Responses to referee 2 comments

We thank anonymous referees for their constructive comments and helpful suggestions.
We have revised our manuscripts based on their comments. We wrote responses to each referees' comments below.
Referee's comments are indicated in Italics and underscored, and then our answer follows immediately.

Overview Overall, there are some interesting climate connections and feedbacks eluded to in this manuscript. Unfortunately, the major deficiency lies in both the conclusions drawn and their communication. I agree with previous reviewers that the additional analysis has improved the paper substantially, but feel it is tacked on (which I guess is technically true as it's the entirety of the Appendix). This is great work and a nice analysis, but this manuscript needs major revisions before it should be accepted for publication in ACP.

Major comments
First and most importantly, there is too much narrator-like reporting of model output. While necessary, this should not be the focus of a paper of this nature. A more appropriate approach would be to describe the climate relationships and features of the model first, and then use figures to support your statements. This is especially true for the Results section, which as is is a difficult read.

We greatly appreciate this comment. According to this comment, we revised many descriptions, mainly in Result sections, and also added descriptions needed in contexts of the paragraphs or sections. Since many descriptions have been modified and added in the revised manuscript, we would like to show you several descriptions modified or added as examples below. Then, we would like to ask you to make sure all the changes on the track-changes version of our manuscript or compare the revised manuscript with the original manuscript.

(Section 3.1, Simulated change of Arctic sea ice and clouds in the revised manuscript)

"According to observations, the seasonal minimum SIA occurs in September, and Arctic sea ice cover generally begins to recover in October. The overall feature of the Arctic SIA seasonal cycle (e.g., summer reduction and fall recover) were reproduced by MIROC5, though there are small differences between the observations and simulations (Komuro et al., 2012). Figure 2a shows the simulated seasonal SIA cycle in MIROC5, averaged for the periods 1976-1985 (blue line) and 1991-2005 (red line), has a maximum in March and a minimum in August. Figure 2b displays the changes in the simulated seasonal cycle between the two periods, 1976-1985 and 1991-2005. The decreases in the simulated Arctic SIA in all months and the maximum reduction in September, consistent with observations of the Arctic SIA (Comiso et al., 2008), probably due to recent global warming are found.

As for the simulated cloud cover averaged over the Arctic Ocean (Figures 2c and 2d), low-level cloud cover is at maximum of 50% in summer and continuously decreased during fall and winter, reaching a minimum in April. The simulated seasonal amplitude of the total cloud cover was similar to that of the low-level clouds; the seasonal cycle of the total cloud cover can be explained by the low-level clouds in MIROC5……"

"Geographical match of the reduction of sea ice and the increase in cloud cover in the Arctic Ocean is crucial to discuss the interaction between changes in sea ice and cloud cover in the Arctic Ocean. The geographical distributions of the simulated linear trends in total cloud cover and sea ice concentrations (SICs) from 1976 to 2005 in September, October, and November are shown in Fig 3. The linear trends were calculated using the least squares method at each grid, and tested for statistical significance to determine whether the trend was zero using a t-test…."

(Section 3.2.1 Autocorrelation and lead/lag correlation analysis in the revised manuscript)

"We have analyzed causality between reductions of SIC and increasing cloud cover with the autocorrelation and lead/lag correlation analysis during 1976-2005. In addition to negative correlation between cloud cover and SIC in October, negative correlation between cloud cover in October and sea ice in September would mean reduction in sea ice causes increase in cloud cover. Figures 4a shows the geographical distribution of one-month-lagged autocorrelations of sea ice concentrations between September and October, and Figure 4b does that of instantaneous correlations of cloud cover and sea ice concentrations in October. For the autocorrelation in sea ice concentration between September and October, large positive correlation coefficients were found over most of the Arctic Ocean; the correlation coefficient exceeded 0.6 from the Beaufort Sea to the Barents Sea (Fig. 4a). As for the temporal changes of the autocorrelation in the representative sub-region of the Arctic Ocean (109-221°E, 69-78°N), shown with the broken line in Fig. 4a, it was high for SIC (blue circle in Fig. 4c), and become low in early and late months more slowly than that for the cloud cover (black circle in Fig. 4c). That is because SIC has a substantially longer memory than cloud cover. These results imply that sea ice changes in October tend to depend on sea ice changes in September in MIROC5; i.e., small SIC in September is likely to results in small SIC in October."

