, respectively.

We revised some sentences in **section 3.1.1.**

lines 197-216: ***Figures 4 and 5 show the comparison between the simulated temperature and salinity profiles of the control runs and the ITP observations (the details of the 6 ITPs datasets for comparison with the simulated results are listed in Table 1). The results of the one-dimensional model reasonably reproduce the seasonal variations of the vertical temperature and salinity***

structure in the Arctic Ocean. It should be noted that this study does not aim to perfectly replicate the variability of the ITP profiles, as the variability of the Arctic Ocean temperature and salinity structure is influenced not only by surface freshwater fluxes but also by an array of external local forcings, such as high-frequency variations in wind fields, local precipitation or evaporation, horizontal transport of freshwater, and observational errors. Despite some discrepancies between the simulated and observed vertical profiles, the simulations of these ideal experiments are still qualitatively consistent with the observations. Therefore, the simulation results obtained in this study are reliable.

ITP41 measured relatively complete temperature and salinity data along its pathway (green line in Fig. 1) in the Canadian Basin from May 2011 to April 2012, and the data measured by ITP41 in May 2011 also serve as the initial field for station A4 in the model. Therefore, we compared the complete time series of the temperature and salinity of the ITP41 observations with the simulations. Both the observations and simulations show that large quantities of freshwater, primarily melt water, cover the ocean surface during the melting season, typically lasting from June to September. As a result, a significant salinity gradient forms between the surface water and underlying water layers, creating a new, fresher surface layer (Fig. 4b and d). And the model also successfully reproduces the NSTM at the base of the summer ML, present at approximately 10-20 m (Fig. 4a and c). During the freezing season (October to the next April), brine rejection enhances the turbulence scale perturbations, leading to a deeper ML, and the NSTM generated during the summer progressively cools and vanishes (Fig. 4a and c).

Furthermore, we compared the simulated values with actual summer and winter observations gathered from select stations in the vicinity of the simulation. Figure 5 shows …

2) L74 in the model description the authors write that the sea ice package is based on viscous-plastic sea ice model. Although this is true, perhaps there should be a sentence specifying that in 1D case the dynamics don't play a role (or do they?) and the ice growth is determined by thermodynamics alone.

We added a sentence in **section 2.1.**

Lines 92-93: ***Although the one-dimensional model includes a dynamics sea ice module, sea ice changes are only determined by thermodynamics processes.***

3) Ice thickness initialization to 2.5 m is an idealization (of multiyear ice), and that is fine as such, but I'd imagine the simulations are relatively cheap to do so I wonder if it would be worth repeating the experiments with thinner initial ice (something that represents first year ice). I would think that most locations in the Eurasian basin rarely have 2.5 m thick ice these days.

This suggestion is very helpful. We added experiments with thinner ice (1.5m) at four stations A3, A6, E2 and E7. We found that the feedback of melt water on sea ice melting is not significant in summer. however, it is more effective in hampering upward mixing of Atlantic water and melting sea ice during winter. We added **section 3.3 (lines 390-422)** to discuss the thinner ice experiments.

3.3 Sensitivity experiments with thinner sea ice

In recent decades, it has been observed that Arctic summer sea ice appears to be decreasing rapidly (Perovich et al., 2019), with larger ice-free areas in summer and thinner winter sea ice (Haine and Martin, 2017). Thus, several experiments are conducted using thinner initial ice (1.5 m). To highlight the effects of strong or weak CHL, we selected stations A3, A6, E2 and E7 to do the thinner ice experiments.

In the control run, the initial thinner ice of 1.5m completely melts in late July (Fig. 14a), and

the maximum ocean-ice heat flux can reach 330Wm^{-2} (Fig. 14b). During winter, E7 station produces less sea ice because it possesses a weaker stratification (see Fig. 14a), which is consistent with experiments that had an initial ice thickness of 2.5 m.

