Responses to referees' comments

We thank anonymous referees for their constructive comments and helpful suggestions. We have improved the manuscripts based on the comments from the referees.
Referee's comments are indicated in *Italics*, and then our answer follows immediately.

Responses to the comments from Anonymous Referee #1.

The authors present a number of conclusions or a priori assumptions about the interactions between sea ice and clouds that are neither established scientific understanding nor underpinned by the presented data and arguments. In particular, the authors do not convincingly demonstrate a causal relationship, let alone a mechanism for such a relationship, between sea ice changes and cloud changes beyond some overlap in the corresponding maps.

A: This comment is the same as one of the comments from the Referee #2. Based on the comment from the Referee #2, we have conducted the instantaneous and lead/lag correlation analysis to infer causality of the interaction between sea ice and cloud cover. From the result, we confirmed that the cloud cover in October is likely to increase due to decrease in sea ice concentration. This result has been added in subsection 3.2 of the revised manuscript. Related to this addition, we have divided the content in subsection 3.1 of the original manuscript in two subsections. The titles of subsections 3.1 and 3.2 in the revised manuscript were changed to "Simulated change of the Arctic sea ice and clouds" and "Relationship between changes in sea ice and cloud cover during fall", respectively. The description added in subsection 3.2 of the revised manuscript is as below,

"Figures 4a and 4b show geographical distribution of autocorrelations of simulated sea-ice concentration between September and October and instantaneous correlations of simulated cloud cover and sea-ice concentration in October, respectively. The correlation coefficients were calculated for 1976-2005. In the autocorrelation in sea ice concentration between September and October, large positive correlation coefficients are found over most of the Arctic Ocean, with the larger positive correlation coefficients above 0.6 over the lower latitude regions from the Beaufort to the Barents Sea (Fig. 4a). Over the Arctic subregion exhibiting highly autocorrelation of simulated sea-ice concentration (109-221° E, 69-78°N), which is shown in Fig. 4a with black broken lines, autocorrelations of simulated sea ice concentration (blue circle in Fig. 4c) decay with a slower time lag than those of simulated cloud cover (black circle in Fig. 4c), since the autocorrelations of simulated sea ice concentration reflect a substantially longer memory in sea ice. These results suggest that, in MIROC5, sea ice change in October tends to depend on sea ice change in September: small sea ice concentration during September is likely to continue a small sea ice concentration during October.

Negatively stronger correlations between sea-ice concentration and cloud cover in October are found in grids with dominant negative trend in sea-ice concentration during 1976-2005 in MIROC5 (Fig. 4b). These indicate that increased cloud cover in the grids tends to be associated with a smaller sea ice concentration. The negative relationship between sea ice concentration and cloud cover in MIROC5 are consistent with the observed results in Palm et al. (2010) and Liu et al. (2012). Lead/lag correlations in the Arctic subregion show that cloud cover in October is negatively correlated with the lead/lagged sea-ice concentration (green diamond in Fig. 4c). This negative correlation of could cover in October with sea-ice concentration in September suggests that, in October, small sea ice concentration continuing from September makes cloud cover increase, because of the strong autocorrelation of sea ice concentration between September and October in MIROC5. Also, as the autocorrelation of simulated cloud cover between September and October is weaker than the correlation between simulated cloud cover in October and simulated sea ice concentration in September, the increase in cloud cover in October is unlikely to represent a continuing increase in cloud cover from September in MIROC5. On the other hand, sea ice concentration in October is also negatively correlated with lead/lagged cloud cover (red diamond in Fig. 4c). Correlation of sea ice concentration in October and cloud cover in September is weaker than that of cloud cover in October and sea ice concentration in September. Therefore, we concluded that, in MIROC5, cloud cover is likely to increase due to decrease in sea ice concentration during October. This results supports previous result with the satellite data in Liu et al. (2012) that decrease in sea ice concentration lead to increases in cloud cover."

The two main diagnostics used – cloud cover and CRE – may both be misleading in the Arctic: Some models tend to produce 'empty clouds' at cold temperatures, which lack condensate and thus do not affect radiative fluxes, and the CRE may change purely through temperature changes without any change in cloud properties. The authors do not discuss to what extent these problems affect their results.