(Section 3.2.2 Sensitivity experiment by using atmospheric GCM)

“The annual cycles of cloud cover averaged for the Arctic Ocean were reasonably simulated and similar to that in the historical MIROC5 simulations in all of the sensitivity simulations, though the cloud coverage in July and August (from October to May) was slightly smaller (larger) than that in the historical simulations (Fig. 5b). Causes of these differences between the sensitivity experiments and the historical runs might be that changes in SST and sea ice and variability of interactions between atmosphere and ocean (sea ice) in time-scale smaller than month are not included in the sensitivity experiments, and also that the internal variability in atmospheric circulation varies between the sensitivity experiments and the historical runs. ..”

“Geographical agreement of the differences in cloud cover and sea ice cover is important to prove the impact of sea ice reduction on cloud cover increase, as examined in the historical simulations (Fig. 3). The geographical maps of cloud cover in October for the CTL and ALL2000 experiments and the differences in each experiments from CTL are shown in Fig. 6. Increases in cloud cover are remarkable in the SIOF2000 and ALL2000 experiments particularly at the grids with large sea ice reductions (Figs. 6d and 6f). These indicate that the large increases in cloud cover are due to sea ice reduction. Besides, increases in cloud cover were also found at the grids with small reductions in sea ice. ….”

(Section 3.3. Cloud cover changes resulting from reduced sea ice in the revised manuscript)
“We compared the vertical profiles of cloud fraction, relative humidity, specific humidity and air temperature in cases with and without the substantial reduction of sea ice and those differences between the cases in October, to clarify a mechanism of the increase in cloud due to the sea ice reduction (Fig. 8). In Fig. 8, the “ΔSI-” case is defined by grids with substantial reduction in SIC (a linear trend in SIC of less than -0.1/decade). As shown in Fig. 3b, many of the ΔSI- grids were located over a broad region, including the Laptev Sea, the East Siberian Sea and the Beaufort Sea. The “ΔSI+” case is defined by grids without substantial reduction in SIC (a linear trend in SIC exceeding -0.1/decade) over a limited latitude band (i.e., 65°-73°N). …”

Secondly, I feel that the emphasis should be shifted from MIROC model output to the lead-lag correlation analysis and the sensitivity simulations currently included in the Appendix. These are the most compelling aspects of this paper but are overshadowed by an overabundance of standard model output discussion. My suggestion is to move the lead-lag and correlation analysis to its own section. I feel that the sensitivity results should also be in the main body. After a brief introduction on how the model performs compared to observations, then discuss the correlation between sea ice and cloud fraction, and finally reinforce those correlations with results from the sensitivity analysis.

We appreciate this comment. Based on this comment, we modified result section. In the revised manuscript, both results of autocorrelation and lead/lag correlation analysis and sensitivity experiments were included in subsection 3.2 of the main body. These changes should make the results more noticeable rather than those in the original manuscript. Related to this modification, descriptions on the linear trend of sea ice and cloud cover in subsection 3.2 of the original manuscript were moved to subsection 3.1.

(Section 3.2 in the revised manuscript)

"

3.2 Causality between changes in Arctic sea ice and cloud

3.2.1 Autocorrelation and lead/lag correlation analysis

We have analyzed causality between reductions of SIC and increasing cloud cover with the autocorrelation and lead/lag correlation analysis during 1976-2005. In addition to negative correlation between cloud cover and SIC in October, negative correlation between cloud cover in October and sea ice in September would mean reduction in sea ice causes increase in cloud cover. Figures 4a shows the geographical distribution of one-month-lagged autocorrelations of sea ice concentrations between September and October, and Figure 4b does that of instantaneous correlations of cloud cover and sea ice concentrations in October. For the autocorrelation in sea ice concentration between September and October, large positive correlation coefficients were found over most of the Arctic Ocean; the correlation coefficient exceeded 0.6 from the Beaufort Sea to the Barents Sea (Fig. 4a). …..

