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Accelerating Arctic Summer Sea Ice Decline Driven by the Dipole Anomaly

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Since the beginning of the satellite era (1979), record lows and highs of Arctic summer sea ice extent are found to be caused not only by dynamically-forced meridional wind advection, but also by the intensified ice/ocean albedo feedback, both of which are triggered by the Arctic atmospheric Dipole Anomaly (DA) pattern. This local, secondary mode of anomalous sea-level pressure (SLP) in the Arctic produces a strong anomalous meridional wind, which was responsible for driving more sea ice out of the Arctic Ocean from the western to the eastern Arctic into the northern Atlantic during the summers of 1995, 1999, 2002, 2005, and 2007-2012 during its positive phase. In September of 2012, a new record minimum in Arctic sea ice extent was caused by the combined dynamic wind forcing of +DA and thermodynamic forcing, accelerating melting, and advective loss of Arctic sea ice. Sea ice extent in August 2012 exceeded the previous record low of September 2007, occurring one month earlier in the summer season. In addition, high summer sea ice extent was associated with the –DA dynamic wind forcing and +AO's divergence effect. A new feedback mechanism for the Pacific Arctic region's atmosphere-ice-ocean climate system is hypothesized to be responsible for the accelerating decline of Arctic summer sea ice. In this hypothesis, the DA provides an intermittent, pulse-like forcing to the system, directly driving sea ice loss by wind forcing and enhancing northward transport of warm Pacific water, and indirectly driving its loss through thermal melting associated with positive ice/ocean albedo feedback and negative ice/cloud feedback. These processes contributed to a series of summer ice minima, particularly occurring since 1995, in which the +DA was associated with accelerating the Transpolar Drift Stream and sea ice export, and amplifying the melting of sea ice.

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1. Introduction

The extent of Arctic sea ice reached its all time low in September 2012, shattering all previous record lows since satellite record-keeping began 33 years ago (Fig. 1) (Comiso et al. 2008) including the previous record low in September 2007 (Zhang et al. 2008, Wang et al. 2009). The Arctic sea ice extent was about 20% less in September 2012, when it was $3.41x10^{6}$ km^2, compared to September 2007, when it was $4.3x10^{6}$ km^2. If Arctic summer sea ice continues to decline at this rate, which is much faster than any climate models predict, but a conservative estimate based on recent empirical data, then the Arctic summer is expected to become ice free by ~ 2035. Should this occur, then society must be prepared to mitigate and adapt to the impacts caused by this unprecedented change in the Arctic environment. For example, as a result of diminishing Arctic sea ice, cold winter and extreme winter weather events have become more frequent over the northern North Atlantic and Eurasia, which further strengthens the declining trend of winter surface air temperature (SAT) over Eurasia (Honda et al. 2009). The cause of this abrupt decline was thought to be 1) the combined effects of Arctic Oscillation (AO)-induced and greenhouse gas-induced thermal warming (Wang and Ikeda 2000), 2) the cumulative effects of ice/ocean-albedo positive feedback (Wang et al. 2005), 3) the increase of Arctic clouds and water vapor (Ikeda et al. 2003), and 4) the anomalously increasing meridional wind forcing associated with the Dipole Anomaly (DA) pattern (Wu et al. 2006; Wang et al. 2009; Ikeda 2012).

Since 1995, the decline in summer Arctic sea ice has accelerated, without any obvious increasing trends in neither cyclone activity nor total net solar radiation. At the same time, while there is some evidence suggesting a weak link between the AO and rapid sea ice retreat during recent years, the AO index has been highly variable, shifting among positive, neutral, and mostly negative states (Wang et al. 2009). Although accelerated sea ice melting has been attributed to Arctic temperature amplification associated with the positive ice-ocean albedo (Wang et al. 2005) and ice-cloud feedback processes (Ikeda et al. 2003), this is clearly not the whole story behind the rapid sea ice decline. Wang et al. (2009) invoked the DA to explain the complete series of intermittent ice minima observed in1995, 1999, 2002, 2005, 2007, and 2008. Clearly, an improved quantitative understanding is needed to explain the recently observed, unprecedented loss of sea ice (Maslanik et al. 2011).

