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Is the Dipole Anomaly a major driver to record lows in Arctic summer sea ice extent?

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[1] Recent record lows of Arctic summer sea ice extent are found to be triggered by the Arctic atmospheric Dipole Anomaly (DA) pattern. This local, second–leading mode of sea–level pressure (SLP) anomaly in the Arctic produced a strong meridional wind anomaly that drove 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. In the 2007 summer, the DA also enhanced anomalous oceanic heat flux into the Arctic Ocean via Bering Strait, which accelerated bottom and lateral melting of sea ice and amplified the ice–albedo feedback. A coupled ice–ocean model was used to confirm the historical record lows of summer sea ice extent. **Citation:** Wang, J., J. Zhang, E. Watanabe, M. Ikeda, K. Mizobata, J. E. Walsh, X. Bai, and B. Wu (2009), Is the Dipole Anomaly a major driver to record lows in Arctic summer sea ice extent?, *Geophys. Res. Lett.*, *36*, L05706, doi:10.1029/2008GL036706.

1. Introduction

[2] The extent of Arctic sea ice reached its all time low in September 2007, shattering all previous lows [*Serreze et al.*, 2007; *Comiso et al.*, 2008; *Stroeve et al.*, 2008; *Gascard et al.*, 2008] since satellite record–keeping began nearly 30 years ago (Figure 1). The Arctic sea ice extent in September 2007 stood at $4.3 \bullet 10^{6}$ km^{2}. Compared to the long–term minimum average from 1979 to 2000, the new minimum extent was lower by about $2.56 \bullet 10^{6}$ km^{2} – an area about the size of Alaska and Texas combined, or 10 United Kingdoms. The cause of this significant ice loss was thought to be the combined effects of Arctic Oscillation (AO)–induced warming [*Thompson and Wallace*, 1998] and export of multiyear ice [*Rigor and Wallace*, 2004; *Steele et al.*, 2004], warming trend due to greenhouse gases, and the culmination of an ice/ocean-albedo positive feedback [*Ikeda et al.*, 2003; *Wang et al.*, 2005].

[3] Since 2002, when summer Arctic sea ice continued to set one record low after another, the AO index has become mostly neutral or even negative [*Maslanik et al.*, 2007], suggesting a weak link between the AO and the rapid sea ice retreat in the recent years. Thus, there must be a new explanation for the record low sea ice since 1995. Such an explanation will help understand the internal variability of Arctic climate and sea ice.

[4] Whenever the Arctic sea ice has reached a new minimum, search for mechanisms responsible for the individual year's event received much attention [*Serreze et al.*, 2007; *Nghiem et al.*, 2007; *Gascard et al.*, 2008; *Stroeve et al.*, 2008]. However, there has been no convincing physical explanation that accounts for the complete series of such events (1995, 1999, 2002, 2005, and 2007). Based on our previous studies [*Wu et al.*, 2006; *Watanabe et al.*, 2006], in this paper, we argue and conclude that the DA, which was defined the second EOF (Empirical Orthogonal Function) mode of SLP north of 70°N, is the major driver of the sea ice record lows, not only valid for 2007, but also generally for the previous record lows. Note that DA, an Arctic regional mode, differs from the PNA (Pacific-North America) pattern and their correlation is only 0.12.

2. Data and Methods

[5] 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-present based on 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) Reanalysis dataset from 1948 to 2008 were used to derive the EOF modes for individual seasons: winter (DJF), spring (MAM), summer (SSA), and autumn (SON). Oceanic heat flux via the Bering Strait was calculated using in situ shipboard measurements and satellite-measured SST across the Bering Strait (K. Mizobata et al., Estimation of heat flux through the eastern Bering Strait, submitted to *Journal of Oceanography*, 2008). A Pan-arctic Ice-Ocean Modeling and Assimilation System (PIOMAS) [*Zhang et al.*, 2008] was used to simulate the sea ice and ocean circulation for the period 1978–2008 under daily NCEP forcing.