3.2.2 Sensitivity experiment by using atmospheric GCM

To further examine the effect of reduced sea ice on Arctic cloud cover, we conducted sensitivity experiments with atmospheric component of MIROC5 (MIROC5-AGCM) under different combinations of SST, sea ice and other forcings, such as greenhouse gases, aerosols, and land use, in 1980s to 2000s (Table 1). The setting of these experiments is described in section 2.

…

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Minor comments

-The Introduction is often redundant due to organizing the discussion by "data type". This way, each process is discussed multiple times but from different perspectives, leading to reader confusion about what the actual state of knowledge on sea ice – atmosphere interaction is. For example, Schweiger et al., 2008 shows up multiple times in the introduction, sometimes in agreement and sometimes not.

According to this comment, we revised the introduction, which treats in turn topics of “Arctic warming and Arctic amplification”, “increased cloud cover with sea ice reduction”, “radiative effect of increase cloud on Arctic warming” and “model study on increased Arctic cloud”.

(Section 1. Introduction in the revised manuscript)

“Satellite observations have shown that Arctic sea ice has decreased gradually since the 1980s (Comiso et al., 2008). Recent significant reductions in Arctic sea ice occurred in 2007 and 2012. A further reduction in Arctic sea ice is likely to result from future global warming. In turn, the reduction in sea ice can accelerate surface warming in the Arctic region through various feedback processes. A major feedback process in climate change is the ice-albedo feedback, in which reduced sea ice decreases the global albedo and increases shortwave radiation entering the climate system (e.g.,Curry et al., 1995; Dickinson et al., 1987; Manabe and Stouffer, 1980; Perovich et al., 2007). This feedback is likely to occur in high-latitude regions, where snow cover and sea ice are seasonally extended. However, as Yoshimori et al. (2014) mentioned with the climate model results that Arctic surface warming in autumn-winter is attributed to seasonal reduction of ocean heat storage and increased cloud greenhouse effect, other processes such as ocean heat uptake process, atmospheric stability, and low-level cloud response may require further attention to better understand the Arctic warming mechanism.

The reduction in sea ice also involves other feedback processes in the Arctic region (Serreze and Barry, 2011). Previous studies have suggested that extended periods of open ocean resulting from reductions in sea ice increase Arctic cloud cover and enhance Arctic amplification (e.g., Holland and Bitz, 2003; Screen and Simmonds, 2010; Serreze and Barry, 2011; Vavrus et al., 2009; Yoshimori et al., 2014). Liu et al. (2012) used satellite data to show that a 1% decrease in sea ice concentration leads to a 0.36-0.47% increase in cloud cover. These authors also suggested that the total variance in cloud cover from July to November can be explained by the sea ice-cloud feedback. Recent ship observations have found that cloud base heights tend to increase in September over the Arctic Ocean without sea ice cover due to heating from the ocean (Sato et al., 2012). This heating is enhanced because of the increased temperature gradient between the atmosphere and the ocean, weakening the stable conditions in the atmospheric boundary layer. This previous study indicated that convective clouds become more numerous over the Arctic Ocean. However, whereas Kay and Gettelman (2009) showed that increased turbulent transport of heat and moisture promotes low-cloud formation, Schweiger et al. (2008) showed that low-level clouds may decrease and middle-level clouds simultaneously increase in coverage because the decreased static stability and a deepening atmospheric boundary layer contribute to a rise in the cloud level. Simulations run by Porter et al. (2012) with the Weather Research Forecasting (WRF) model support an increase in middle-level clouds in September and increases in low-level cloud cover from October to November. The cloud cover change resulting from sea ice loss and its vertical profile are under debate.

Wu and Lee (2012) suggested that the enhanced downward longwave radiation (DLR) resulting from increased cloud cover may have been responsible for the enhanced autumnal increase in the surface air temperature (SAT). In addition, the enhanced DLR can prolong the sea ice melt seasons and lead to a positive feedback involving Arctic sea ice loss (Serreze and Barry, 2011). However, Schweiger et al. (2008) concluded that the radiative effect of this change is relatively small because the direct radiative effects of cloud cover changes are compensated by changes in the temperature and humidity profiles associated with varying ice conditions. A regional climate model simulation has also shown that the radiative effect of cloud cover changes is likely to be smaller than that of changes in air temperature and humidity (Rinke et al., 2013). Because of the deficiency in observed radiation data at the surface, the radiative effect of cloud clover changes in the Arctic warming remains controversial.

