Response to Reviewer #1's Comments:

General

This paper is telling is that September sea ice conditions are strongly shaped by atmospheric circulation patterns during summer, and that atmospheric circulation patterns are variable and have shifted over time. We have known this for many years, and a number of previous efforts have also noted that as the ice thins, relationships between atmospheric circulation anomalies and sea ice responses may be changing. In this sense, the present paper, while impressive in terms of depth of analysis, isn't really telling us anything fundamentally new.

→ 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 sea ice 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.

Specific

Abstract, Page 1, Line 15: What month is this correlation based on? September ice extent against summer circulation? Be specific.

→ The correlation is calculated between the summer Arctic Dipole index (JJA) and the September Sea ice extent, which is -0.05 in the past period and becomes 0.57 in the recent period. This information will be added in the revised manuscript.

Page 1, line 24: The downward trends in sea ice extent involve more than “rapid melting”.

→ “Rapid melting” will be replaced by “radical change”.

Page 1, Line 25-28: Over what period did Serreze et al. [2007] compute the trend? The 12.4% per decade trend cited in later studies is not “expedited”, it is simply based on a longer sea ice record. Also, percent per decade trends are meaningless numbers without clearly citing the baseline averaging period.

→ The trend of September sea ice extent was calculated for 1979-2006 (-8.6% per decade) in Serreze et al. (2007), while Stroeve et al. (2012) used 1979-2010 (-12.6% per decade).

The sentence is somewhat misleading and it will be modified as “Based on the National Snow and Ice Data Center (NSIDC), the linear trend of the SIE during 1979-2018 relative to 1981-2010 average is -12.8 % per decade, with a more rapid declining trend in recent years”. See below for the NSIDC record.

Year of September Average Extent	Extent (million sq. km.)	Anomaly Relative to 1981-2010 Average (million sq. km.)	Anomaly Relative to 1981-2010 Average (%)	Anomaly Relative to Previous Record (million sq. km.)	Anomaly Relative to Previous Record (%)	Linear Trend Since 1979 (sq. km. per year)	Linear Trend Since 1979 Relative to 1981-2010 Average (% per decade)
2002	5.83	-0.58	-9.1	-0.25	-4.1	-45900	-7.2
2003	6.12	-0.29	-4.6	0.29	5.0	-47400	-7.4
2004	5.98	-0.43	-6.8	0.15	2.6	-49400	-7.7
2005	5.50	-0.91	-14.2	-0.33	-5.7	-54300	-8.5
2006	5.86	-0.55	-8.6	0.36	6.5	-55300	-8.6
2007	4.27	-2.14	-33.4	-1.23	-22.4	-66600	-10.4
2008	4.69	-1.72	-26.9	0.42	9.8	-72700	-11.3
2009	5.26	-1.15	-18.0	0.99	23.2	-73800	-11.5
2010	4.87	-1.54	-24.1	0.60	14.1	-76500	-11.9
2011	4.56	-1.85	-28.9	0.29	6.8	-79900	-12.5
2012	3.57	-2.84	-44.3	-0.70	-16.4	-87400	-13.6
2013	5.21	-1.20	-18.8	1.64	45.9	-85500	-13.3
2014	5.22	-1.19	-18.6	1.65	46.2	-83400	-13.0
2015	4.62	-1.79	-28.0	1.05	29.4	-83900	-13.1
2016	4.53	-1.88	-29.4	0.96	26.9	-84300	-13.1
2017	4.82	-1.59	-24.8	1.25	34.0	-83200	-13.0
2018	4.71	-1.70	-26.6	1.14	31.9	-82300	-12.8

September Average Extents, 2002-2018: Calculated by Walt Meier and Julienne Stroeve, National Snow and Ice Data Center. All values in this table estimated based on the NSIDC Sea Ice Index Version 3. Note that these figures show September average extents rather than minimum extents.

[NSIDC]

Page 1, Line 29: Surface warming is not Arctic amplification – AA refers to a comparison between temperature trends between the Arctic and the globe as a whole (or the northern hemisphere). And there seems to be a misunderstanding here – a large component of AA seems to be due to ice loss (the ocean loses heat to the atmosphere in autumn and winter), rather than the cause of it.

→ We agree and the “Arctic Amplification” will be replaced with “global warming”.

Page 2, line 3 and elsewhere in the text: A "declining trend" implies that the trend is getting smaller. The correct term is "downward trend"

→ Will be corrected as "downward trend".

