Response to Reviewer #2's Comments:

This study examines the rapidly increasing influence of summer Arctic dipole mode (AD) on September sea ice extent over the last decade using reanalysis and observational data. The authors show that the negative AD event has been more frequent since mid-2000's (Fig. 3), and has strongly influenced September sea ice extent (Fig. 5) by decreasing sea ice cover over the Pacific sector of the Arctic (Fig. 6). The authors further present that the increasing influence of AD on summer sea ice cover is partly because of sea ice thinning (Fig. 8), which increases the sensitivity of sea ice cover to southerly winds. This study nicely expands on the work of Wang et al. (2009), but the main conclusions of this study are somewhat redundant with those of Serreze et al. (JGR 2016), which carefully analyzed the relationship between AD and summer Arctic sea ice extent. While it is a little difficult to argue that this study has enough novelty to justify publication at this stage, I think this study has great potential to become an influential paper. I am optimistic that the authors will be able to improve the manuscript through the revision. I recommend publication subject to the following major revisions.

→ We appreciate the reviewer's encouraging and constructive comments on the manuscript. As we received a similar comment regarding the novelty of this study from another reviewer, we repeat our responses in the below.

As the reviewer commented out, this study basically supports the existing studies in that atmospheric circulation patterns have profound impacts on the sea ice variability in the Arctic, especially in the summer. Below we highlight our new findings with respect to the existing studies.

The Arctic Dipole (AD) mode has been known to be linked with the September sea ice extent (SIE). Wang et al. (2009) identified AO and AD as principal modes (i.e., EOF1 and EOF2, respectively) of the sea level pressure (SLP) variability in the Arctic from the analysis of the long-term data for 1948-2008, and suggested that negative AD years such as 2007 tend to show more linkage with the SIE minimum. Overland et al. (2012) also suggested that the Arctic sea ice has decreased by the series of negative AD years persistent during 2007-2012. In extending this study, Serreze et al. (2016) examined the decadal changes in the SLP patterns, and the SLP anomalies in the recent years resemble more the negative AD pattern to which the sea ice decrease was attributed. However, there was no quantitative assessment of the relationship between the sea ice extent and the AD variability was provided in the previous studies. This may be partly because the correlation between the sea ice extent and the AD index vanishes when the entire analysis period was applied since the 1980s (Fig. 5d).

What is new that we try to convince from this study is to provide a new perspective to the mechanisms responsible for the change in the relationship between SIE and AD. It is hypothesized that the principal modes may have experienced a significant change in their center of actions across the decades. In our analysis, this is particularly the case for the 2nd EOF mode (AD), although the 1st EOF mode (AO) is still predominant with no significant change in the spatial pattern. The change in the AD spatial pattern is statistically significant when the analysis period was separated before and after the late 1990s (See the statistical test result in our response to the specific comment below), and it explains why the correlation between SIE and AD is statistically significant just for the recent period (1998-2017), not in the past (1982-1997). This aspect is highlighted in detail in the manuscript based on the quantitative analysis based on the time series correlations (Fig. 5d).

This study detailed the mechanisms of how the spatial pattern change in the AD mode provides more favorable conditions for the interannual variation of the SIE, based on comprehensive analyses to the dynamic and thermodynamic fields. Among them, the sea ice dynamics associated with the low-level wind change could explain better for the sea ice variability in the recent period, rather than changes in temperature advection or heat flux from the atmosphere.

Finally, the remaining question what drives the AD pattern change in the recent decade is addressed newly in the manuscript. We highlight that the AD pattern change could appear recurrently depending on the phase of the Pacific Decadal Oscillation (PDO). Our statistical analysis based on the long-term reanalysis data (NCEP R1) dated back to 1948 proves that a similar change in the spatial pattern of AD has occurred during the negative PDO phase. We admit this is from statistics and the causal relationship could be elucidated by some numerical experiments, but this is not easy to experiment and well beyond the scope of current research.

General Comments

(1) Net surface heat flux anomalies associated with AD: Sea ice growth & melting rates are associated with the net surface heat flux. I suggest examining the response of net surface heat flux to the summer negative AD. In particular, is there an increasing sensitivity of net surface heat flux (more downward heat flux anomalies) to the summer negative AD? The net surface heat flux anomalies might be presented in the lower panel of Figure 7.

→ Following the reviewer's comment, we examined the net surface heat flux associated with the AD. Figure R1 below compares the net heat flux anomalies regressed onto the AD index between the past and the recent decade. Overall, the net surface heat flux anomalies are increasing in the high latitudes, the signal is less clear or even negative in the central Arctic. As this pattern does not match directly with the region of sea ice decrease, the sea ice dynamics impacted by surface wind anomalies seem to be more responsible for the sea ice variability, rather than thermodynamic processes. This aspect supports the results and conclusion in the manuscript.