In addition to the analysis of observations, several studies have employed climate model simulations. Climate models that have simulated sea ice reduction show that Arctic cloud cover increases in fall (Vavrus et al., 2011; Vavrus et al., 2009). An increased area of open ocean enhances the heat and moisture transport from the ocean to the atmosphere, resulting in increased cloudiness. These studies have analyzed the change in cloudiness resulting from sea ice losses in simulations with increased greenhouse gas concentrations. The effects of reduced sea ice in these analyses are stronger than those occurring in the late 20th century. Therefore, these results are not always appropriate for the change in Arctic cloudiness that has occurred since the late 20th century, in which sea ice has only decreased in limited regions. These investigations may be insufficient to understand recently observed events and may not effectively explain recent processes in simulated climate models."

-Nearly every paragraph starts with "Figure X shows. . .", leading to a figure-driven discussion. While this nicely walks the reader through the figures, it requires themselves to make the connections between the climate components.

This comment is related to the second major comment. We modified descriptions commented here according to the second major comment. Thus, we would like to ask you to read our responses to the second major comment.

-There is a lot of discussion of low-cloud versus total cloud. This tends to be confusing, but am also skeptical of climate models ability to delineate these different cloud types.

We agree with that climate models have problems on simulating different cloud types, particularly in the Arctic region. However, in the Arctic region, vertical profile of cloud cover changes due to sea ice reduction or global warming is important to understand a mechanism of the cloud change and a radiative effect of the increased cloudiness, as previous studies (e.g., Schweiger et al 2008, Cuzzone and Vavrus 2011) also focused on this point. Thus, although several discussions on this point were removed in the text, descriptions on this point were modified so that the descriptions do not confuse an issue of this study.

(Section 3.3 Cloud cover changes resulting from reduced sea ice)

"These results were consistent with the changes in cloud fraction. The simulated vertical structures of cloud fraction and relative humidity in the latter period for the ΔSI- are very similar to those for low sea ice years in the ERA-interim data set (Cuzzone and Vavrus, 2011) and those for below-normal ice concentration in ERA-40 data set (Schweiger et al., 2008), although the values in this study differ from those in the reanalysis data sets. Furthermore, our results are consistent with those of the satellite measurements of Palm et al. (2010), which showed increased autumnal clouds near the surface (within 500 m) over sea ice rather than open ocean."

-Figures 4 is the most compelling result of the main text. As such, I would split it into two, separating the autocorrelation and the sea ice-cloud correlation, and give this analysis its own section in the paper. Similarly, Figure 6 and the attending text is a very nice result but currently somewhat buried.

We appreciate your comment. According to this comment, we modified the manuscript so that subsection 3.2.2 of the revised manuscript deals with analysis of the autocorrelation and the lead-lag correlation between sea ice and cloud cover. However, because comprehensive results from analyses of autocorrelation and lead/lag correlation between sea ice and cloud cover suggests a possible causality between increase in cloud cover and reduction of sea ice, separating the autocorrelation and the lead-lag correlation was not made in this revision.

For the comment on Fig. 8 (Fig. 6 in the original manuscript), we modified section 3.3 based on this comment and reviewer1's comment. Descriptions on Fig. 8 which are not main issues in this study were removed according to reviewer1's comment.

-For myself, Figures A1 and A2 are some of the most interesting of the paper. Really try to get these featured more prominently (and definitely in main text).

This comment is the same as the second major comment. We would like you to read our responses to the second major comment.

Specific comments

Page 1 Line 17: "not a minimum" – more precise language needed

We removed the sentence commented here according to the reviewer1's comment.

Page 3 Line 6-7: "Therefore . . ." – many sentences in the introduction take the form "the disagreement in the literature imply we don't know anything and need more studies", but only one is needed.

We removed several sentences and modified the related paragraphs, based on this comment. This comment is related to the first minor comment, so we would like to ask you to read our response to the first minor comment.

Page 3 Line 16-17: ". . . enhanced DLR. . ." – is there a reference for this?