Page 2, line 5: To state that the underlying mechanisms for sea ice variability in summer are still "under debate" is quite a stretch. Scientists have been looking at these mechanisms (atmospheric and oceanic variability) for many years. The authors should be citing earlier pioneering studies – from the way the text reads, there was no research on mechanisms behind sea ice variability before the dawn of the 21st century. We all stand on the shoulders of those before us. Give credit where credit is due.

→ We just tone down the text as " … are suggested with on a variety of mechanisms". We will include early pioneering studies as in the below.

Thorndike, A. S., & Colony, R. (1982). Sea ice motion in response to geostrophic winds. Journal of Geophysical Research: Oceans, 87(C8), 5845-5852.

Curry, J. A., Schramm, J. L., & Ebert, E. E. (1995). Sea ice-albedo climate feedback mechanism. Journal of Climate, 8(2), 240-247.

Parkinson, C. L., Cavalieri, D. J., Gloersen, P., Zwally, H. J., & Comiso, J. C. (1999). Arctic sea ice extents, areas, and trends, 1978–1996. Journal of Geophysical Research: Oceans, 104(C9), 20837-20856.

Page 3, lines 1-3: As I recall, Ogi et al. [2007, 2008] were discussing what called the "summer AO" pattern, not the AD.

→ Will be corrected as "summer AO".

Page 4, line 12: I leave it to another reviewer to comment on the validity of conducting an EOF analysis over such a very restricted spatial domain (70 to 90 deg. N).

→ The definition of the AD is the 2nd EOF mode of SLP anomalies in the area north to 70°N in Wu et al. (2006) and Watanabe et al. (2006) for winter. Wang et al. (2009) and Overland and Wang (2010) used the same domain for their summer analyses. We also found that various recent studies adopt this definition.

Wu, B., Wang, J., & Walsh, J. E. (2006). Dipole anomaly in the winter Arctic atmosphere and its association with sea ice motion. Journal of Climate, 19(2), 210-225.

Watanabe, E., Wang, J., Sumi, A., & Hasumi, H. (2006). Arctic dipole anomaly and its contribution to sea ice export from the Arctic Ocean in the 20th century. Geophysical research letters, 33(23).

Overland, J. E., & Wang, M. (2010). Large-scale atmospheric circulation changes are associated with the recent loss of Arctic sea ice. Tellus A, 62(1), 1-9.

Page 4, line 25: Again, Arctic amplification is not about the Arctic temperature trends alone, it's about the comparison between Arctic and global temperature trends. And it's not "polar amplification" - it's just the Arctic.

→ We agree and the phrase will be modified as "under global warming".

Page 5, lines 14-15. Assuming that the "Pacific section" refers to the Beaufort/Chukchi seas, why would there be a greater ice loss here in the later period when the motion is more onshore than in the previous period and would tend to transport thick ice from north of the Canadian Arctic Archipelago into the region?

→ A greater sea ice loss in this region cannot be simply explained by enhanced northerly winds toward the Beaufort Sea in the recent period as the transpolar drift stream also carries the sea ice toward the Atlantic section. Much sea ice loss and retreat in the sea ice line in the Pacific section seems to be a consequence of various contributions such as air temperature warming, warm inflow from the Pacific, and the ice thickness change.

Page 6, line 5: As far as I can see, no trend analysis has been performed on the time series. And I don't see much of anything resembling decadal scale variability in PC1. What I see is a series of ups and downs.

→ Agreed and the sentence will be deleted in the revised manuscript.

Page 6, lines 15-25: I have a very hard time convincing myself that the patterns for the earlier and later periods shown in Figure 4 are very different. In my opinion the authors are trying to read too much into these figures.

→ We elaborate more on Fig. 4 by changing the color scheme (See below for the modified Fig. 4). 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 below Fig. S1, 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.