Compared to the control runs and the MWP20%-80% runs, the sea ice melts more slowly in the MWP-0% runs (Figures 14c-f), which contrasts with the experiments with a thicker initial ice. This may be due to the fact that the thinner initial ice contribute to the presence of a larger open ocean during the summer and increased wind input enhances the mixing level, resulting in more heat being mixed into the deeper ocean. As a result, the heat available for melting sea ice is reduced. Figures 15a-d clearly demonstrate the process by late July, the temperature of the upper ocean is remarkably lower in the MWP-0% runs, while the temperature below 10m is considerably higher compared to the other runs.

During winter, the role of melt water in hindering the upward mixing of AW is more evident in the thinner initial ice experiments. Removing 40% of melt water during the summer in the thinner initial ice runs can enable the upward mixing of the AW (Fig. 16d and h) and subsequent melting of sea ice in winter (Fig. 14f and Fig. 17b). However, it would require the thicker initial ice runs to remove over 80% of melt water to achieve similar results (Fig. 9f and l).

The thinner ice experiments indicate that as multi-year ice in the Arctic Ocean is replaced gradually by seasonal sea ice, melt water will play a more significant role in impeding vertical mixing and winter ice melting in the future.

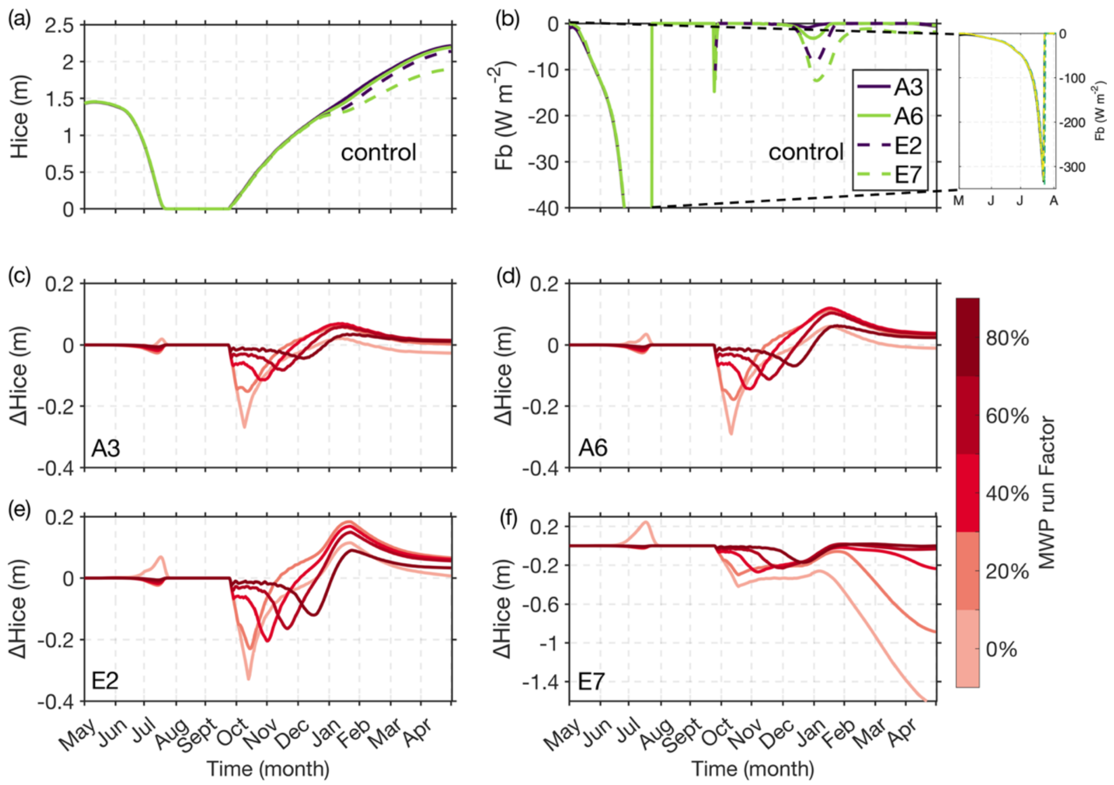

Figure 14: Time series of the (a) effective sea ice thickness and (b) ocean-ice heat flux (negative values represent the heat transfer from ocean to ice) for control runs with thinner initial ice thickness. The subplot in (b) shows the time series of ocean-ice heat fluxes between May and August, indicating that ocean-ice heat fluxes can reach a maximum of 330Wm^{-2}. (c)-(f): Time series of the anomalies of effective ice thickness for stations A3, A6, E2 and E7. The anomalies are obtained from the MWP run minus the control run.