A: In our composite analysis, we averaged data for grids with or without dominant reduction of sea ice across all ensemble members. Simulated vertical profile of cloud fraction shown in Fig 5a was calculated with the same way, showing clearly the increase in cloud fraction for the case with dominant reduction of sea ice. Therefore, we can say with confidence that the point of 'empty cloud' from the Referee #1 is not relevant to our analysis of the radiation and the related discussions. Then, in the analysis of surface downward longwave radiation (DLR), we calculated the change of each component of the radiation with the same way as in the vertical profile of cloud fraction.

We also have considered the impact of changes in both water vapor and air temperature on the surface DLR using the clear-sky surface DLR in our analysis. However, it is very tough work for us to distinguish the impact of water vapor from the impact of air temperature, due to limited data. In the original manuscript, we had not included the change in each component such as the cloud radiative forcing (CRF) of surface DLR and the clear-sky surface DLR in Fig. 7 and detailed descriptions of the each component in the original manuscript. These might complicate understanding of the results and the discussions on the radiation changes. We have included the change in each component in the revised Fig. 7 and explained these in the revised content. The added and revised descriptions are as follows,

"Figure 7a shows the change in CRF of surface DLR ($\Delta \mathrm{CRF}_{\mathrm{SDLR}}$) and clear-sky surface DLR ($\Delta \mathrm{CS}_{\mathrm{SDLR}}$) between the former and the latter periods. The changes in the figure were averaged for the Δai- grids and Δai+ grids in each month. Positive $\Delta \mathrm{CS}_{\mathrm{SDLR}}$ are ascendant in the both cases. Particularly, during autumn-winter-spring, positive $\Delta \mathrm{CS}_{\mathrm{SDLR}}$ is dominant in the case Δai-, rather than that in the case Δai+. This positive $\Delta \mathrm{CS}_{\mathrm{SDLR}}$ resulted from both warming and moistening due to the increased open ocean and the global warming. Thus, this indicates the positive $\Delta \mathrm{CS}_{\mathrm{SDLR}}$ due to increase in both water vapor and air temperature can affect largely the surface energy balance in the grids with dominant reduction of sea ice concentration.