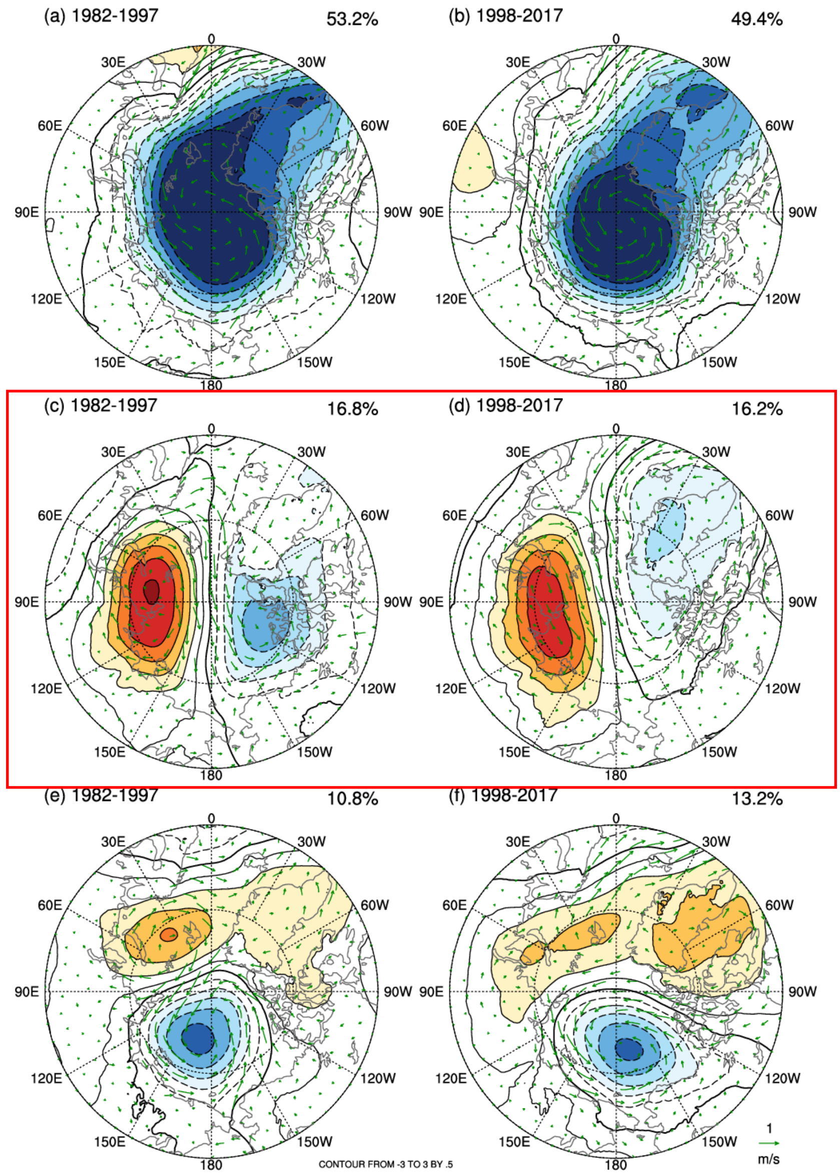

Figure 4. The three leading EOFs of JJA-mean SLP (contour) in the early (1982-1997, left panels) and the recent (1998-2017, right) period. (a) and (b) for the first mode, (c) and (d) for the second, and (e) and (f) the third mode, respectively. The shaded area shows strong variability region of each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

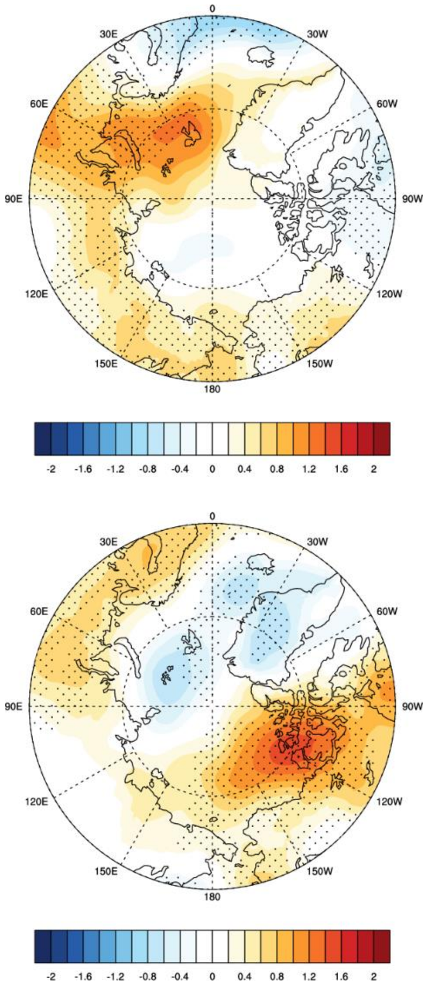

Figure R1. The difference of the leading EOFs (top: EOF 1 and bottom: EOF 2). The dotted area indicates the statistical significance at the 5 % level from the F-test. The EOF vectors were scaled by the variance represented by each mode and subject to the F-test for the variance ratio at each grid point. The degree of freedom is 15 for the early vector and 19 for the recent.

