Response to the Review's Comments

The manuscript has been revised carefully according to the reviewer's constructive comments. We believe the manuscript is further improved by more clarifications, particularly for the dynamical and thermodynamical processes engaged with the AD variability. Below is our line-by-line response to the reviewer's specific comments.

(1) Calculating the net surface heat flux anomalies associated with the summer AD
The decrease in upward shortwave radiation (decreased albedo) is usually a dominant factor for the net surface heat flux (SW_up + SW_dn + LW_up + LW_dn + SHF + LHF). I cannot understand why the authors were not able to see the decreased net surface heat flux over the regions where SIC decreased. I would urge the authors to re-calculate the net surface heat flux anomalies during the summers of strong negative AD. The authors should be able to see a significant decrease in upward shortwave radiation at the surface (SW_up) over the regions where SIC is anomalously small even though the SIC reduction was primarily driven by winds. Also, the net surface heat flux anomalies over the land need not be plotted because we are focusing on the heat flux over the Arctic Ocean.

➔ Following the reviewer's comment, we modified Figure S3 by showing the total net surface heat flux anomalies associated with the summer AD including radiative flux terms. We also masked out the values over the land.

➔ As the reviewer surmised, the surface heat flux change driven by AD (Fig. S3) corresponds well with the sea ice concentration change pattern shown in Fig. 6. The net downward surface heat flux anomalies are negative in the sea ice increasing region such as in the Atlantic sector of the Arctic Sea, and positive for the rest of the regions where the sea ice decreases. The surface heat flux anomalies are mostly contributed by the changes in the shortwave radiation terms (See Fig. R1 below for the comparison of each contributing terms to the total surface heat flux). In particular, the upward shortwave radiation (Fig. R1e) tends to decrease significantly in the East Siberia, Chukchi, and Beaufort Seas where the sea ice melting signal by AD is pronounced in the recent period (Fig. 6b). This process is also reflected in the reduction of surface albedo due to the sea ice decrease (Fig. R2). The response of surface albedo becomes larger and much clearer in the recent period.

➔ As the reviewer commented out, aforementioned changes in surface flux associated with the summer AD suggest that the sea ice-albedo feedback may also contribute to the changes in sea ice concentration in addition to the transpolar sea ice drift by AD wind anomalies. Therefore, one cannot rule out the important role of the thermodynamical process for the sea ice variability associated with AD.

➔ We reflected this point in the revised manuscript (Page 8 line 14-25).