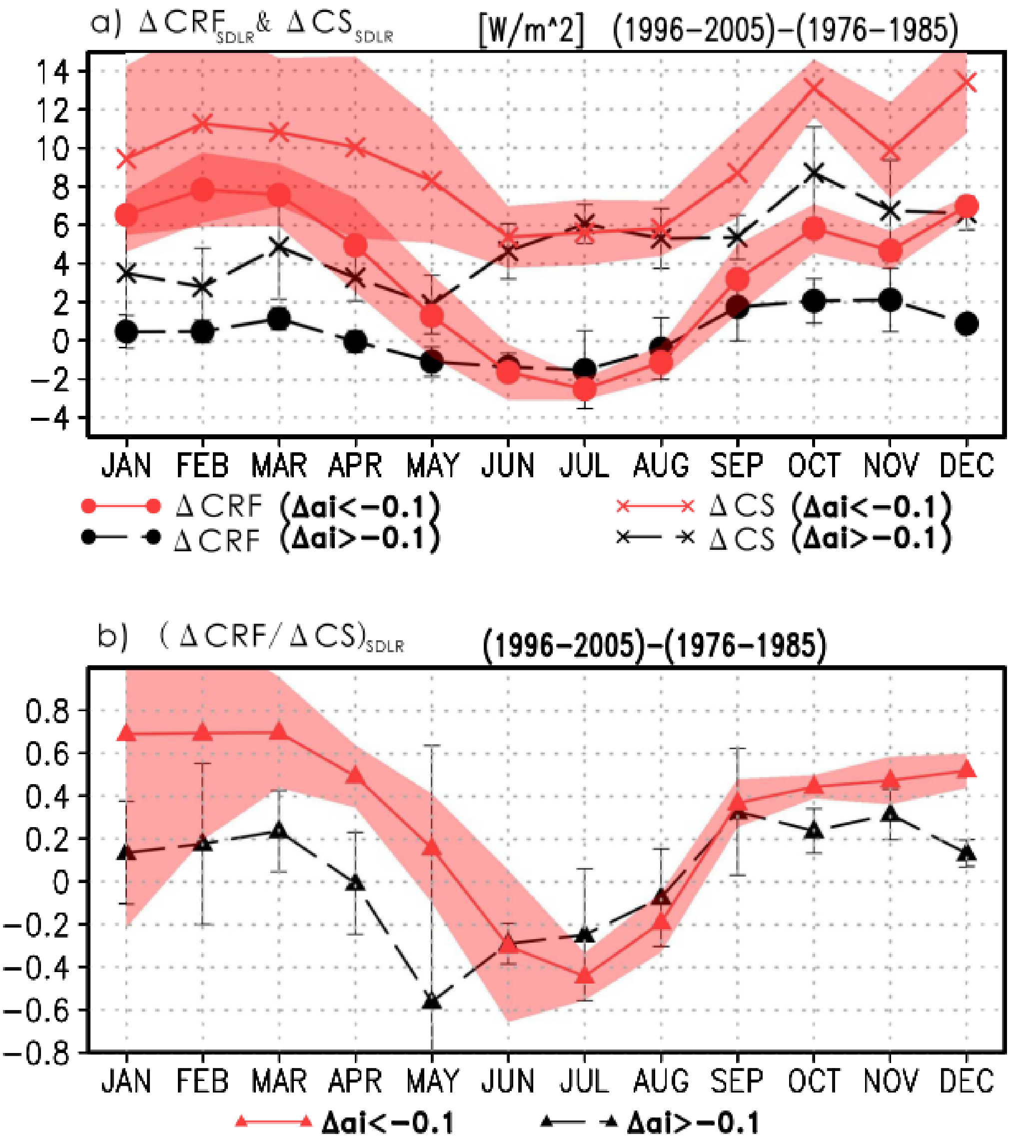
Positive large $\Delta \mathrm{CRF}_{\mathrm{SDLR}}$ in the case Δai- are found during September-April, whereas that in the case Δai+ is small. This result suggests the increase in the CRF of surface DLR is not negligible and potentially contribute to increasing the radiation energy into the surface at the grids with dominant reduction of sea ice concentration. However, compared with positively large $\Delta \mathrm{CS}_{\mathrm{SDLR}}$, $\Delta \mathrm{CRF}_{\mathrm{SDLR}}$ is smaller.

During summer, positively large $\Delta \mathrm{CS}_{\mathrm{SDLR}}$ and small $\Delta \mathrm{CRF}_{\mathrm{SDLR}}$ are found in the both cases, but the differences between the cases are quite small. This means that, in MIROC5, reduction of sea ice is unlikely to enhance difference in variation of surface DLR during summer.

Here, we introduce an index defined by the ratio ($(\Delta\mathrm{CRF}/\Delta\mathrm{CS})_{\mathrm{SDLR}}$) between $\Delta\mathrm{CRF}_{\mathrm{SDLR}}$ and $\Delta\mathrm{CS}_{\mathrm{SDLR}}$. Using this index, we evaluate relative importance of the change in CRF of surface DLR to the dominant change in clear-sky surface DLR. Figure 7b shows the annual time series of the index, $(\Delta\mathrm{CRF}/\Delta\mathrm{CS})_{\mathrm{SDLR}}$. The $\Delta\mathrm{CRF}_{\mathrm{SDLR}}$ is positive in grids in which the sea ice is reduced because the cloud cover increases as a result of reduced sea ice during fall-winter-spring, but that is negative during summer (Fig. 7a). Additionally, the $\Delta\mathrm{CS}_{\mathrm{SDLR}}$ is positive over the entire Arctic Ocean because of the increased air temperature and moisture (Fig. 7a). The indexes in Figure 7b are approximately 0.4-0.7 during the fall, winter and early spring, varying among the seasons. Although the indexes during winter are larger than that in the fall, the uncertainties shown with error-bar are quite large during winter. Further, the uncertainties in the indexes during spring are also large. The greater uncertainties are due to the small sample numbers of Δai- grids during winter and spring. Thus, it is hard to obtain a substantial result on the indexes during winter-spring. Further, as described above, during summer, no substantial differences between the cases in both the clear-sky surface DLR and the CRF of the surface DLR are found. This is common in the indexes during summer, showing no substantial differences in the indexes between the cases Δai- and Δai+ during summer (Fig. 7b).