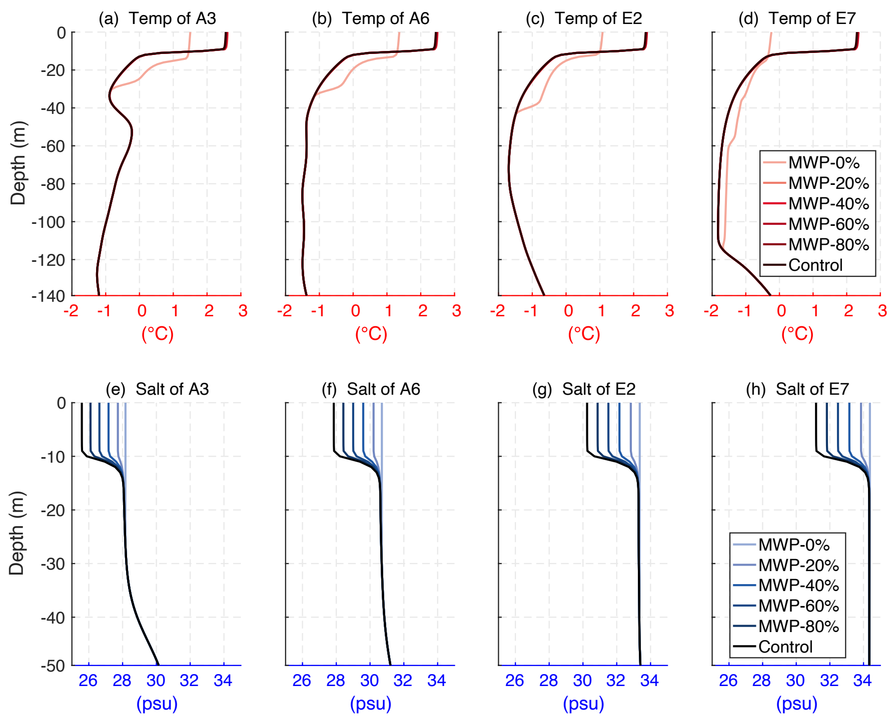

Figure 15: Simulated temperature (top row) and salinity (bottom row) profiles of MWP runs and control runs in late-July for stations A3, A6, E2, and E7 of the thinner initial ice experiments.