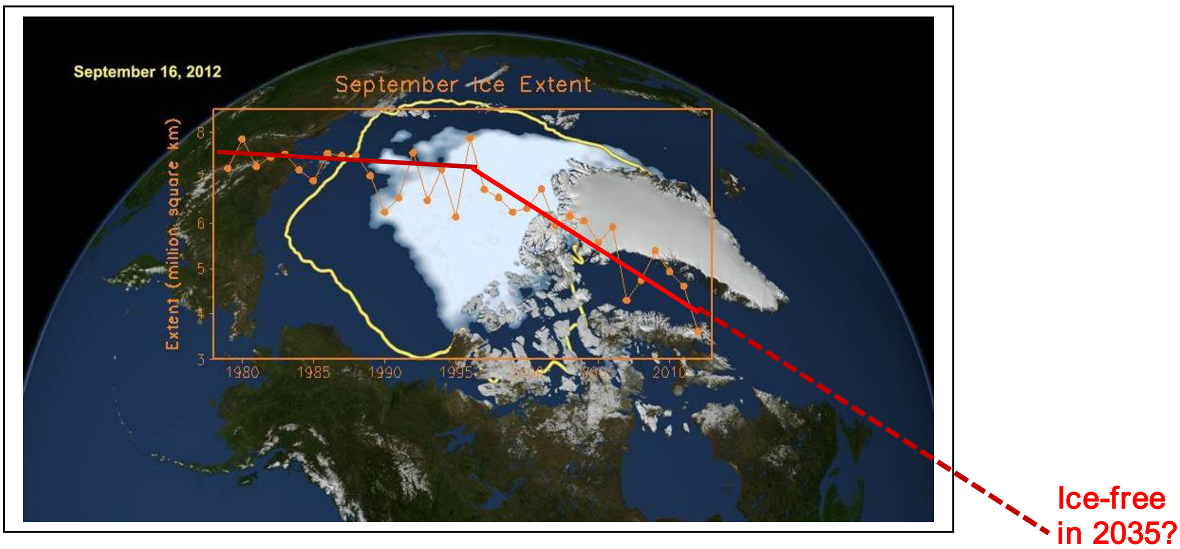

Figure 1. Time series of average September sea ice extent from satellite measurements from 1979 to 2012 and the spatial minimum sea ice extent on September 16, 2012. A linear trend is fit to the period of 1979-1996, and a second trend is fit to 1996-2012. The second trend is illustrated with a dashed line and is extended to an ice- free summer at ~2035, conservatively assuming that the ice/ocean albedo feedback and ice/cloud feedback processes maintain the same rate between now and then.

In this paper, we attempt to establish a new mechanism to explain the accelerated decline of Arctic summer sea ice, especially in the Pacific Arctic sector. This mechanism includes the previously recognized ice/ocean albedo (Wang et al. 2005) and ice/cloud (Ikeda et al. 2003) feedback processes and also includes +DA forcing. When these two climate feedback processes are triggered, even intermittently by DA forcing, the effects can accelerate sea ice loss by direct dynamic forcing as well as by spinning up positive ice/ocean albedo feedback.

2. Data and methods

The average September sea ice extent was obtained from SMMR (Scanning Multichannel Microwave Radiometer) for 1978-1987 and SSM/I (Special Sensor Microwave Imager) for 1987 to present based on the NASA Goddard algorithm (Comiso et al. 2008) archived in the National Snow and Ice Data Center (NSIDC). The monthly NCEP (National Centers for Environmental Prediction) sea-level pressure (SLP) of north of 70^{o}N from 1948 to 2012 was used to derive the empirical orthogonal function (EOF) modes for monthly indices and individual seasons: winter (DJF), spring (MAM), summer (SSA), and autumn (SON), following the previous studies (Wu et al. 2006; Watanabe et al. 2006; Wang et al. 2009, 2014). Then, the first (second) EOF mode is defined as AO (DA).