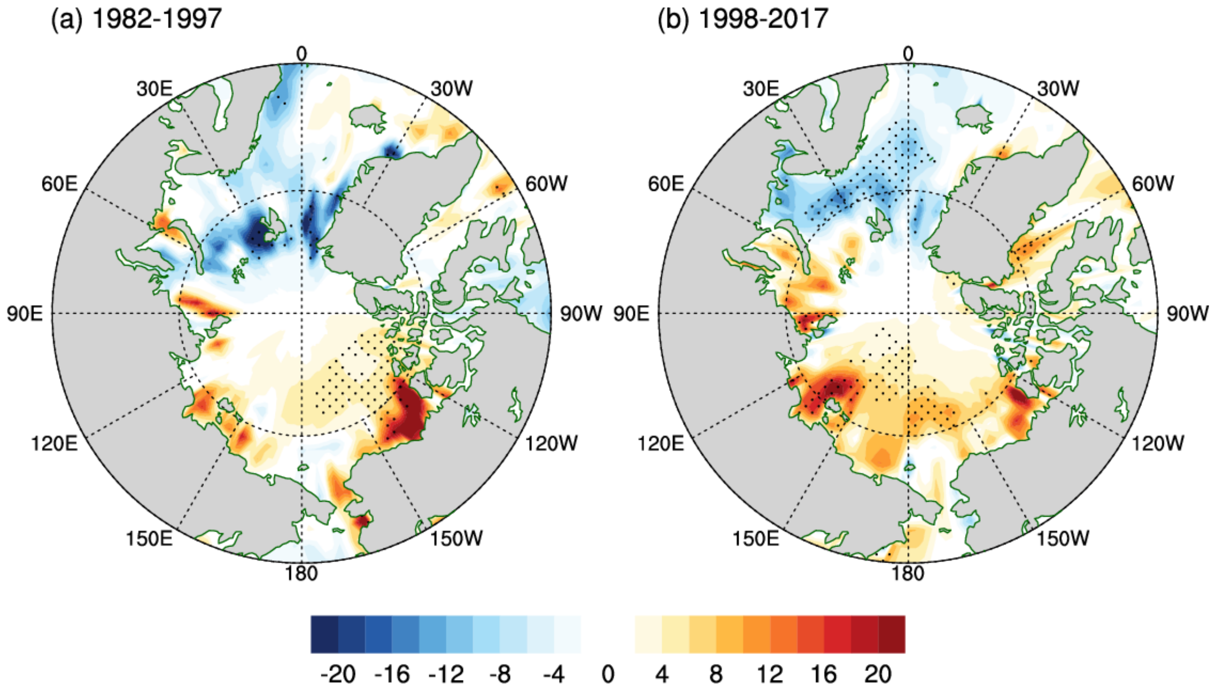

Figure S3. Regression patterns of net downward surface heat flux (sensible + latent + net short wave + net long wave, W m-2) onto the AD index for (a) the early (1982-1997) and (b) the recent (1998-2017) period. The heat flux is defined as positive for the downward, and the AD index is reversed in sign before regression. Dotted area indicates the statistically significant region at the 95% confidence level.

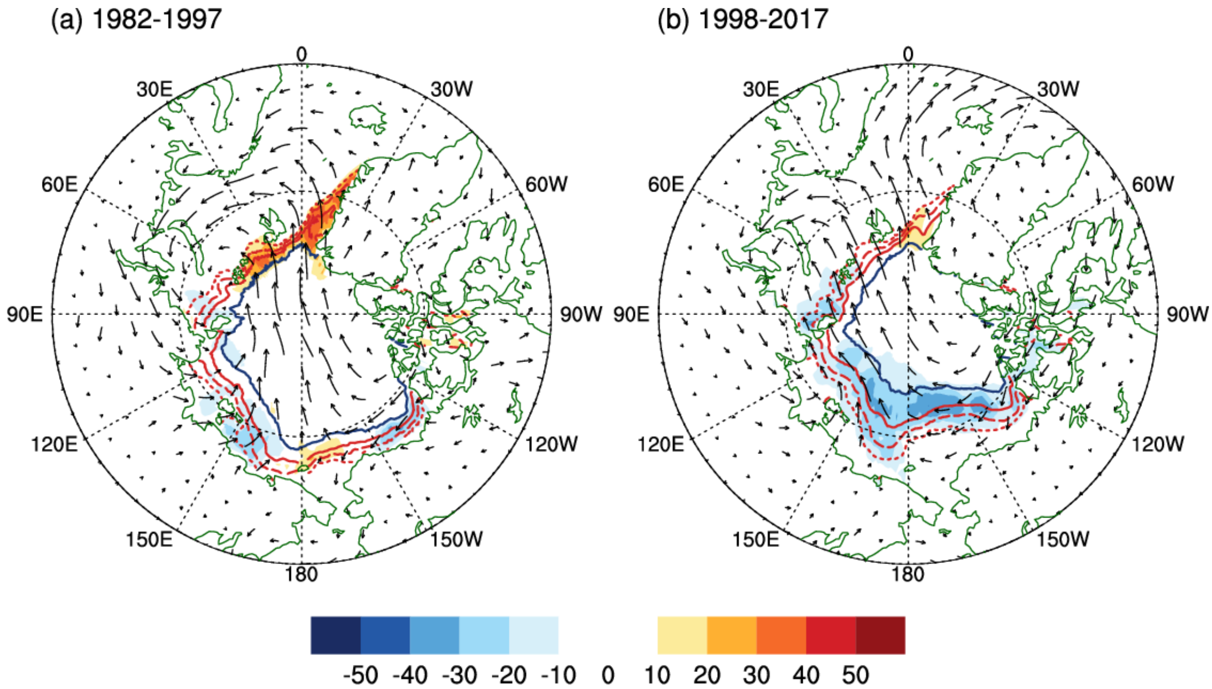

Figure 6. Regression patterns of sea ice concentration (shaded, %) and the surface wind anomalies (vector, m s-1) onto the AD index for (a) the early (1982-1997) and (b) the recent (1998-2017) period. The AD index was reversed in sign for the melting phase of sea ice. Colored lines indicate the time-mean sea ice concentration of 15 % (red dotted), 30 % (red dashed), 50 % (red solid) and 80 % (blue solid) in each period