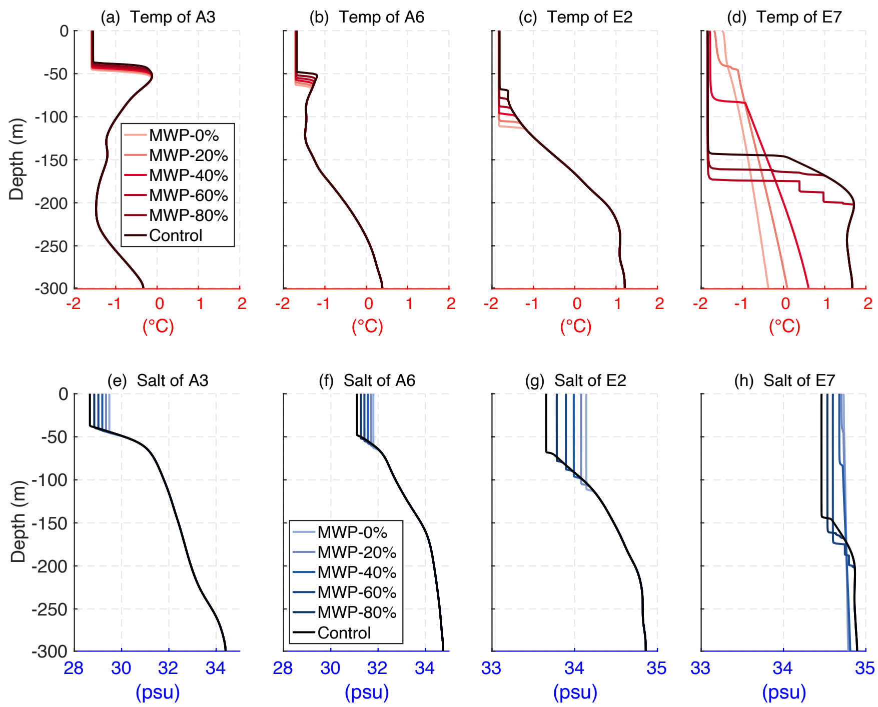

Figure 16: Same as figure 15 but in mid-April.

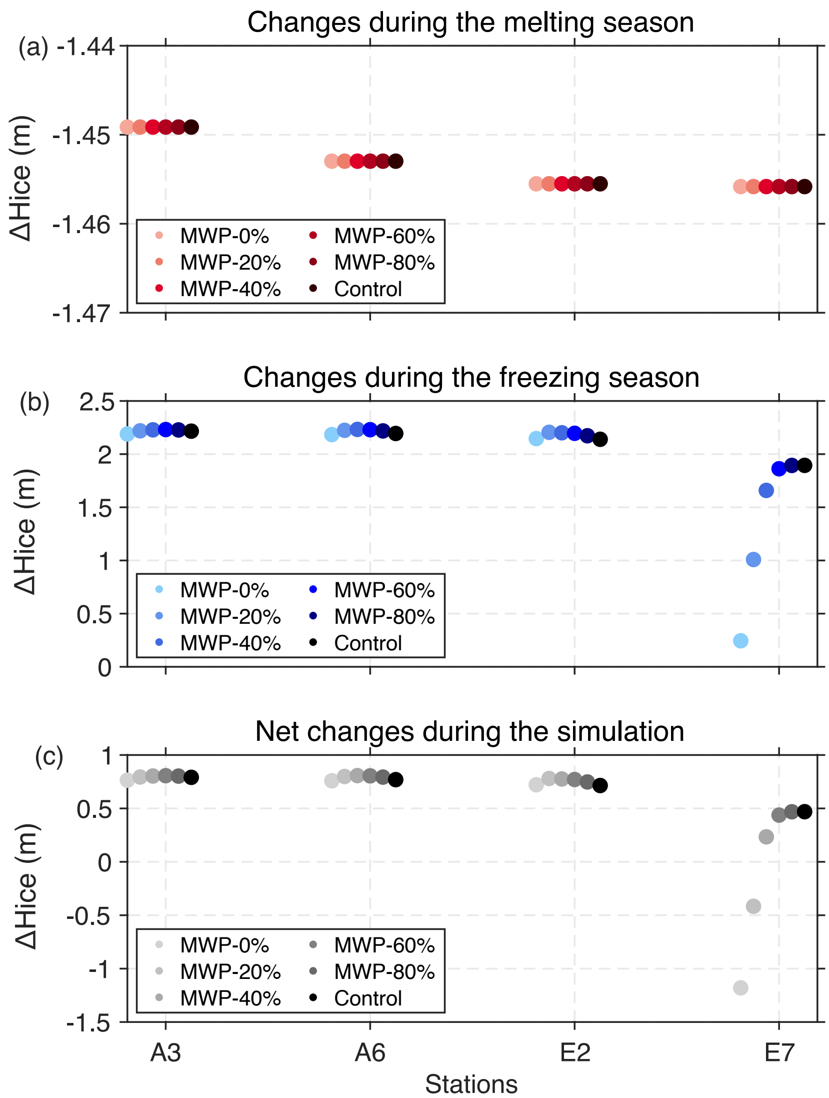

Figure 17: Same as figure 11 but for stations A3, A6, E2 and E7 of the thinner initial ice experiments.