We can combine these figures with the original Figure 7, as suggested, and add relevant discussion in the revised manuscript.

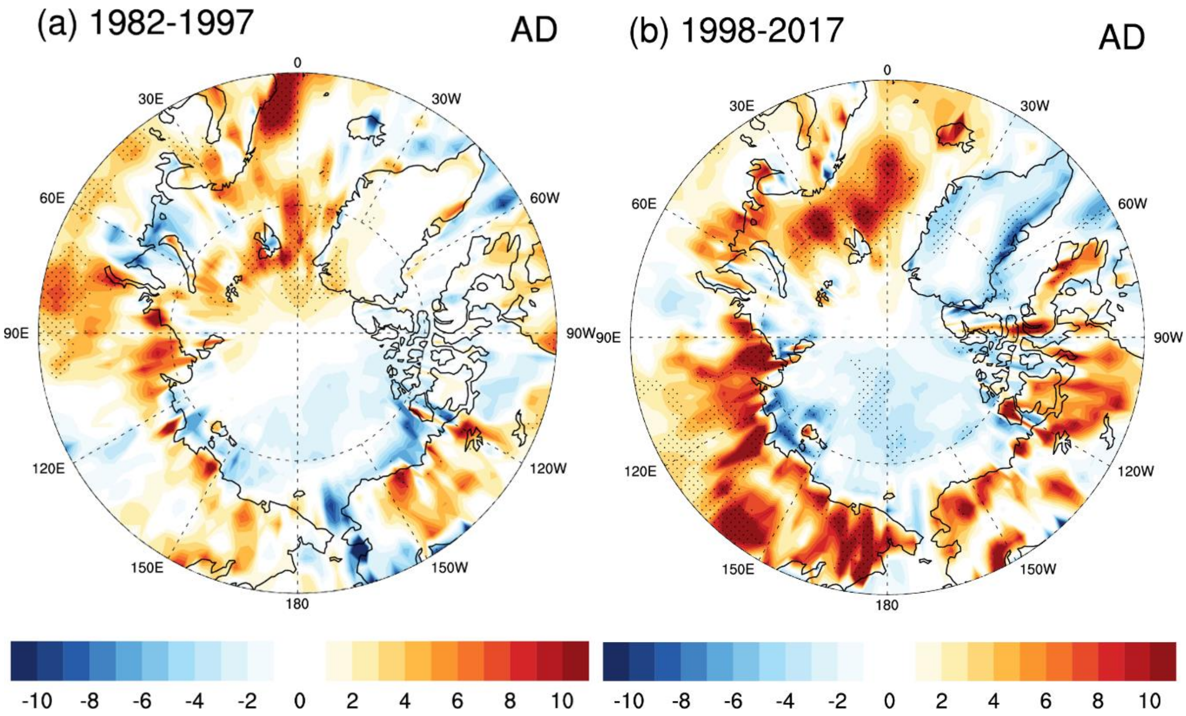

Figure R1. Regressed pattern of net surface heat flux onto the AD index in (a) the past and (b) the recent period. The positive values indicate downward.

(2) Increasing sensitivity of sea ice cover to southerly wind strengthening: Figures 6 and 8 are the main findings of this study and these results should be explained further in detail. As the authors stated, Arctic sea ice becomes more vulnerable to the dynamical forcing such as southerly wind strengthening because

of the continuous ice thinning. I recommend showing the PIOMAS ice thickness in the lower panel of Figure 8. Although PIOMAS ice thickness has large uncertainties, the general trend of ice thinning is reasonably well captured by PIOMAS.

→ Following the reviewer's comment, we show Figure R2 below. In the recent period, sea ice thickness becomes thin clearly, and the surface wind anomalies pass over this thin area in the edge of the Arctic sea ice extent. This sea ice thickness figure supports well our discussion with Figure 8, and we will use this figure in the revised manuscript.