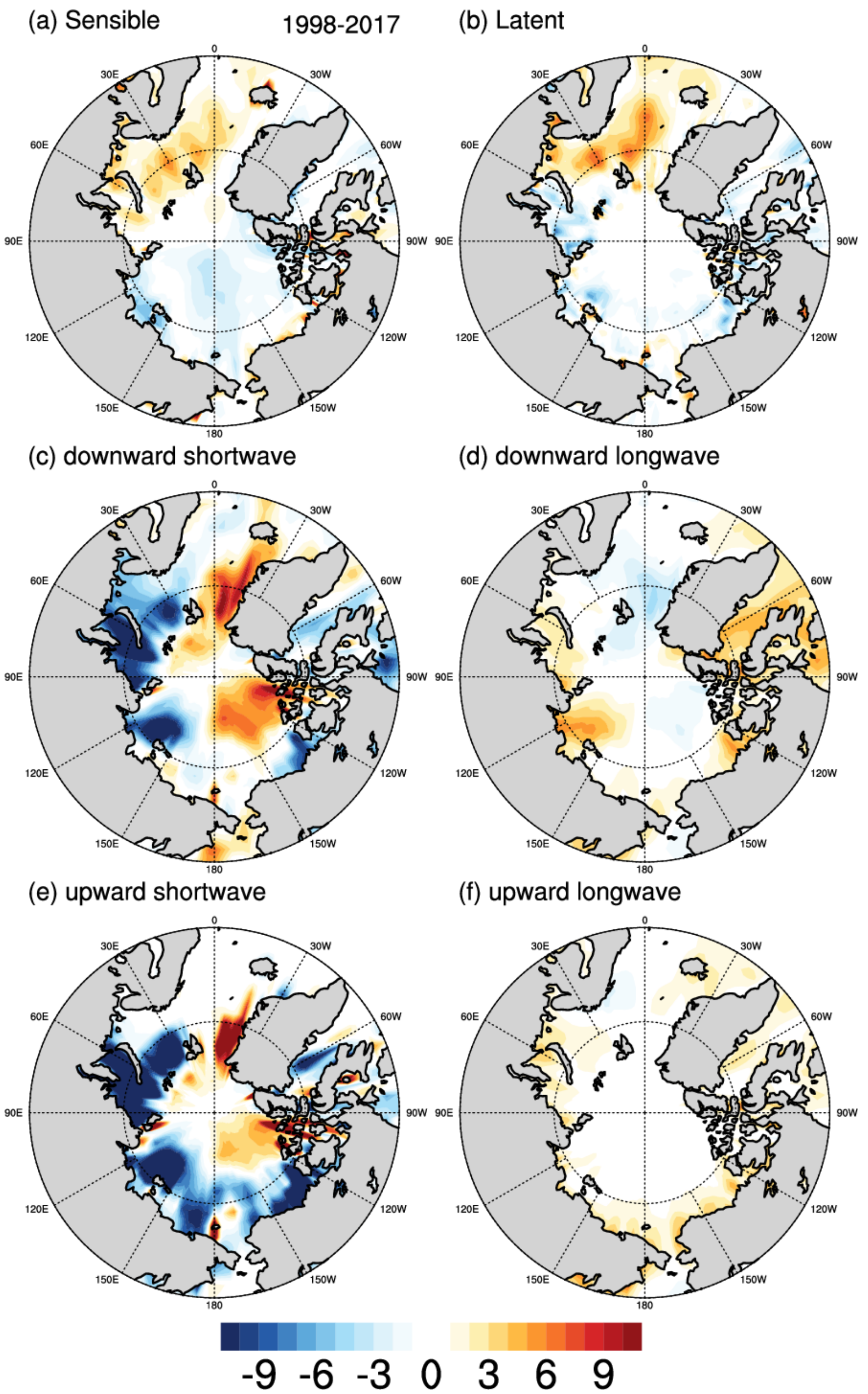

Figure R1. Surface heat flux changes associated with the summer AD in the recent (1997-2017) period. Sensible and latent heat fluxes are defined as positive for the upward. The AD index is reversed in sign before regression.