We added a sentence in **section 5.**

Lines 490-492: ***3. Sensitivity experiments with thinner initial ice indicate that as multi-year ice in the Arctic Ocean is gradually replaced by seasonal sea ice, melt water will play a more significant role in hindering vertical mixing and winter ice melt in the future.***

4) Similar to the comments by the other reviewer, the model experiment need to be better documented (when are they initialized, how long are they run for etc.). Some of this information is in discussion section, but that comes far too late for the reader.

As requested by Reviewer #1, we supplemented the missing experimental information by adding several sentences in **section 2.4.**

Lines 159-160: ***To investigate the impact of the release of melt water on ocean stratification and sea ice, a total of six experiments were conducted at each station for a simulation period of 1 year, starting on May 1 and ending on April 30 next year.***

Lines 162-164: ***The experiment started on 1 May with the objective of conducting a full melting period followed by a complete freezing phase in the model, which helps to better investigate the***

feedback effects of melt water on sea ice melting in summer, as well as its impact on subsequent freezing in winter.

Line 165: ***… the melt water flux of a timestep (600s) is determined by the freshwater content of the …***

5) I would change the order of discussions and conclusions.

Thanks for the suggestion. We changed the order of the discussion and conclusion.

6) Figure 3: are the labels in f and g correct, or should they be the other way around?

We made a writing error in the caption where we wrote (g) instead of (f). We corrected this error in the new MS. We apologize to the reviewers for any inconvenience caused by this error.

7) Figure 5 and other similar figures: I would encourage the authors to show anomalies from a control case instead of the full values (it is hard to appreciate the differences at the moment).

We redraw these figures in the new MS to show the anomalies.