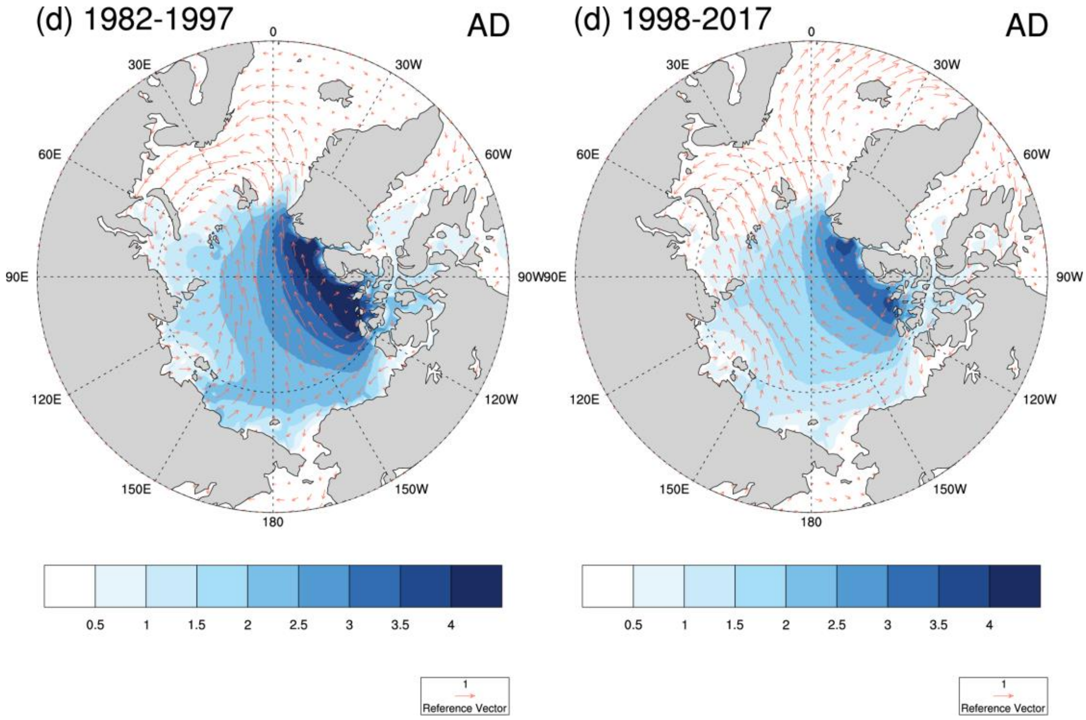

Figure R2. Regressed surface wind anomalies onto the AD index and the time-mean sea ice thickness in the past and the recent period. The sea ice thickness data was obtained from the Pan-Arctic Ice Ocean Modeling and Assimilation System (PIOMAS) reanalysis by Polar Science Center.

(3) Case study: As shown in Serreze et al. (JGR 2016), I recommend examining the impact of AD on sea ice cover during the recent summers of 2016 and 2107. As noted in Serreze et al. (2016), each negative AD event has markedly different pressure and temperature patterns.

→ Serreze et al. (2016) showed the specific patterns in each year when the sea ice extent is relatively high and low, respectively. As their analysis has been done until 2015, the reviewer suggested it might be interesting to see the impact of AD on sea ice cover in recent years as a case study. Following it, we examined anomalous circulation patterns in 2016 and 2017, which are presented below in Figure R3.

Both years were featured by large negative SLP anomalies in the central Arctic and by dominant cyclonic circulation anomalies (Fig. R3), seemingly projected as typical positive AO years (See Fig. 3a and 3d in the original manuscript). Flow patterns are quite symmetric and weakly projected onto the AD mode, although both years can be classified as negative AD years (Fig. 3e). The strength of the AD mode is relatively weaker in these two years. This weak AD impact seems to be reflected in the time series of sea ice extent anomalies (Fig. 1c, see below with blue and red circles), where the downward trend of sea ice cover tends to slow down in these two years.

It is also interesting to see the difference between the two years. In 2016, SLP anomalies resemble more the negative AD mode than in 2017, with positive SLP anomalies in Greenland and negative in the eastern hemisphere. Accordingly, sea ice extent anomalies were relatively lower in 2016 than in 2017.

This supports well the dynamical mechanisms presented in this study, as well as in Serreze et al. (2016).