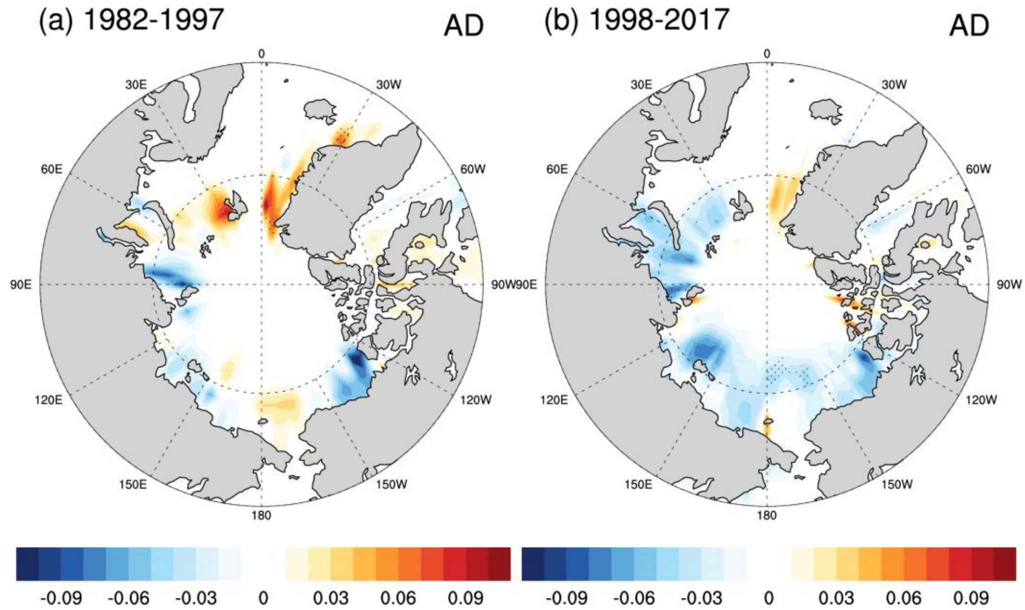

Figure R2. Surface albedo changes associated with the summer AD in (a) the past (1982-1997) and (b) the recent (1997-2017) periods, respectively. The AD index is reversed in sign before regression.

(2) Calculating the ice flux divergence using reanalysis data such as PIOMAS and ORAP-5
The authors should be able to calculate the wind-driven ice flux divergence anomalies associated with the summer AD using reanalysis data such as PIOMAS and ORAP-5. I understand that this study attempts to illustrate the processes using observations, but the suggested processes – the increased impact of summer AD on sea ice (Figures 5 and 6)– are not highly original as pointed out by the other Reviewer. Therefore, more quantitative analyses are required to justify publication.

➔ Following the reviewer's comment, we tried to calculate the ice flux divergence using PIOMAS data. In Park et al. (2018), the ice flux divergence is represented as:

$$\frac{\partial h}{\partial t} = -\left[\frac{\partial}{\partial x}(uh) + \frac{\partial}{\partial y}(vh)\right],$$

where h is sea ice thickness, and u and v are the ice drift in zonal and meridional direction, respectively.

Park, H. S., Stewart, A. L., & Son, J. H. (2018). Dynamic and thermodynamic impacts of the winter Arctic Oscillation on summer sea ice extent. Journal of Climate, 31(4), 1483-1497.

➔ Figure R3 shows the regressed ice flux divergence pattern associated with the summer AD. Comparing the recent and past period, the sea ice convergence is dominant over the Fram Strait in the past period, whereas the ice flux convergence becomes much weaker in the recent period. Overall, the ice flux convergence pattern basically shows the contrast between the Pacific sector (ice flux divergence) and the Atlantic sector (convergence) driven by AD, regardless of periods. However the signal becomes weaker and disorganized in the recent period, and we speculate for the reason the sea ice thickness must have decreased in the Pacific sector significantly in the recent period. In fact, the climatological sea ice thickness is less than 1.5 m over this region. Therefore we conclude the PIOMAS is not adequate for the quantitative analysis to highlight the mechanisms suggested in this study.

➔ Instead of ice flux convergence using PIOMAS reanalysis, we calculated the convergence of sea ice motion obtained from the Polar Pathfinder daily gridded sea ice motion data (Fig. S4). The convergence of sea ice motion is defined as:

$$-\nabla \cdot \mathrm{V} = -\left(\frac{\partial}{\partial x}u + \frac{\partial}{\partial y}v\right)$$

where u and v are the sea ice motion.

➔ The result shows that the sea ice divergence anomalies associated with the AD becomes clear in the Chukchi and the Beaufort Seas due to more enhanced transpolar sea ice drift motion toward the Atlantic sector.

➔ We add the discussion and the supplementary figure in the revised manuscript (Page 8, line 33-Page 9, line 2).