3. Results

Arctic climate regimes can be decomposed into the Arctic AO and DA modes, the first (Wang and Ikeda 2000) and second (Wu et al. 2006; Wang et al. 2009, 2014) EOF modes, respectively, of Arctic sea level pressure (SLP). Model (Watanabe et al. 2006; Zhang et al. 2008; Wang et al. 2009) and data (Lei et al. 2013) analyses have shown that the Arctic DA pattern is the major driver of Arctic sea ice transport from the western Pacific Arctic to the northern Atlantic (Wu et al. 2006; Wang et al. 2009; Ikeda 2012), although the AO is also a dominant mode affecting Arctic sea ice-ocean circulation. Based on the time series from 1979 to 2012 (Fig. 1), 11 minimum and 12 maximum sea ice years were chosen (Minima: 1979, 1981, 1985, 1990, 1993, 1995, 1999, 2002, 2005, 2007, and 2012; Maxima: 1980, 1983, 1986, 1987, 1988, 1992, 1994, 1996, 2001, 2003, 2006, and 2009) to conduct the composite analysis.

The response of sea ice outflow to +DA due to the existence of year-round TDS is the key dynamic process in the accelerating Arctic sea ice decline (de Verdal et al. 2008); however, it also plays an important role by spinning up the ice/albedo feedback in the Pacific Arctic. Since the +DA can also advect anomalous warm Pacific water into the Chukchi Sea (Fig. 2a; Woodgate et al. 2010; Mizobata et al. 2010), it has both dynamic and thermodynamic effects on sea ice in the Pacific Arctic, as will be discussed shortly. During –DA (Fig. 2b), the TDS is slowed by an opposing wind anomaly that runs against the TDS. As an approximation, the wind generates a surface ocean current running at ~ 2% of the wind speed (Hu et al. 2011, see their Fig. 6a). Therefore, a wind anomaly of 5 ms^{-1} running against the TDS reduces its speed by ~0.1 ms^{-1}, resulting in a surface advection velocity anomaly of 0.1 ms^{-1} from the East (Atlantic) Arctic toward the West (Pacific) Arctic.

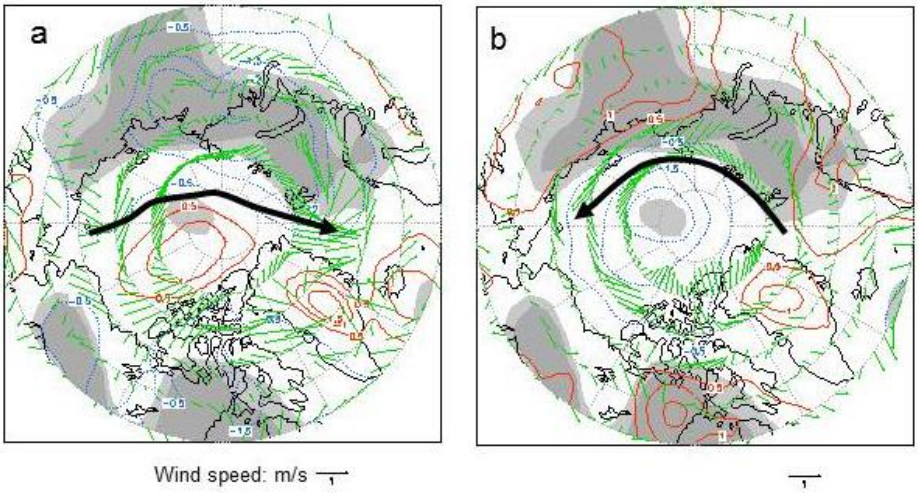

Figure 2. Composite SLP anomaly and anomalous wind vectors during the ice minimum (a) and maximum (b) years. The spatial SLP differences between ice minimum and maximum years are computed at the 95% (heavy shaded) and 90% (light shaded) significance levels based on a Student t-test. The pressure intervals are in 0.5hPa increments. The thick arrows indicate the directions of maximum wind velocity anomalies.

The composites of the SLP anomaly and wind velocity anomalies during the ice minima and maxima were calculated (Fig. 3). It was found that during the years of ice minima, the SLP anomaly shows a +DA pattern with two action centers (Fig. 3a), while during the years of ice maxima, it shows a –DA pattern (Fig. 3b). The areas of significant SLP anomalies correspond to the action centers of the DA. This result based on sea ice minimum and maximum extents reconfirms the finding of Wu et al. (2006) using the composite analysis based on the DA index.