Page 7, line 16: Is melting the only thing going on here?

→ The sign of the AD vector can be reversed as the reviewer commented. The sentence will be modified as “to better represent the southerly wind-induced ice loss over the Pacific sector of the Arctic".

Page 8, line 1: The differences in ice motion between the two periods seems very nuanced to me. Again, I get the impression that that the authors are trying to read too much into the differences.

→ Following 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 wind 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 R2 below. Sea ice motion difference (Fig. R2a) 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. R2b) 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.

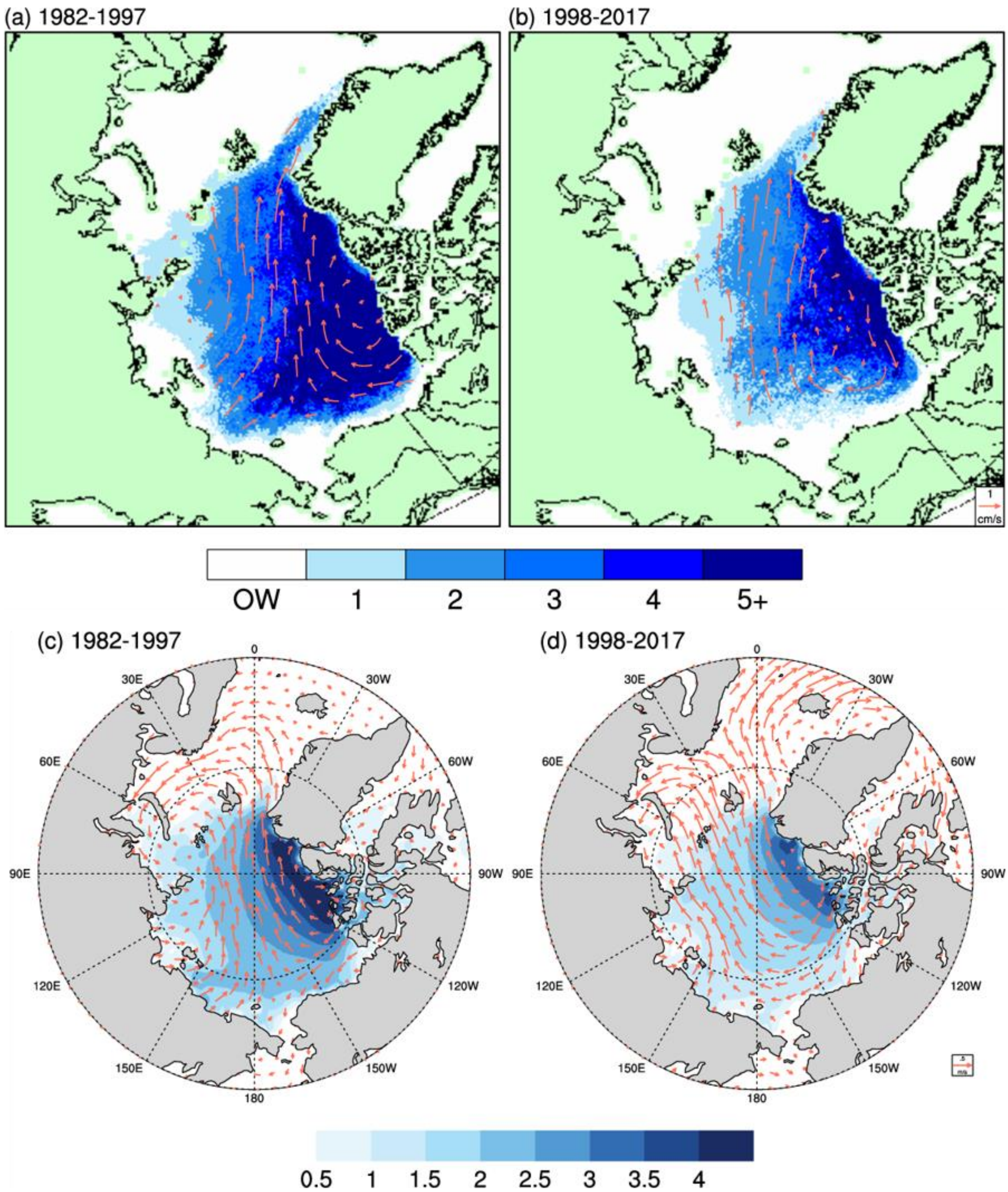

Figure 8. Regression pattern of sea ice motion (top, vector) and surface wind (bottom, vector) onto the AD index in the early (1982-1997, left) and the recent (1998-2017, right) period. Shaded is the sea ice age (top) and the sea ice thickness (bottom) in September averaged over each period.