In contrast, the uncertainties in the indexes during October-December are small in both the cases Δai- and Δai+. An increase in the cloud cover as a result of reduced sea ice enhances the surface DLR. The indexes during October-December means the all-sky surface DLR in the case Δai- increases by approximately 40-60% compared to the clear-sky surface DLR change. The indexes in the Δai- grids are larger than that in the Δai+ grids, although, in November, the index in the Δai- is not distinguished clearly from the index in the Δai+ grids. Thus, considering the reduction of sea ice area in October, the change in the CRF because of the reduced sea ice cannot be disregarded as a factor affecting the Arctic warming. This finding disagrees with Rinke et al. (2013). However, the index shown in Figure 7b is different from the averaged value over the Arctic Ocean. The averaged value is smaller in the winter and early spring because the area with a significant sea ice reduction is small during these seasons. "

The revised Figure 7 is put below.



Some questions and thoughts that might help guide further research:
Cloud cover appears to transition from a high summertime to a lower wintertime state in autumn. Is the increase in October just a delay in that seasonal cycle or does a new state emerge in a changing climate? How does cloud height change over the seasonal cycle?

A: We have confirmed that the increase in cloud cover in October is identified as a delay in the seasonal cycle.
In the late 20th century of the historical simulation by our model, the positive trend of cloud cover does not appear in September even at grids with the dominant reduction of

sea ice. However, there are the positive and large trend in the height of the cloud top and base at the grids during September and October. This result has been added in section 3.2 of the revised manuscript as below,

"In the region of the East Siberian and Beaufort Sea, where the sea ice significantly decreases, larger positive trends in the cloud cover are found. Further, the heights of the simulated cloud top and base increase dominantly in the region with large reduction of sea ice during October, while this is common in September."

Is there a clear dynamical distinction between areas with increasing cloud cover with and without sea ice retreat? Moisture convergence also occurs in some of the areas with sea ice retreat.

A: The dynamical distinction has been unclear, because our analysis focuses on vertical thermos-dynamical effect and the composite analysis used in this study may make horizontal effect obscured. Further, the additional analysis which is recommended by Referee #2 suggests that the enhanced moisture convergence only may be not sufficient to lead the increase in cloud cover in the grids without dominant reduction of sea ice. Analysis focusing on the dynamical effect on the Arctic cloud change is expected to be our future challenge.

Increases in cloud cover are substantial around Bering strait, but much weaker (or shifted to November) in the Barents sea, and very weak near Greenland. Why?

A: Variance of the linear trend in the cloud cover among ensemble members is large in the Barents Sea and near the Greenland, and then the averages of the linear trend for the all ensemble members are not significant. We have analyzed the difference in vertical profile of cloud fraction, air temperature, and specific humidity between regions. We also have analyzed the differences between ensemble members. Based on this analysis, we have included the following discussion in the content.

"In the Barents Sea and near the Greenland, however, significant positive trend in the simulated cloud cover are not found, despite of the dominant reduction of sea ice. Dynamical impact on atmosphere from the lower latitude region is strong in the Barents Sea and near the Greenland, as major atmospheric flows from the lower latitude are found during the fall, in MIROC5. Thus the dynamical impact may weaken the thermo-dynamic effect resulting from the increased open ocean in some ensemble members."

Related to the above: Is there a spatial pattern in the seasonal cycle of cloudiness? If so, is that pattern related to sea-ice cover?

A: No. Over the Arctic Ocean, cloud cover is maximum during summer and then decrease during fall. During winter cloud cover is minimum and then increases during spring. The seasonal cycle of cloudiness over the Arctic Ocean with sea ice are very similar.

Can you demonstrate the thermodynamic effect of later refreezing of the sea surface on clouds e.g. in a single-column model?

A: No, we can't. Unfortunately, we do not have a single-column model. In the future, if we are available a single-column model, we would like to try it. We had thought about another method to demonstrate that, but had not come up with any good ideas. However, we believe that our results without the demonstration show adequately the thermodynamic effect of the reduction of sea ice on clouds.