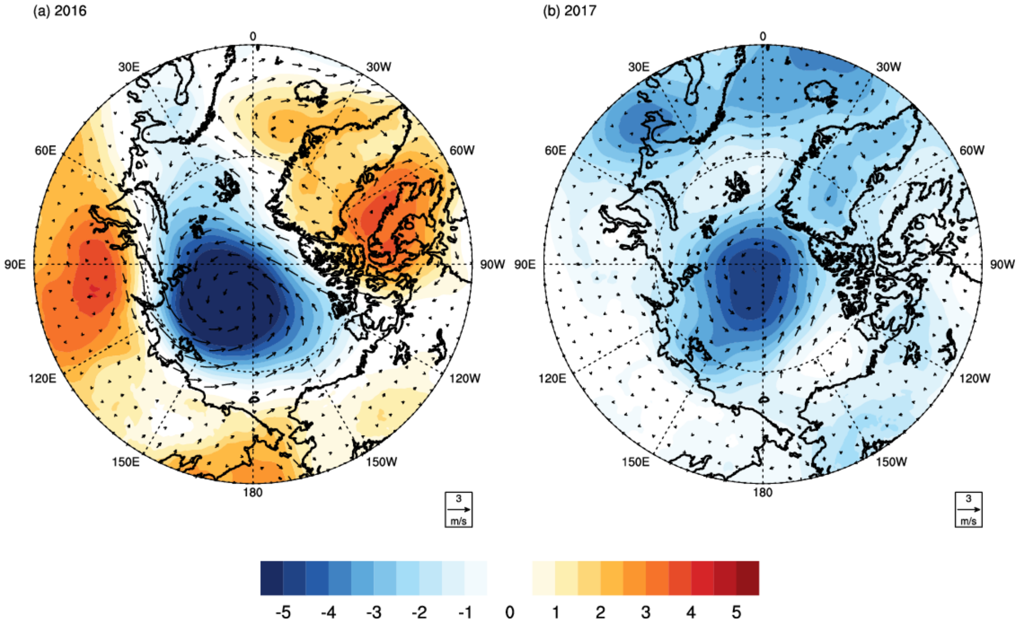

Figure R3. Sea level pressure and surface wind anomalies in 2016 (left) and 2017 (right) summer (JJA), respectively.

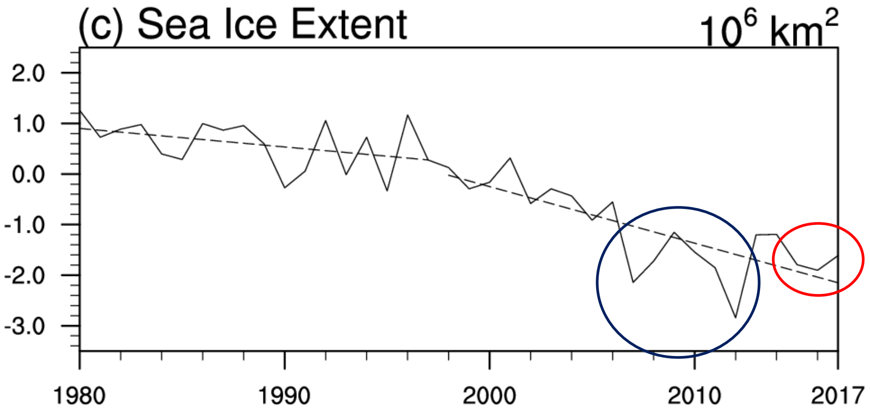

Figure 1c. The Arctic sea ice extent (SIE) in September in the region north of 70 N. The anomalies are the departures from the average of 1981-2010. Dashed line shows the trend before and after 1998.

(4) Possible impacts of PDO on AD (Figures 9 & 10): The connection between PDO and AO is highly speculative. I am not sure whether these results need to be presented. I recommend deleting Figures 9 and 10 as well as Section 4 (Further Discussion).

→ We admit the reviewer's comment that the relationship between PDO and AO is highly speculative. As we replied to the reviewer's comment in the above, without presenting numerical experiments, it is rather difficult to isolate the impacts by PDO onto the 2nd EOF mode in the Arctic SLP variability. Nevertheless, the statistical relationship between PDO and AO is quite robust and depends less on the data analysis period, suggesting a possible role of PDO onto the AD mode.

Following up this comment, we elaborate further on our statistical analysis. The AD mode during the negative PDO years for 1948-2017 (Fig. 10d) resembles much the AD mode obtained during the negative years before the 1980s (Suppl. Fig. S3b). They all show a similar center of action over

Greenland, and the correlation coefficient between the two is as high as 0.95 just for the area of the western hemisphere (60-90N, 0-180W). This convinces that the shift of the center of action in the AD mode is closely related to the phase of PDO.

In this statistical reasoning, we would like to keep this part (Section 4, Further Discussion) with Figs. 9 and 10.

Specific Comments

(5) Page 1 (lines 28-29): "Screen and Simmonds (2010) suggested the surface warming in the Arctic (a.k.a. polar amplification) plays a critical role in sea ice melting": This is not true. Screen and Simmonds (2010) suggested that diminishing sea ice has had a leading role in recent Arctic amplification.

→ We agree and the sentence will be removed.

(6) Page 6 (lines 16-17): It is difficult to tell the difference of PC time series between Fig. 3 and Fig. 5a-c. I thought these two are identical - both are PC time series of JJA mean SLP in the Arctic - am I misunderstanding? Please explain the differences more in detail.

→ The PC time series in Fig. 3d-f are repeatedly shown in Fig. 5a-c as solid lines, and they are identical. Here we present the black dashed lines in black from the “separate” EOF analysis before and after 1998. As the EOF loading patterns are not identical from the analysis with the total period and the one with a partial period, the PC timeseries are not supposed to be identical. The timeseries show much resemblance in each corresponding mode, and it suggests that each EOF modes are robustly identified as internal modes, regardless of analysis time.