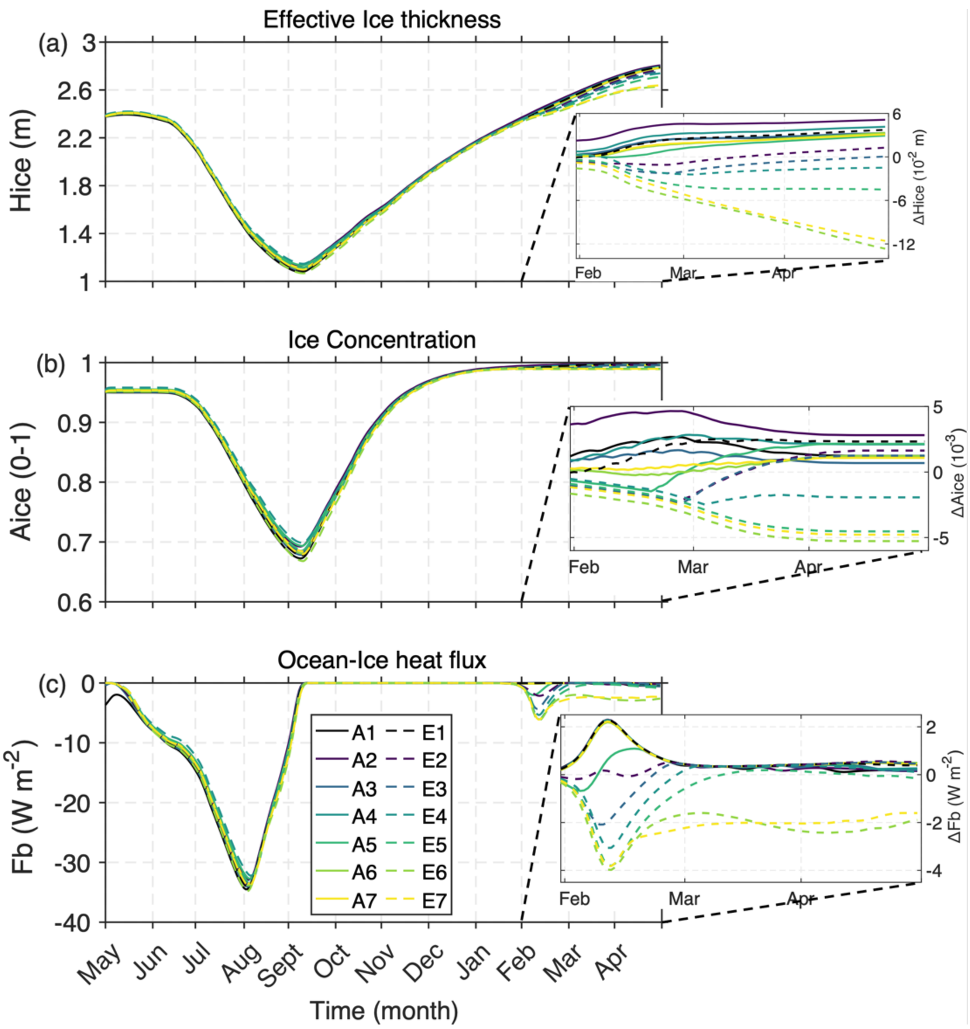

Figure 6: Time series of the (a) effective sea ice thickness (Hice), (b) ice concentration (Aice) and (c) ocean-ice heat flux (Fb, negative values representing the heat transfer from the ocean to the ice) for all control runs. The amplified subplot shows the anomalies (each control run minus the average of all control runs) during the months of February to April.

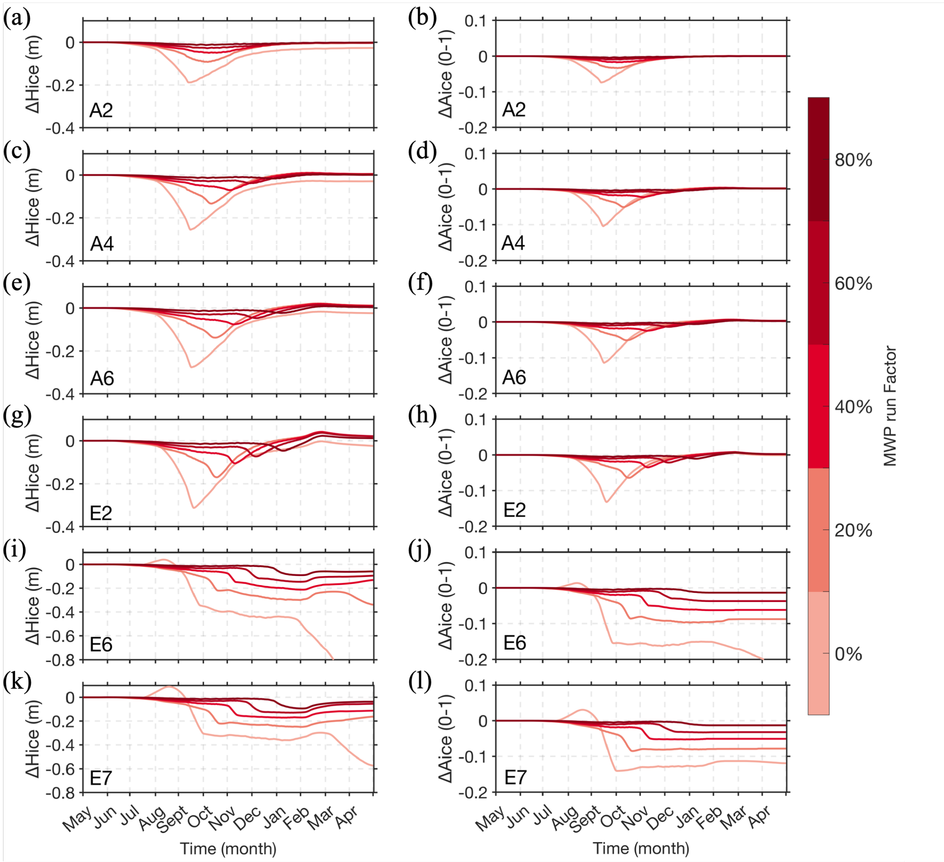

Figure 10: Time series of (left) the anomalies of effective ice thickness and (right) anomalies of ice concentration for stations A2, A4, A6, E2, E6 and E7. The anomalies are obtained by the MWP run minus the control run.