3. Results

[6] The Arctic Dipole Anomaly (DA) pattern is an important driver of the Arctic sea ice transport from the western Pacific Arctic to the northern Atlantic based on data analysis for the period 1962–2002 [*Wu et al.*, 2006] and a fully

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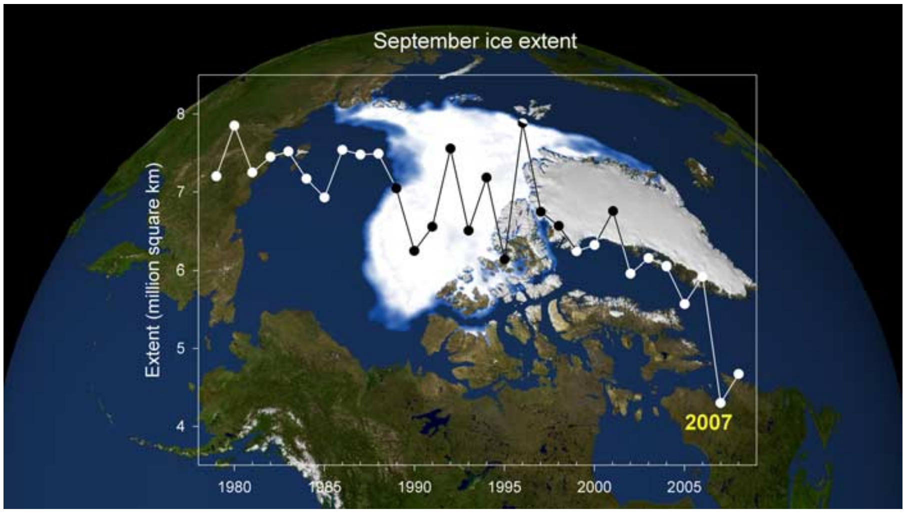

Figure 1. Time series of average September sea ice extent from satellite measurements from 1979 to 2008 and the spatial minimum sea ice extent on September 14, 2007 (SSM/I, source: NASA, Courtesy of Dr. Comiso, see http://svs.gsfc.nasa.gov/vis/a000000/a003500/a003547/index.html).

coupled global climate model for the period 1900–2010 [*Watanabe et al.*, 2006]. The DA (Figures 2b and 2d) differs from the AO (Figures 2a and 2c) in both winter and summer because the anomalous SLP has two action centers in the Arctic, while AO has one annular (circled) center covering the entire Arctic. The resulting wind anomaly for the DA is meridional, while the AO-derived wind anomaly is either cyclonic during its positive phase or anticyclonc during its negative phase [*Wu et al.*, 2006]. During a positive phase of the DA (i.e., the SLP has a positive anomaly in the Canadian Archipelago and negative one in the Barents Sea), the anomalous meridional wind blows from the western to the eastern Arctic, favorable to the Trans-polar Drift Stream (TDS) that flushes sea ice out of the Arctic into the Barents and Greenland seas [*Wu et al.*, 2006; *Watanabe et al.*, 2006]. During the negative phase of the DA, the opposite scenario occurs, i.e., more sea ice remains in the western Arctic [*Watanabe et al.*, 2006]. During the positive/negative AO (i.e., Arctic SLP has a negative/positive anomaly), a cyclonic/anticyclonic wind anomaly occurs, indicating a sea ice divergence/convergence. The divergence (anomalous cyclonic circulation) of sea ice leads to anomalous ice export, while the convergence results in retention of sea ice inside the Arctic Ocean [*Wu et al.*, 2006].

[7] The question is: Is the AO or the DA dynamically more important in terms of ice advection? We conducted the cross composite analysis of both phases of the DA and the AO. A matrix was constructed based on the combination of the two leading drivers that account for about 75% of the total variance. Following *Watanabe et al.* [2006], the Arctic climate patterns can be described by the following four climate states (Table 1): 1) +AO+DA, 2) +AO−DA, 3) −AO+DA, and 4) −AO−DA. It was found that a positive DA is the key, regardless of the sign of the AO, to flushing sea ice out of Arctic due to its dominant meridional (southerly) wind anomaly [*Maslanik et al.*, 2007] while a negative DA-derived wind anomaly can retain sea ice in the western Arctic (Figures 2b and 2d). In other words, the DA is dynamically more important and more effective than the AO in how much sea ice is driven out of the Arctic. These four states can describe major atmospheric circulation patterns in the Arctic, which are the major drivers of sea ice and ocean circulation. The importance of the air temperature advection by the DA is consistent with *Overland et al.*'s [2008] recent finding that the central Arctic Ocean's warm anomalies of the 2000–2007 period are driven by meridional advection from the south. *Ogi et al.* [2008] and *L'Heureux et al.* [2008] have also pointed out the importance of meridional wind anomalies as drivers of sea ice anomalies in the Arctic Ocean.