(7) Page 6 (lines 19-24): I cannot agree with this argument. To me, there is no significant difference in the AD’s SLP composites between the early and the late periods. There has been more frequent negative AD events since mid-2000’s, but the individual negative AD’s amplitude and pattern may not have changed much.

→ We elaborate more on Fig. 4 by changing the color scheme (See below for our modified version of Figure 4 in the original manuscript). Now the figure shows that the center of action tends to shift counterclockwise, and in particular the variability maximum in the western hemisphere shifted from Queen Elizabeth Islands to Greenland. To test the statistical significance, we applied the F-test for the two EOF vectors. The AD pattern change is notable over the regions of Queen Elizabeth Islands and Greenland, with the statistical significance at 5 % level (See Fig. R4 below, bottom). Moreover, the pattern correlation between the two AD modes (i.e., Figs. 4c and 4d) is as low as 0.58, while that of AO (Figs. 4a and 4b) is as high as 0.99 for the area of the western hemisphere (60-90N, 0-180W). This implies that AD has experienced a significant pattern change in the recent decade, whereas AO has not.

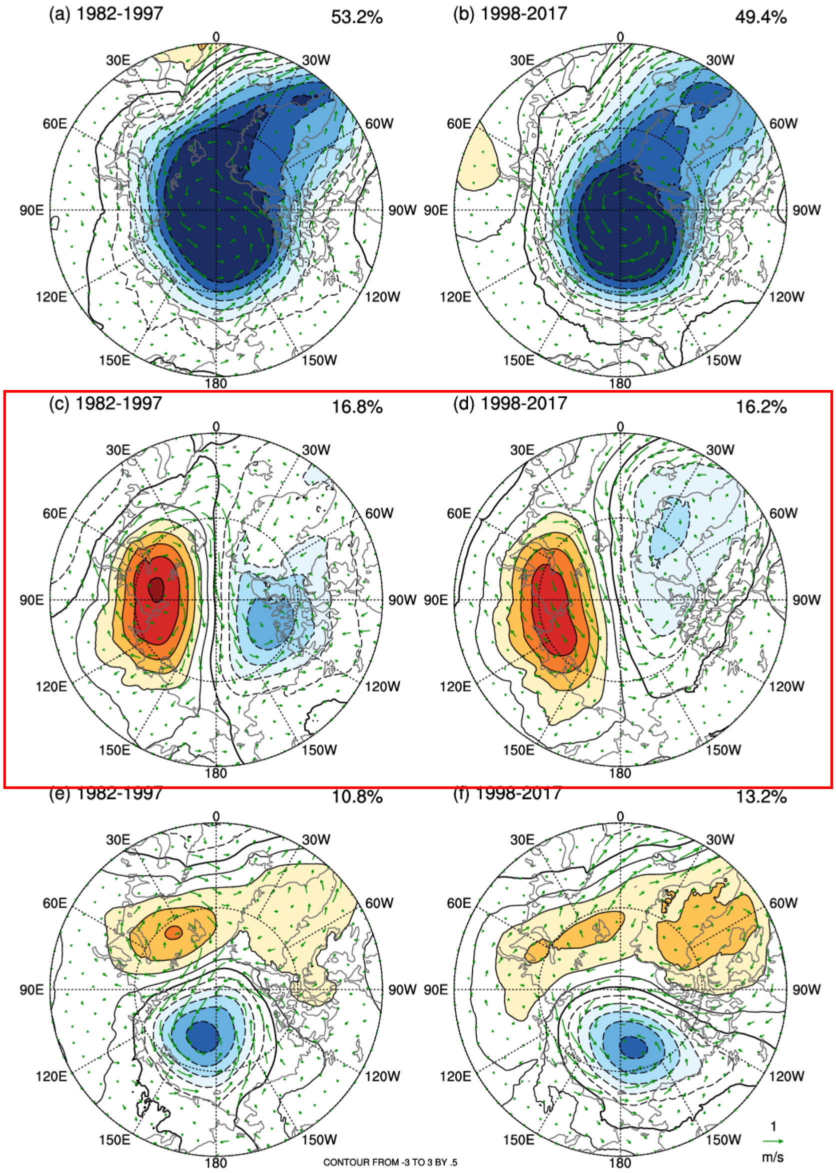

Figure 4. The three leading EOFs of JJA-mean SLP (contour) in the early (1982-1997, left panels) and the recent (1998-2017, right) period. (a) and (b) for the first mode, (c) and (d) for the second, and (e) and (f) the third mode, respectively. The shaded area shows strong variability region of each mode. The regression pattern of surface wind anomalies (vector) is also shown in each map.