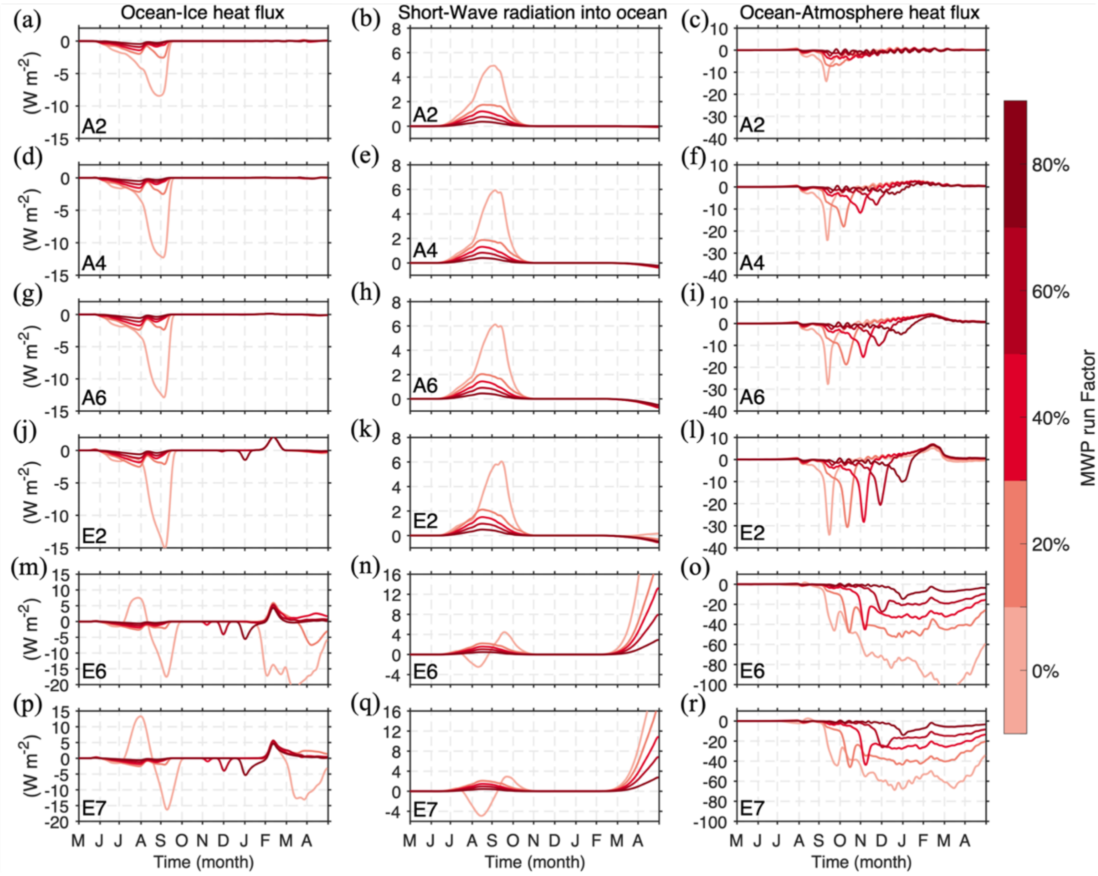

Figure 13: Time series of (left) the anomalies of ocean-ice heat flux, (middle) the anomalies of shortwave radiation, and (right) the anomalies of ocean-atmosphere heat flux for stations A2, A4, A6, E2, E6 and E7. The anomalies are obtained from the MWP run minus the control run. The negative (positive) value indicates heat gain (loss) by the ocean in the MWP run compared to the control run. The color of each line represents the MWP run factor.