To what extent are changes in LW CRE at the surface caused by temperature changes, and to what extent by changes in cloud properties?

A: This comment is very similar to or the same as the second comment from Referee #1. Please read our response to the second comment.

Besides these suggestions for further research, the following major issues should be addressed before resubmission or submission of a revised version.

As mentioned above, the visual match between changes in two quantities does not establish a causal relationship. Please make sure to only claim causality where this has been convincingly demonstrated in your own manuscript or in elsewhere in the literature.

A: This comment is the same as the first comment from Referee #1. So, please read our response to the first comment.

I recommend reserving the use of "significant" for instances where a formal statistical significance test has been carried out. In these cases, the significance level (e.g. the p-vale obtained) should be documented.

A: We agree with the comment. In linear trend analysis, we have conducted a statistical test, in which we tested if the linear trends in grids are zero or not. We revised descriptions of results without statistical test, as commented.

We included dots which shows statistical significance at the 95% level in the revised Fig. 3. We changed "significant" to "dominant" or "substantial" in descriptions about results without statistical test.

AA refers to larger temperature change in the Arctic compared to lower latitudes. To make a statement on how a feedback affects Arctic amplification, one therefore needs to assess the feedback both in the Arctic and at lower latitudes. This is trivial for the albedo feedback, which is absent at low latitudes, but non-trivial for cloud and water vapour changes, which also affect low-latitude warming. It may thus be more specific to discuss cloud effects on Arctic warming rather than on AA.

A: We appreciate and agree with the comment.
We changed "AA" to "Arctic warming" in section 3, result, and section 4, discussion, of the revised manuscript.

How relevant is the shortwave effect of increases in cloudiness in October compared to the LW effect (again, CRE is a dangerous measure as it strongly depends on the underlying albedo)?

A: We have additionally analyzed the shortwave effect of cloudiness. We includes Figure A on this analysis below. Upper figure of Fig. A shows annual cycle of the difference in the cloud radiative effect (CRE) of surface downward shortwave radiation (DSR) between the early and the latter periods. The differences are averaged for the grids with or without the dominant reduction of sea ice. The black and red lines in the figure indicate the difference for the grids with or without dominant reduction of sea ice, respectively. Lower figure of Fig. A is the same as upper figure except the ratio of the difference o CRE of surface DSR to clear-sky surface DSR. The result show that the change in the CRE of surface DSR is quite small compared with the clear-sky surface DSR.