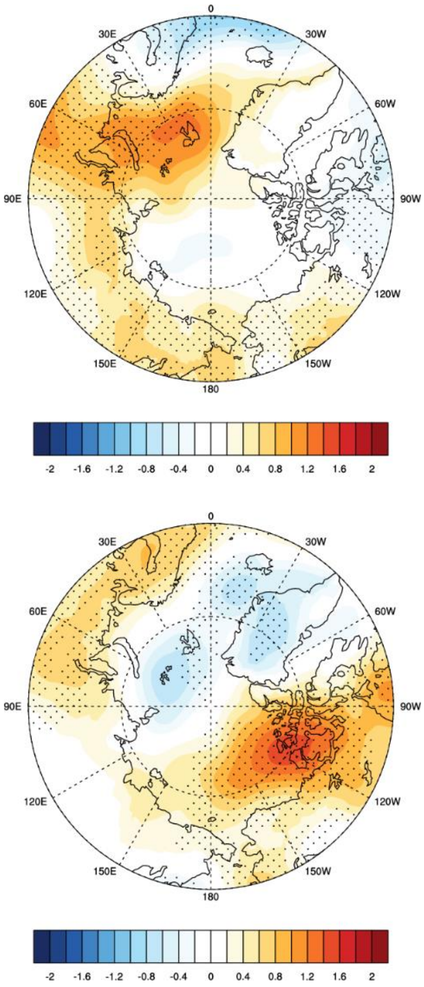

Figure R4. The difference of the leading EOFs (top: EOF 1 and bottom: EOF 2). The dotted area indicates the statistical significance at the 5 % level from the F-test. The EOF vectors were scaled by the variance represented by each mode and subject to the F-test for the variance ratio at each grid point. The degree of freedom is 15 for the early vector and 19 for the recent.

(8) Page 7 (lines 1-3): Rigor et al. (2002), more recently by Park et al. (2018) showed a strong relationship between winter AO and summer sea ice extent. Park, H.-S., A. L. Stewart and J.-H. Son, 2018: Dynamic and thermodynamic impacts of the winter Arctic Oscillation on summer sea ice extent. Journal of Climate, 31, 1483-1497.

→ Park et al. (2018) will be added in the revised manuscript. We will also briefly discuss the results from Park et al. (2008), which highlight the connection between wintertime AO circulation anomalies on the following summer sea ice extent.

(9) Page 7 (line 5): "AD in the recent period, which feature is not evident in the early period": I suggest checking grammar of this sentence.

→ Will be modified as "….AD in the recent period. This feature is not evident in the early period".

(10) Page 7 (lines 16-17): "in order to better represent the condition for sea ice melting over far off the coast of Russia and North America": How about changing this to "to better represent the southerly wind-induced ice loss over the Pacific sector of the Arctic"?

→ The sentence will be changed as suggested.

(11) Page 7 (lines 26-29): Again, this speculative statement should be quantitatively diagnosed by calculating the net surface heat flux anomalies.

→ It was rather difficult to find the direct relationship between the net surface heat flux anomalies and the sea ice cover changes in response to the AD change. See our reply to the reviewer's specific comment (1) in the above.

(12) Page 7 (lines 32-33): Ogi et al. (2010) did not explicitly state that the surface wind-induced ice drift is more important than other factors. Please rephrase or delete this sentence.

→ Agreed and the reference will be removed in the sentence.

(13) Page 8 (lines 4-7): I found it difficult to understand this sentence. If Figure 8 has limitation in explaining the recent changes of the AD's effect on sea ice, why is this plot presented?

→ The analysis of the sea ice motion was conducted to examine its strong relationship with the surface wind in the Arctic. Even though the sea ice motion can be detected only over the ice-covered region, it shows good correspondence with the surface wind anomalies. Due to limitation in understanding sea ice motion, Figure 8 in the original manuscript will be replaced by Figure 8 shown below which includes surface wind pattern.

(14) Page 8 (lines 10-11): I am not sure whether the outflow through the Fram Strait has recently increased. There is no obvious difference between Figs. 8a and 8b.

→ Following up the reviewer's comment, we elaborate this part more. Figure 8 in the original manuscript will be replaced by Figure 8 shown below, in which we modify the color of the vector for better display. In addition, the data has been updated up to 2017 with the Sea Ice Motion version 4.

The sea ice motion associated with AD (c.f. Fig. 8a and 8b) becomes faster in the mid Arctic around the edge of the sea ice extent. In the recent period, sea ice is drifted more clearly toward the Norwegian Sea and discharged to the North Atlantic. This sea ice motion change is consistent well with the change in the surface wind driven by AD (c.f. Fig. 8c and 8d). Northerly winds have been strengthened from the Arctic to the North Atlantic in the recent period to provide a more favorable condition for sea ice to be discharged to the Atlantic.