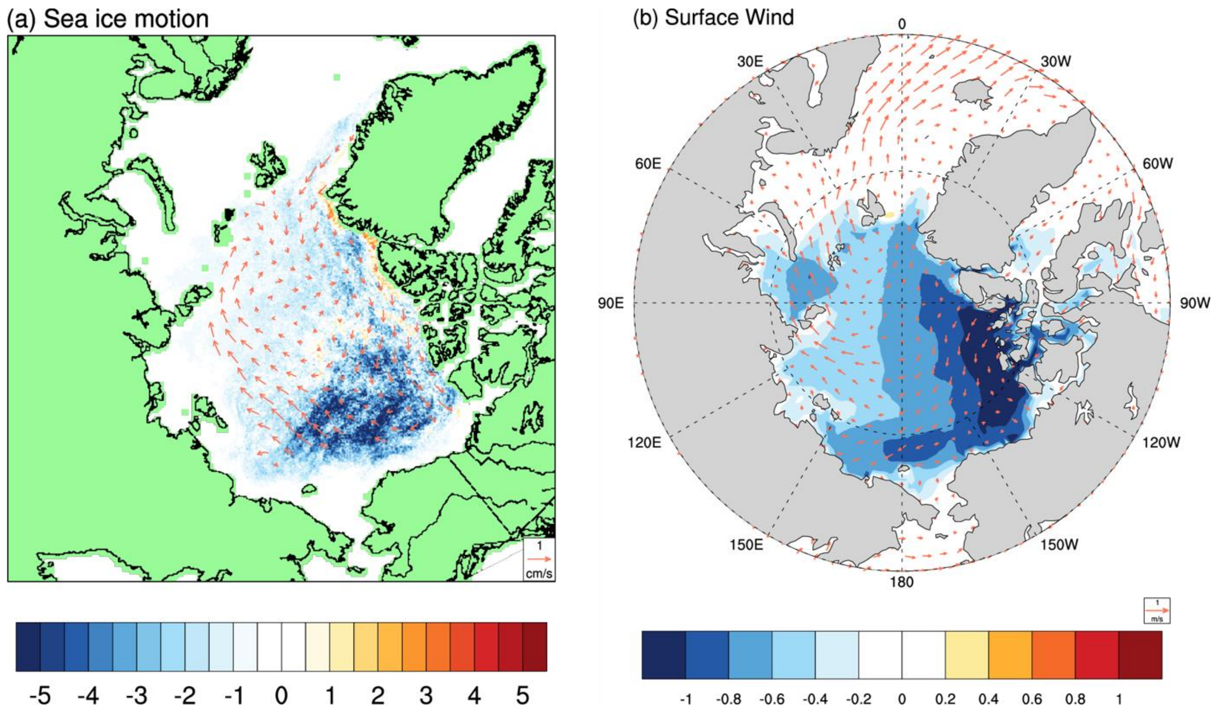

Figure R2. Difference of (a) sea ice motion and (b) surface wind associated to the AD in each period. Shaded is difference of (a) sea ice age and (b) sea ice thickness in September averaged over each period.

Page 8, line 12: Rebecca Woodgate has a number of papers addressing links between the Bering Strait heat inflow and sea ice conditions in the Chukchi Sea and potentially beyond. Also see: 10.1002/2016JC011977, which specifically examines predictability of ice conditions in the Chukchi Sea based on the Bering Strait heat inflow.

→ As indicated, Woodgate et al. (2010) and Serreze et al. (2016) discussed the mechanisms of the warm ocean current through Bering Strait and its impacts on the sea ice in the Chukchi Sea. These studies will be added in the revised manuscript, in addition to the studies of Shimada et al. (2006) and Carmack et al. (2015).