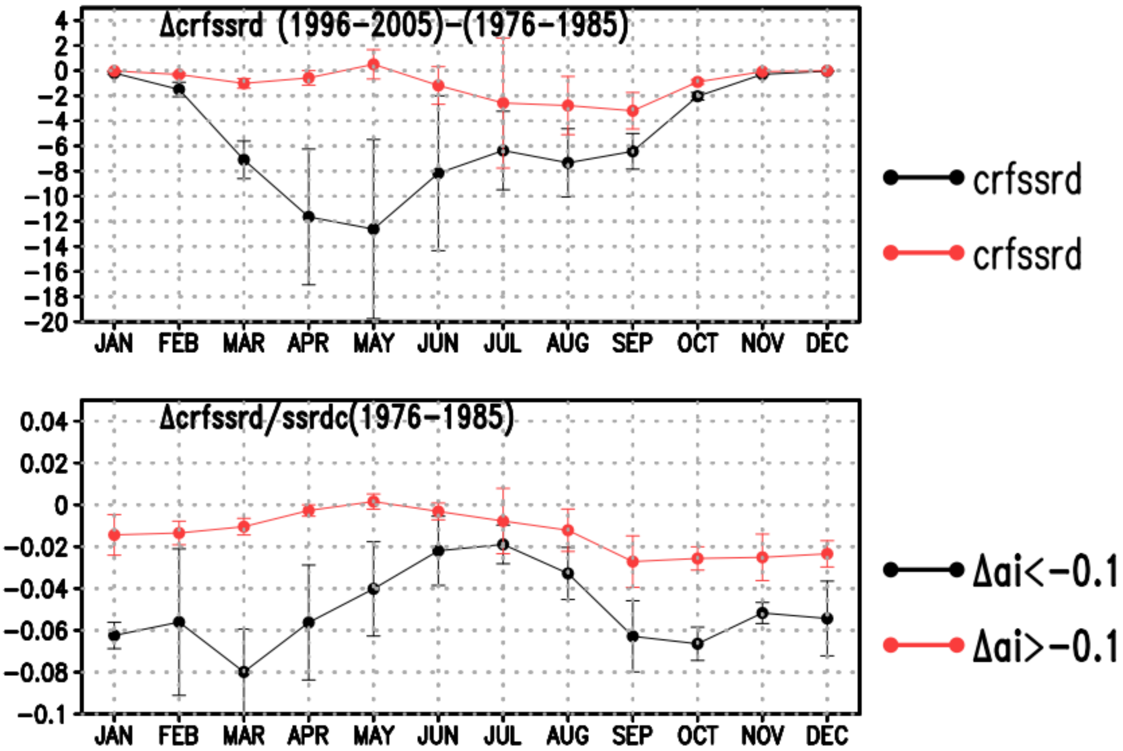


Figure A. (Upper) Annual cycle of the difference in the cloud radiative effect (CRE) of surface downward shortwave radiation (DSR) between the early and the latter periods. (Lower) the same as upper figure except the ratio of the difference of CRE of surface DSR to clear-sky surface DSR. The differences are averaged for the grids with or without the dominant reduction of sea ice. The black and red lines in the figure indicate the difference for the grids with or without dominant reduction of sea ice, respectively.

We have included the result in the final paragraph in the subsection 3.4 of the revised manuscript as below,

"We also compared the change in the CRF of the surface downward shortwave radiation (DSR) with clear-sky surface DSR in both the cases Δai- and Δai+. The change in the CRF of the surface DSR in the case Δai+ is a small fraction of the clear-sky surface DSR over the year. The result in the case Δai- shows that the change in the CRF of the surface DSR is less than 10 percent of clear-sky surface DSR during summer, fall and winter, and also that the change during spring has large uncertainty in the case Δai- (not shown). In addition, during winter, clear-sky surface DSR is close to zero. Therefore, we can conclude the impact of the cloud cover change resulting from the reduction of sea ice on the surface DSR is quite small during fall.."

where are the gridpoints with positive trends in sea ice located? Atmospheric profiles *between both groups of points already differ in the earlier period – are those points dynamically different? Could this affect differences in the trends in cloud cover as well as sea ice trends?*

A: We appreciate this comment. We had checked this point. In the original analysis, many sample grids with positive trends in sea ice were located mainly near the Barents Sea. In additional checks, we found that many of the sample grids with the positive trend were included in one ensemble member and the number of the sample grids with the positive trend was much smaller than that of sample grids with the dominant negative grids in October. These may not totally satisfy a purpose of our analysis. In this revision, thus, we have modified a sampling way for the Δai+ used in the composite analysis to improve the samples for Δai+. The Δai+ grids in the revised manuscript are grids with the linear trend of sea ice concentration above -0.1 /decade in 65-73°N. The reasons why the grids are limited in the latitude band, 65-73°N, are that the Δai- grids with the dominant trend of sea ice in October are located mainly in the this latitude band and to sample the Δai+ grids so that the sum of the Δai+ grids is similar to the sum of Δai- grids in October. (Those in the original manuscript were grids with that above 0 (zero) /decade over entire the Arctic Ocean.) Although this modification affects some results, major results in this study did not influenced by this modification of sampling way. Furthermore, by this modification, in Fig. 5, the simulated vertical profiles in the earlier period for Δai- is very similar to those for Δai+, because the grids in both cases are located in the equivalent latitude band. Thus, the difference of the vertical profiles between the earlier and the latter periods for Δai- is easily distinguishable from that for Δai+.