For a better illustration of the changes in the sea ice motion and surface wind, we prepare Figure R5 below. Sea ice motion difference (Fig. R5a) shows clockwise rotation anomalies with a more enhanced transpolar drift to the Atlantic section. Although this sea ice motion change can be detected only over the sea ice covered area, corresponding surface wind change (Fig. R5b) shows the dominant feature in the downstream side where the strong outflow anomalies are found from the Arctic to the Barents Sea and to the Norwegian Sea. This study highlights that the AD pattern change provides a more favorable condition for the Arctic sea ice loss to the North Atlantic based on these analyses.

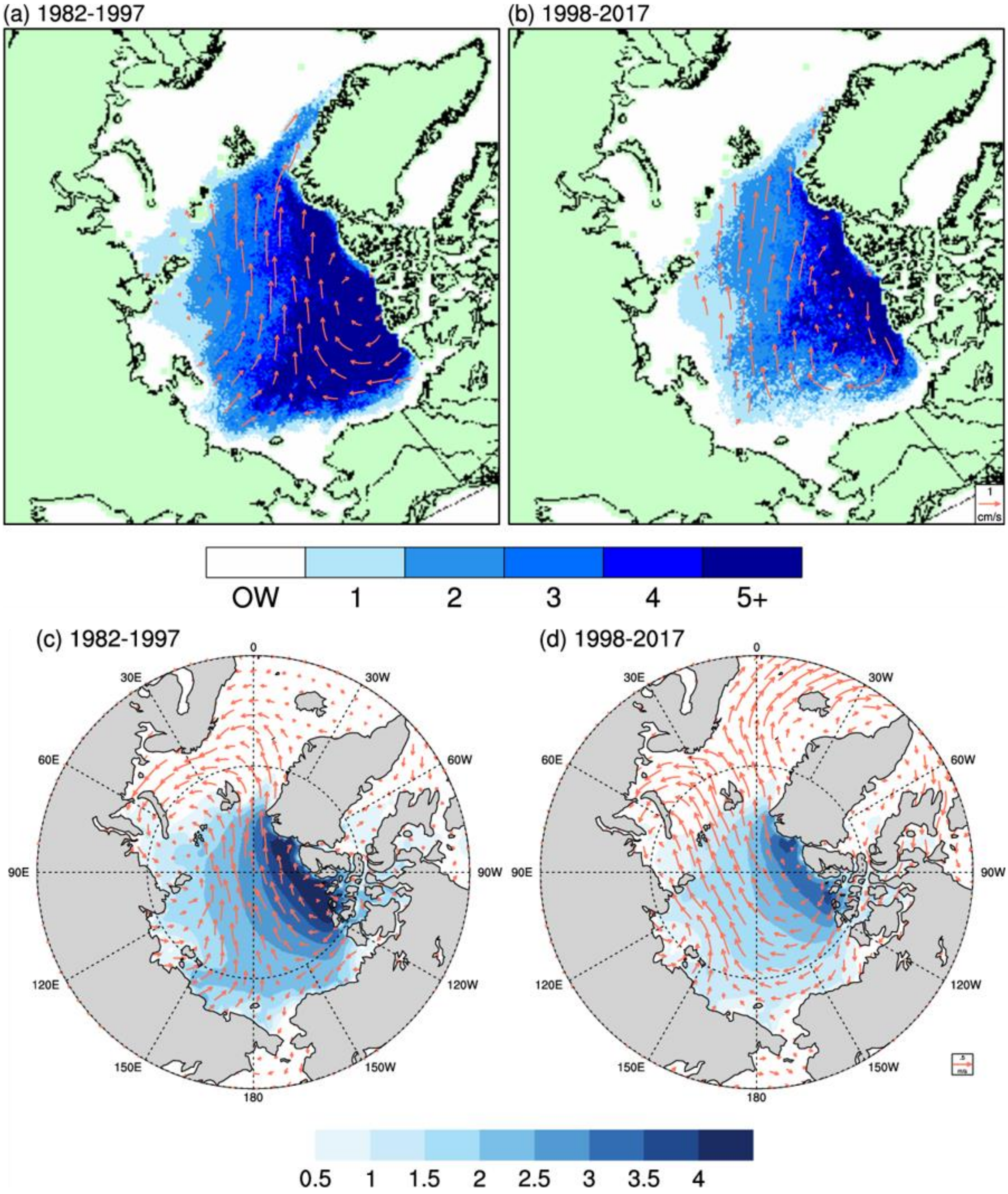

Figure 8. Regression pattern of sea ice motion (top, vector) and surface wind (bottom, vector) onto the AD index in the early (1982-1997, left) and the recent (1998-2017, right) period. Shaded is the sea ice age (top) and the sea ice thickness (bottom) in September averaged over each period.