We added a reference as follows,
(Introduction in the revised manuscript)
" In addition, the enhanced DLR can prolong the sea ice melt seasons and lead to a positive feedback involving Arctic sea ice loss (Serreze and Barry, 2011)."

Page 4 Line 4-5: "Recent ship observatins. . ." - is there are reference for this?

We moved a reference used in the following sentence to a reference for this sentence.
(Introduction in the revised manuscript)
"Recent ship observations have found that cloud base heights tend to increase in September over the Arctic Ocean without sea ice cover due to heating from the ocean (Sato et al., 2012)."

Page 6 Line 14: ". . .divided. . ." – this sentence is not clear. How are they divided? Spatially? Categorically?

They are divided by sea ice thickness categories. We modified the text related to this topic as follows,
(Section 2. Model and Experiments in the revised manuscript)
"The sea ice in each horizontal grid is divided into five ice thickness categories in addition to open water. The lower bounds of ice thickness for these categories are 0.3, 0.6, 1.0, 2.5, and 5.0 m."

Page 6 Line 21-26: "Historical. . ." - each of the first three sentences start exactly the same.

According to this comment, we modified these sentences as follows,

(Section 2. Model and Experiments in the revised manuscript)
"Historical simulations are performed from 1850 to 2005 using anthropogenic forcings recommended by the CMIP5 project. In the simulation, changes in the solar constant are applied according to Lean et al. (2005). Also, the optical thickness of volcanic stratospheric aerosols are given by Sato et al. (1993), and subsequent updates are available (http://data.giss.nasa.gov.modelforce/strataer/)."

Page 7 Line 10-23: I feel like this paragraph and some of the next do not fit in the Results section.

We appreciate this comment. We moved the paragraphs to the previous section, model and experiments, because the paragraphs explained reproducibility of MIROC5.

Page 9 Line 6: "agrees" – in what way does this agree with the cited studies?

We modified the sentence.

" The largest increase in simulated cloud cover in October agrees with previous studies using satellite data and climate model simulations (Liu et al., 2012; Vavrus et al., 2011; Wu and Lee, 2012). "

Page 9 Line 22: "narrow" – what do you mean by this?

We modified the sentence according to this comment.

(Section 3.1. Simulated change of Arctic sea ice and clouds in the revised manuscript)
"Negative trends in SICs remained in October (Fig 3b), although the area with substantial negative trends became smaller than that in September."

Page 10 Line 3: "(not shown)" – all of these "not shown"s are fine if they are a natural part of the story, but as is these only muddle the message by referring to unimportant model results.

We thank you for this comment. We removed the term "not shown".

Page 11 Line 23: - this lead/lag result is nice finding and a highlight of the paper but here is buried at the end of a paragraph!

This comment is the same as the second major comment. We would like you to read our responses to the second major comment.

Page 13 Line 7: "delta ai+" - this nomenclature is confusing. A more wordy alternative might be appropriate. Also, the explanation for these two metrics can be clarified.

We appreciate this comment. Although "ai" is used as variable names of sea ice concentration in our model community, this may be not normal and general. We changed ai to SI that is abbreviation of Sea Ice. The explanation for these metrics was modified.

(Section 3.4, Cloud cover changes resulting from reduced sea ice in the revised manuscript)
"In Fig. 8, the "ΔSI-" case is defined by grids with substantial reduction in SIC (a linear trend in SIC of less than -0.1/decade). As shown in Fig. 3b, many of the ΔSI- grids were located over a broad region, including the Laptev Sea, the East Siberian Sea and the Beaufort Sea. The "ΔSI+" case is defined by grids without substantial reduction in SIC (a linear trend in SIC exceeding -0.1/decade) over a limited latitude band (i.e., 65°-73°N). "

Page 14 Line 22: This discussion of the lapse rate is quite lengthy and really only making a few points. You don't need to discuss every detail of the model results. In fact it detracts from the paper. Your job as author is to interpret your results and then distill your findings down for the reader.

Base on this comment and reviewer1's comment, we removed descriptions on this topic from section 3.3.

Page 14 Line 24: "lapse rate of specific humidity" – is this a real thing?

This term may be not correct, because the term is for air temperature. It may be better to change this term to "decreasing rate of specific humidity with the altitude". However, according to other comments from reviewers, we removed the descriptions including this term.