Related to this comment, we modified a sampling way for the Δai+ as mentioned above, and then we revised Fig. 5. The revised Fig. 5 shows more clearly the differences in the lapse rate of air temperature between the earlier and the latter periods than that in Fig. 5 in the original manuscript. Thus, figures of the lapse rates of air temperature and specific humidity, which are in Fig. 6 of the original manuscript, has been removed in the revised manuscript. This removal is also a recommendation from Referee #2. The revised descriptions in subsection 3.3 are as follows,

"Figures 6e and 6f show that the specific humidity in the lower troposphere increases more dominantly in the case Δai- than that in the case Δai+, although increases in the specific humidity in whole levels shown in the figure are found for both cases (Fig. 6f). Compared with the change in the saturated specific humidity (*qsat*, dot-dot-dash lines in Figures 6e and 6f), in the case Δai-, the increase in the specific humidity is near to that in the *qsat* at levels with increases in the cloud fraction. Therefore, the relative humidity increases and enhances the cloudiness in these levels (Figures 6b and 6d). However, increases in the specific humidity are smaller than those in the *qsat* at thin layers near the surface. The large increase in the *qsat* at the thin layers is attributable to large increase in air temperature in the case Δai-. Figures 6g and 6h show that the air temperature increases with the maximum increase at the surface. The substantial increases in air temperature in the case Δai- are found in layers between the surface and σ=0.85 (approximately 1200 m) (Figure 6f). Therefore, in the surface thin layers, the relative humidity decreases and reduces the cloudiness. These changes in simulated vertical structures in air temperature and specific humidity between the earlier and latter periods for the case Δai- correspond with the differences in those between low sea ice years and high sea ice years in ERA-interim in Cuzzone and Vavrus (2011), although the differences in cloud fractions in the layers near surface are much larger in ERA-interim.

The lapse rate of the specific humidity in the case Δai- becomes large at overall lower tropospheric levels in the latter period, compared with that in the case Δai+ (Fig. 6e). We interpret that this increase in the lapse rate of the specific humidity in MIROC5 reflects an increase in water vapor from open ocean and an enhancement of vertical water cycle including processes of convection, cloud and precipitation, because simulated cloud fractions and precipitation increase in addition to evaporation from the open ocean. Much water vapor from the open ocean can be vertically transported to higher levels by vertical mixing and convection, and then the transported water vapor can be removed from the atmosphere through the phase change in processes of cloud and precipitation at levels at which cloud fraction increases. As a result, the lapse rate of the specific humidity may not decrease at any lower tropospheric levels. Thus these process can transported the water vapor increased near open ocean effectively to the higher levels, contributing to increase in cloud and precipitation. On the other hand, in the case Δai+, as the lapse rate of the specific humidity is small in the layers near the surface, vertical diffusion (turbulent mixing) of water vapor is quite weak. However, in this interpretation of the process of enhanced vertical water cycle, an effect of the horizontal advection of water vapor is not considered, because the horizontal effect was obscured by averaging the data for grids and ensemble members in the composite analysis.

The lapse rate of the simulated air temperature is extremely large in the thin layers close to surface in the case Δai- (Fig. 6g). Increase in sensible heat and longwave radiation from ocean to the atmosphere lead dominant increase in air temperature, because SST in the open ocean is near zero and much higher than air temperature. Further, the radiative cooling in all atmospheric levels can contribute to smaller lapse rate in the air temperature at the layers except the surface thin layer. Thus, the strong heat diffusion (turbulent mixing) in MIROC5 is confined in the surface thin layers."

You seem to argue that because of the steeper lapse rate for temperature than humidity, the latter can more easily be mixed into the free troposphere. However, in the absence of phase changes, turbulent mixing should influence temperature and moisture alike. This is at least misunderstandable. Furthermore, I do not understand the claim that there is no steady moisture sink in the Arctic - is there no (relevant) precipitation in the months and regions you analyse?

A: We appreciate this comment. Explains related to the change in the vertical profiles of air temperature and specific humidity in the original manuscript might be insufficient. Also, we agree with the comment on a lack of the result of precipitation change. Therefore, we have revised the descriptions on the lapse rate of the specific humidity and air temperature, and then we have included the result of precipitation change in the revised description. The point of turbulent mixing from the referee should be correct. However, the vertical profiles shown in Fig. 6 are the results including all processes such as cloud and precipitation. Accordingly, we have revised the description, which is the same as the description in the previous response.