The unprecedented decline of Arctic sea ice has exceeded any climate model's projection (Overland and Wang 2009), reinforcing the idea that these coupled climate models contain many uncertainties. For example, the horizontal and vertical resolutions of present climate GCMs are too coarse to accurately resolve many important ice-ocean processes (Wang et al. 2014) such as Bering Strait and Fram Strait inflows, the Canadian Archipelago outflow, the Arctic Intermediate (or Atlantic) warm water between ~200m to 700m in the Arctic Ocean, and the vertical structures of Arctic temperature and salinity. There are no explicit trends in the Arctic cyclone count; however, there is an upward trend in the meridional wind-speed anomaly over the TDS region (Fig. 3a). In particular, since 2004, this positive anomaly in meridional wind speed has been observed in the Arctic system. The significant cumulative increase has served as a major dynamic forcing behind the series of sea ice minima including the record-breaking events in 2007 (Wang et al. 2009) and 2012 (Fig. 3b). Furthermore, this study proposes that Arctic sea ice loss at such an unprecedented rate can be explained by this dynamic DA-derived meridional wind forcing, combined with the existing thermodynamic ice/ocean albedo feedback processes (Wang et al. 2005; Zhang et al. 2008), leading to the acceleration of ice melting. The polar amplification of atmospheric air temperature was used to partially explain the abrupt decline of Arctic sea ice, but at a much smaller rate, as many GCMs project. The reason for the model underestimates is that sea ice responds not only to the atmospheric forcing aloft, but also to the ocean circulation with its huge heat capacity beneath. Thus, any Arctic amplification must include the ocean dynamics as well as thermodynamics. Hence, the observed Arctic sea ice decline should be attributed to both atmosphere-ice-ocean dynamics and thermodynamics, with +DA forcing providing a key but previously under-appreciated part of the story.

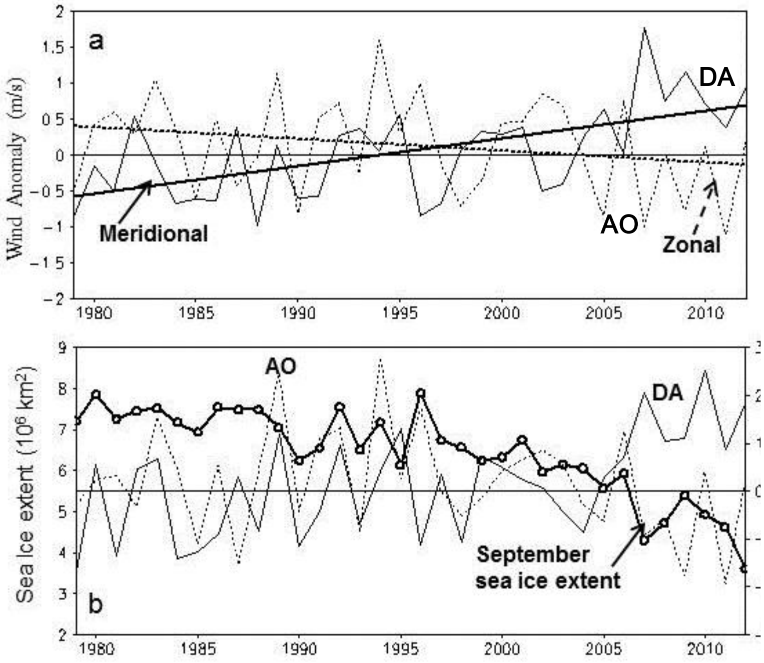

Figure 3. a) Time series of meridional, Wm (solid, with an upward slope of .0388 (m/s per year)), and zonal, Wz (dashed, with a downward slope of -.016 (m/s per year)), wind speed anomalies, respectively, over the TDS region (a rectangular box from 160W-160E and 20W-20E) for the period from 1979-2012. The trends are estimated using squares linear regression model. b) Time series of Arctic September sea ice extent (circled solid line), summer DA index (solid), and summer AO index (dashed). Correlation coefficients were calculated for each pair-wise comparison among these variables (see Table 1).