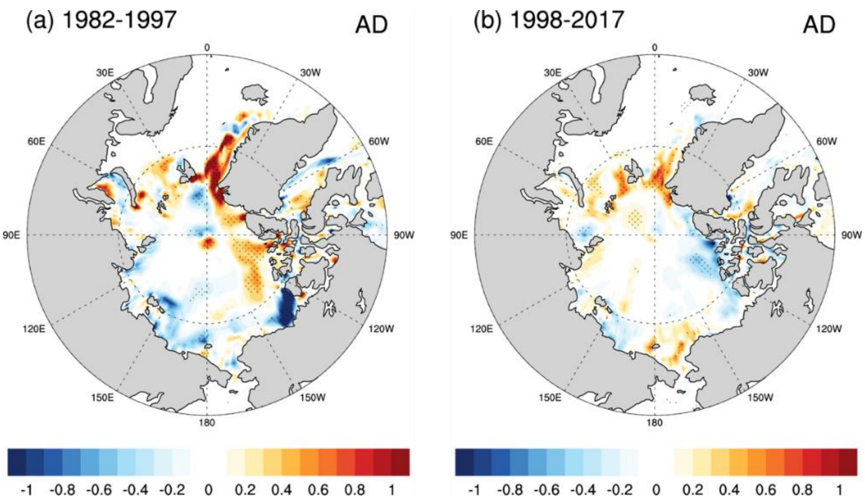

Figure R3. Regressed summer sea ice flux convergence (JJA) associated with the summer AD in (a) the early (1982-1997) and (b) the recent (1998-2017) period, respectively. Sea ice flux is obtained from PIOMAS data (Park et al. 2018).

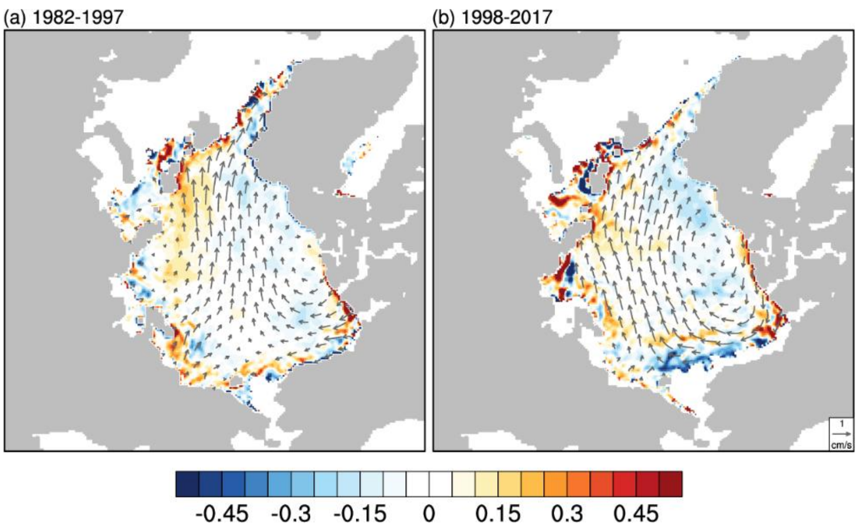

Figure S4. Regressed sea ice motion vector (arrow, cm s^{-1}) and its convergence (shaded, 100 day^{-1}) onto the AD index in (a) the early (1982-1997) and (b) the recent (1998-2017) period, respectively.

(3) Pattern correlation between Fig. 4c and 4d

I still cannot see any significant difference in the AD's SLP pattern before (Fig. 4c) and after 1997 (Fig. 4d). More explanations are needed on the pattern correlation. While the pattern correlation coefficient 0.58 is not low, the authors argue that this value verifies a statistically significant difference between these two SLP patterns, which I cannot understand.

➔ As the atmospheric circulation anomalies are varying in large spatial scale, each grid point is not regarded as an independent sample. According to Bretherton et al. (1999), the statistical significance test should be based on the effective sample size, which can be calculated as

$$N^* = N \frac{1 - r_1 r_2}{1 + r_1 r_2},$$

N is the total grid size, r1 and r2 is the autocorrelation applied to the spatial pattern shifted by one grid for the early and the recent pattern, respectively.

Bretherton, C. S., Widmann, M., Dymnikov, V. P., Wallace, J. M., & Bladé, I. (1999). The effective number of spatial degrees of freedom of a time-varying field. Journal of climate, 12(7), 1990-2009.

➔ In the western hemisphere, the total sample size for pattern correlation is 17,620 (61 lat. x 289 lon.) and the effective sample size is much reduced as 6.05 (~ 7), due to the high coherency in the spatial pattern. When the sample size is 7, the 95% confidence level for the similarity should be above 0.76. The correlation coefficient of 0.58 in AD is not significant at the 90% confidence level. While the correlation coefficient of 0.99 in AO is significant at the 99% confidence level.