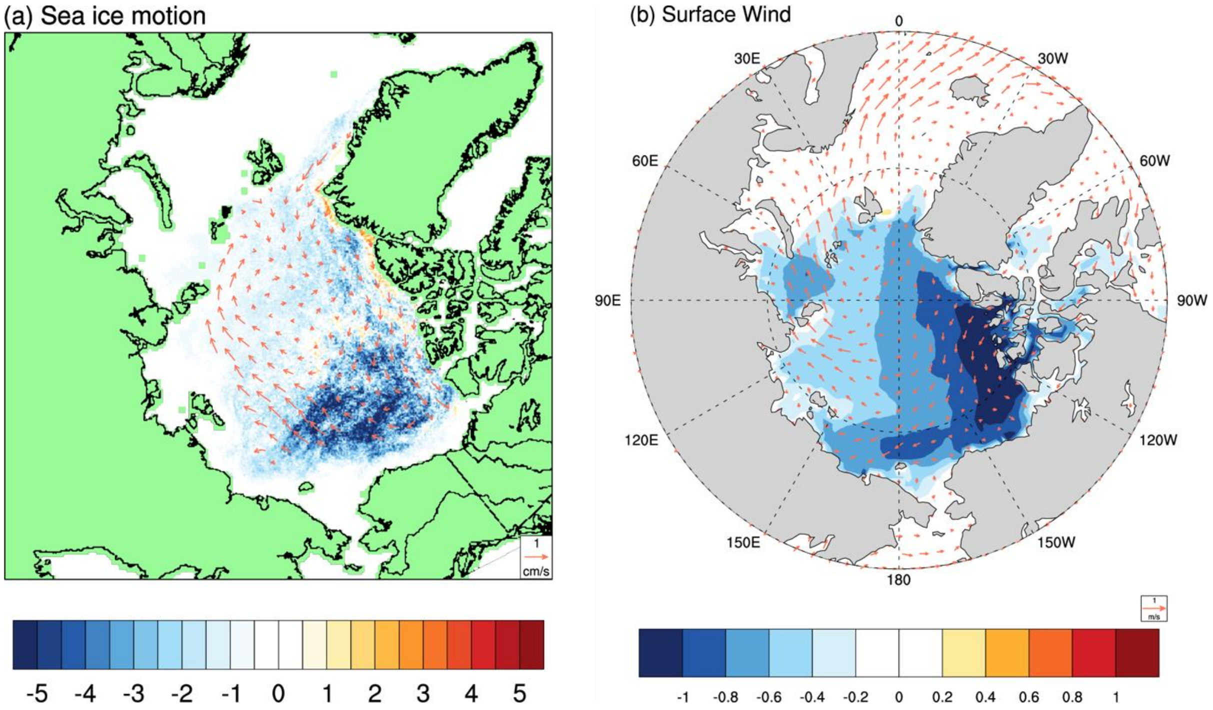

Figure R5. Difference of (a) sea ice motion and (b) surface wind associated to the AD in each period. Shaded is difference of (a) sea ice age and (b) sea ice thickness in September averaged over each period.

(15) Page 8 (lines 13-15): Figure 2b does not show any obvious changes in wind vectors around the Bring Strait.

→ It was mistyped and will be corrected as “Figure 6”. Enhanced easterlies over the Chukchi Sea is related to the Ekman transport of warm oceanic inflow through Bering Strait.

(16) Page 9 (lines 31-32): As the authors stated, the relationship between PDO shifts and the AD center is difficult to elucidate. Again, I suggest deleting Figures 9, 10, and Section 4 (Further discussion), which is a distraction.

→ Please see our response in the above to the comment (4).

(17) Page 10 (line 2): "AO modulates sea ice" should be changed to "winter AO modulates sea ice". Again, more recently, Park et al. (2018) showed a nontrivial connection between the winter AO and summer sea ice.

→ Will be corrected as suggested.

(18) Page 10 (lines 18-19): I cannot understand this sentence. Please rephrase.

→ We wanted to suggest that warmer temperature anomalies in the recent period (Fig. 7b) associated with AD could drive less accumulation of sea ice in the western hemisphere and provides a more favorable condition for sea ice outflow to the Atlantic. As much speculative, this sentence will be removed.

(19) Page 10 (lines 21-22): Did the authors imply "anticyclonic circulation anomalies over the Beaufort Sea"? Again, Figure 6 does not support the authors’ argument.

→ “Cyclonic” circulation is a typo and it will be corrected as “anti-cyclonic” circulation. Strong Beaufort High might drive oceanic inflow through the Bering Strait via Ekman Transport.

(20) Page 10 (lines 26-27): Again, please delete this sentence.

→ Please see our response to the reviewer's general comment and the specific comment in (4).