Table 1. Correlation coefficients among summer sea ice extent, summer DA index, summer AO index, zonal wind (Wz) anomaly, and meridional wind (Wm) anomaly. Values in bold are significant above the 95% confidence level.

	Sea ice extent	AO	DA	Wz	Wm
Ice extent	1	0.40	**-0.57**	0.43	**-0.66**
AO		1	0.017	**0.91**	-0.34
DA			1	0.03	**0.78**
Wz				1	-0.3
Wm					1

Here, we update the hypothetical feedback loop for Arctic sea ice loss by including the conventional ice/ocean albedo feedback loop, proposed by Wang et al. (2005), the ice/cloud feedback loop, proposed by Ikeda et al. (2003), and the newly proposed Pacific water heat transport, which are intermittently triggered by +DA events described in this paper (Fig. 4). This updated feedback loop for the Pacific Arctic can explain both the accelerating advection and amplified melting of Arctic sea ice, leading to the unprecedented decline of Arctic sea ice. Figure 4 shows that the existing annual ice/ocean albedo feedback loop (gray ovals) and the ice/cloud feedback loop (green oval) are extracted from an Arctic decadal climate cycle, described by Wang et al. (2005, see their Fig. 13). The positive feedbacks to

SST/SAT result in negative feedback to Arctic sea ice, i.e., enhancing the melting. This is the conventional Arctic Ocean amplification that causes year-to-year Arctic sea ice decline (Wang et al. 2005). Typically, coupled atmosphere-ice-ocean climate GCMs include only these polar amplification effects. Therefore, it is not surprising that the projections of summer Arctic sea ice by these GCMs are far slower than the observed decline. One of the most fundamental, but potentially important melting mechanisms that these GCMs may miss is associated with the small-scale oceanic heat transport (Woodgate et al. 2010), which is also driven intermittently by the Arctic +DA (see light blue boxes of Fig. 4).

Regardless of AO phase, as long as the DA is positive, it produces a northward wind anomaly in the Pacific Arctic and northern Bering Sea. The northward wind 1) advects warmer SAT into the Pacific Arctic, which increases the SAT anomaly there (see red arrow 1) (Wu et al. 2006); 2) accelerates the TDS, which enhances ice outflow (see red arrow 2; Lei et al. 2014); and 3) directly drives the sea ice

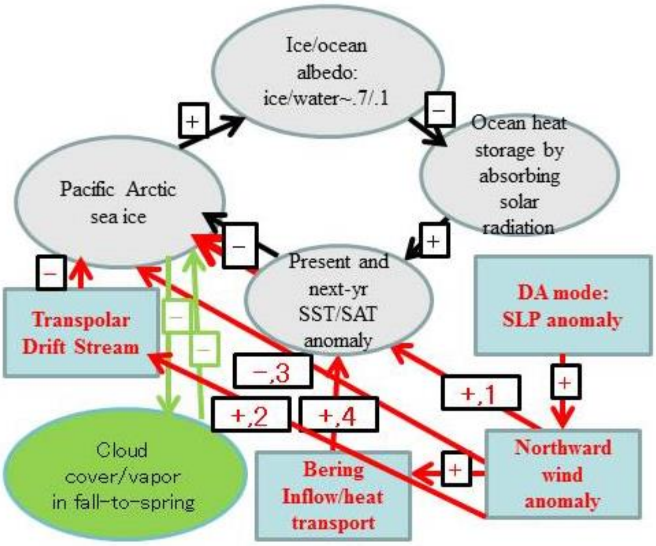

Figure 4. An ice/ocean albedo feedback loop and ice/cloud feedback loop are accelerated by a series of intermittent +DA forcings. The red arrows are associated with +DA forcing, which applies the positive feedback to the SST/SAT, or negative feedback to the sea ice, causing the unprecedented loss of Arctic summer sea ice and a series of record-breaking ice minima. + and – signs denote the positive and negative feedback, respectively. The positive feedback means that a change in one item (say *A*) affects the other item (say *B*), which feeds back so that *A* makes the change in the same direction as the original change. Note that associated with +DA, red arrow 1 indicates the northward advection of warmer SAT in the northern North Pacific to the Arctic by the anomalous meridional wind; Red arrow 2 denotes that anomalous meridional wind directly accelerates the TDS, which promotes export of more ice out of the Arctic; Red arrow 3indicates the direct advection of sea ice by the anomalous meridional wind; and red arrow 4 denotes the warming impact of the ocean heat transport from the Bering Sea promoted by the anomalous northward (or meridional) wind.