Page 8, line 15 It needs to be acknowledge here (or somewhere) that the last three summers have been very cyclonic over the central Arctic Ocean; in other words, the much bandied “intensification” of the Beaufort Sea high appears to have broken down.

→ We agree on the reviewer’s point and it is consistent well with the mechanisms suggested in this study. Strong anticyclonic circulation over the central Arctic induced by the Beaufort Sea High tends to accelerate the transpolar sea ice drift to the Atlantic sector and provides a favorable condition for the decrease of Arctic SIE. This seems to be a dominant process particularly in 2007-2012 when the Beaufort Sea High was relatively strong (See below for Fig. 1 in Overland et al. 2012). Accordingly, the Arctic SIE exhibited below normal condition (See below Fig. R3, blue circled period). On the other hand, the last three summers have been very cyclonic over the central Arctic Ocean, to provide a less favorable condition for the transpolar drift of sea ice. Accordingly, the decline of SIE has slowed down and above the downward trend (Fig. R3, red circled period).

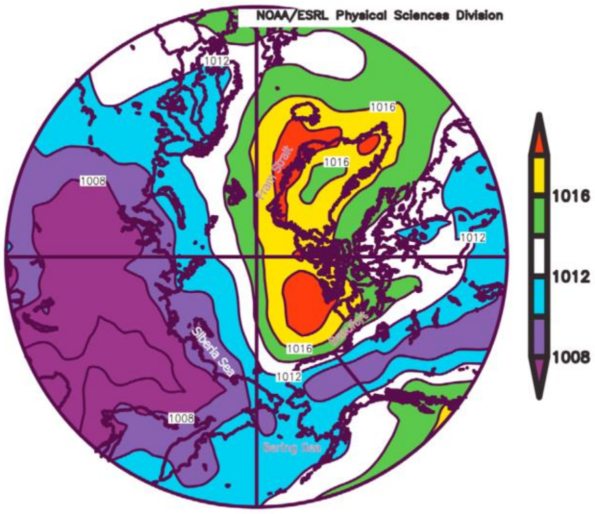

Figure 1. Composite of June sea level pressure (hPa) for 2007–2012. Data are from the NCEP–NCAR Reanalysis through the NOAA/Earth Systems Research Laboratory.

[Overland et al. 2012]

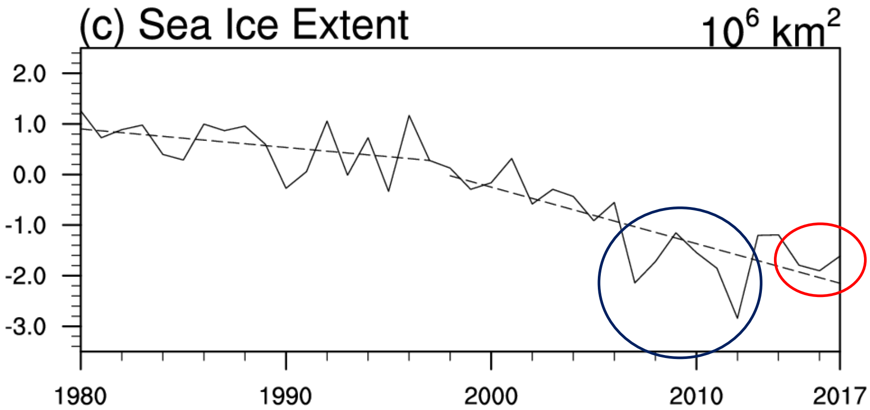

Figure R3. The Arctic sea ice extent (SIE) in September in the region north of 70 N. The anomalies are the departures from the average of 1981-2010. Dashed line shows the trend before and after 1998.

Page 9, lines 16-33: I think it is very difficult to argue that the cause of the shift in the AD is due to a phase change in the PDO. All that one can really say is that the shift in the AD (which seems minor to me) is part of a large-scale pattern of change involving the PDO. The link is certainly interesting, but I'm hesitant to read too much into cause and effect

→ We basically agree with the reviewer in the point that the statistical relationship does not necessarily provide the causality between AD and PDO and it is difficult to conclude the cause of the AD shift is the phase change of PDO. This hypothesis is valid because of statistical relationship and the relevant dynamical processes might be unveiled by well-designed numerical experiments. But this is a very difficult task to experiment, having said that current state-of-the-art models are not able to reproduce realistic AD as the second EOF mode and well beyond the scope of current research.

Instead, 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 the 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.