➔ We documented this in the revised manuscript (Page 6, line 33 – Page 7, line 4). This result is also consistent with our previous F-test results (See our previous Authors' Comment to this issue).

(4) Page 7 (lines 17 – 19): "the strong relationship with SIE is largely due to the change in the AD in the recent period"

It is difficult to understand how the authors could draw such as strong conclusion from the correlation coefficient.

➔ As the reviewer pointed out, the statement is merely based on the statistical relationship, and the responsible mechanism studies are followed in the next subsection. We tone down the statement in the revised manuscript (Page 7, line 20-23)

(5) Page 8 (lines 1 – 2): Again, Figure 6 is the main finding of this study, but comprehensive mechanisms were not suggested by the authors. Why are the recent ADs far more efficient in decreasing the SIC over the Pacific sector of the Arctic? I understand this is not an easy question to answer, but the authors need to provide mechanisms for this. I recommend utilizing sea ice model outputs such as PIOMAS and ORAP-5. For example, PIOMAS provides sea ice thickness changes associated with the ice flux divergence.

➔ Regarding the reason why the recent ADs are far more efficient in decreasing SIC, we tried to convince the readers based on the following processes that we highlighted in the revised manuscript. The relevant text is carefully revised for clarification (Page 9, 1st and 3rd para)

1) Sea ice discharge is much effective in the recent period in the Atlantic sector which can reduce the upstream of sea ice more effectively (Fig. 8, Page 9 line 3-8).

2) The surface wind over the Chukchi Sea is changed from meridional to zonal wind in the recent period. The zonal surface wind seems to transport warm pacific water by Ekman transport, which is also related to the Beaufort High suggested by Wu et al. (2014) (Page 9 line 9-20).

3) Thinner sea ice thickness makes sea ice become more vulnerable to the dynamical forcing (Page 9 line 21-24).

➔ We agree with the reviewer that most processes remain speculative. The responsible mechanisms should be better tested with the numerical simulation or the analysis of the sea ice model outputs. Although we attempted with the sea ice model outputs from PIOMAS, the results turned out to be less clear to support the proposed mechanisms in this study, presumably due to large uncertainty in the numerical models with less constraint from observations. Suggested modeling study or further analysis seems to be well beyond the scope of the current study and it will be pursued in the follow-up studies.

(6) Page 8 (lines 15 – 17): I cannot see any clear difference in ice drift speed in the central Arctic between these two periods (Figs 8a and 8b).

➔ We now add the difference map for sea ice motion vector in Fig. 8c. The sea ice drift becomes much stronger in the recent period over the circled region in the figure below (Page 8 line 28-29).

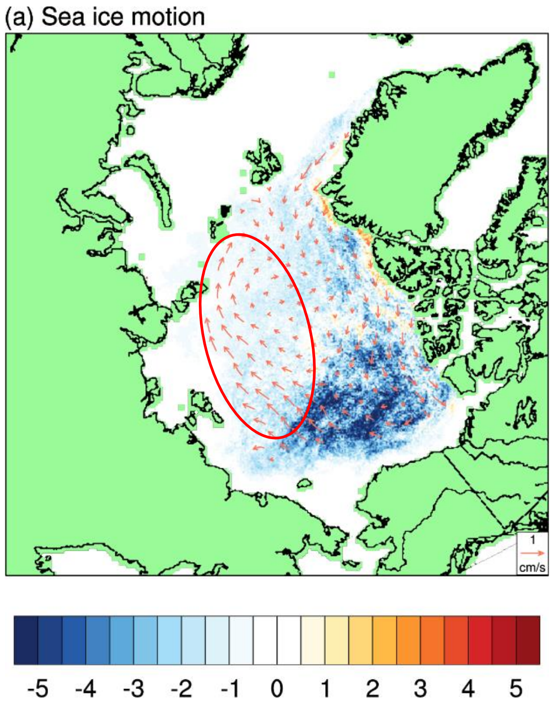

Figure R4. Difference of sea ice motion associated to the AD in each period. Shaded is difference of sea ice age in September averaged over each period.

(7) Page 9 (lines 19 – 27)
The suggested mechanism is highly speculative. I cannot understand why the anomalously low surface air temperature in the Atlantic sector of the Arctic is such an important factor for the wind-driven ice flux divergence over the Pacific sector of the Arctic.

➔ Agreed on the reviewer's comment, we removed our speculative explanation on the role of low surface air temperature. The whole paragraph was rewritten in the revised manuscript (Page 10, line

1-11).