away from the Pacific Arctic to the Atlantic Arctic (see red arrow 3 of Fig. 4) (Wang et al. 2009). The anomalous northward wind induced by the +DA also enhances ocean heat transport into the Pacific

Arctic (see red arrow 4; Woodgate et al. 2010; Mizobata et al. 2010; Wang et al. 2009; 2014). The warm current transport, with its associated large heat content, increases the water temperature (i.e., SST) in the Pacific Arctic (see red arrow 4 of Fig. 4), which directly causes immediate melting, and enhances the seasonal positive ice/ocean albedo feedback, which further amplifies sea ice melting (Shimada et al. 2006). The residual overwintering (or cumulative) heat can enhance the positive ice/ocean albedo feedback from one year to the next (Wang et al. 2005). All of these processes (red arrows), triggered intermittently by +DA forcing, drastically spin up the existing positive ice/albedo and ice/cloud feedbacks to the SST and SAT and accelerate the decline of Arctic summer sea ice in the Pacific Arctic by both wind forcing (dynamic) and melting (thermodynamic). The melting is enhanced by ocean heat flux via current advection, atmospheric heat flux via northward wind advection, and indirect positive ice/albedo feedbacks through cumulative overwintering oceanic heat content.

4. Conclusions and discussion

Based on the analyses above, the following conclusions can be drawn:

1) All six historical record lows in sea ice extent fall into climate state 1 (+DA&+AO; 1995 2002, 2012) or into state 3 (+DA&-AO; 1999, 2005, and 2007). Although sea ice extent for September 2008, 2009, 2010, and 2011 were not record lows relative to 2007 and 2012, they still exhibited the lowest levels of sea ice observed in the satellite records from 1979 to 2006. The cause for the 2008, 2009, and 2011 events was similar to the 2007 event, falling into climate state 3 (+DA&-AO), while 2010 was similar to 2012, falling into climate state 1. The composite analysis shows that minimum sea ice years were related to +DA conditions with neutral AO index values, and maximum sea ice years were related to –DA conditions during summer and +AO values that lead to sea ice divergence (Fig. 2).
2) Regardless of the AO phase, the sign of the DA determines the fate of summer Arctic sea ice. The AO determines the sign of Arctic atmospheric circulation, while the DA controls the acceleration or slowdown of the TDS through anomalous meridional wind speed (Fig. 2).
3) The DA positive phase favors sea ice decline, while the negative phase favors sea ice retention. Furthermore, an upward trend in meridional wind speed and a downward trend in zonal wind speed (Fig. 3) have been observed over the TDS region.
4) The interactions of dynamic meridional wind forcing and cumulative thermodyanamic processes, including the Pacific water heat transport, the ice/ocean albedo feedback, and ice/cloud-vapor feedback loops, are the major processes leading the unprecedented Arctic summer sea ice decline observed since 1995. The recent abrupt decline of Arctic sea ice can be qualitatively explained by +DA-associated changes in dynamic wind forcing and thermodynamic ice melting caused by the ocean-atmosphere interactions/feedbacks (Fig. 4).

The Arctic has entered a new climate state with thin, decreasing multi-year sea ice (Maslanik et al. 2011) that is particularly vulnerable to the anomalous DA-associated meridional wind forcing. The dynamic forcing associated with the DA not only drives sea ice export, but more importantly also spins up the existing positive ice/ocean albedo feedback and negative ice/cloud feedback processes, leading to the fastest melting ever observed. If the current pattern continues, we might expect an ice-free summer in the Arctic Ocean before 2035 (Overland and Wang 2009).

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