[8] It was also found that the 2007 summer falls into state 3: −AO+DA, with the AO and DA indices being −1.5 and +2.2, respectively, both higher than 0.6 standard deviation as shown in Figure 2f (the AO/DA indices in 2007 winter, spring, summer, and autumn are 0.58/0.53, 1.35/0.15, −1.5/2.22, and 0.34/0.03, respectively). The resulting SLP anomaly was a DA-dominated two-center structure, and the wind anomaly was meridional, blowing from the western to the eastern Arctic (Figure 4a). This DA-induced wind anomaly was dynamically responsible for the 2007 summer minimum (Figure 1). The positive AO during the 2007 winter (AO index = 0.5, see Figure 2e) and spring (AO index = 1.35) also contributed warming to the Arctic, further thinning sea ice. To illustrate that the +DA and +AO are the key factors for the past ice minima, we construct the climate states to identify the latest five ice minimum summers against summer DA and AO indices, as shown in Table 2. Except for year 2002 (climate state 1) during which +AO played an important role in the Arctic ice minimum, in all four cases, +DA played a leading role for the summer ice minima, although the −AO tends to converge the sea ice inside the Arctic Ocean.

[9] Since 1995, the AO index was near neutral or negative (see Figure 2e), while the DA was active in both winter and summer (see Figures 2e and 2f). It is well known that the winter and spring wind anomalies affect the subsequent (summer) sea ice anomalies [*Rigor and Wallace*, 2004]. Thus, we combine the contribution of the winter-

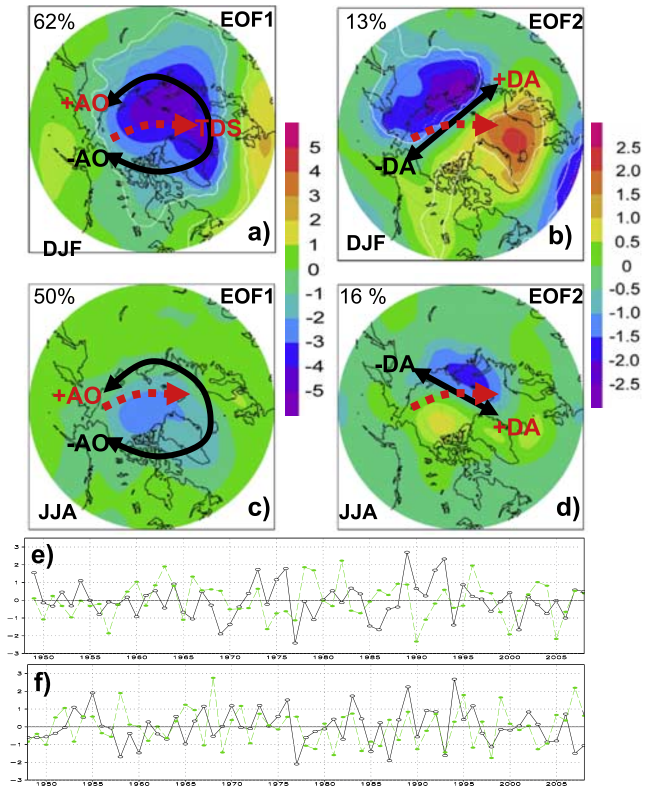

Figure 2. Regression maps of the first two leading modes to the (a and b) winter and (c and d) summer mean Northern Hemisphere SLP field using the NCEP Reanalysis dataset from 1948 to 2008. Contour intervals are 0.5 hPa (see color bars). The time series (or indices) of both AO (black solid line) and DA (green dashed) indices are also shown for (e) winter and (f) summer. White solid and dashed lines represent the 95% and 99% significance level, respectively. The black arrows in Figures 2a and 2c indicate the cyclonic (anticlockwise, divergent) wind anomaly during the +AO phase (which promotes advection of sea ice out of Arctic via Fram Strait) and anticyclonic (clockwise, convergent) wind anomaly during the −AO phase. In Figures 2b and 2d the black arrows indicate that the wind anomaly blows from the western to the eastern Arctic during the +DA phase that accelerates the TDS (in red-dashed arrows), and vice versa during the −DA phase that slows down the TDS.

Table 1. Four Climate States by Combining the AO and the DA

Climate State	+DA	−DA
+AO	1	2
−AO	3	4

Table 2. Summer Ice Minima Versus Summer DA and AO Indices[a]

Year	DA Index	AO Index	Climate State
1995	**1.79**	0.41	**1**
1996	**−1.17**	**1.19**	2
1997	0.29	−0.36	3
1998	**−1.75**	**−1.13**	**4**
1999	**1.65**	−0.15	**3**
2000	0.17	−0.19	3
2001	−0.18	0.05	2
2002	0.06	**0.84**	**1**
2003	**−1.26**	0.14	2
2004	**−0.94**	**−0.85**	**4**
2005	**0.67**	**−0.80**	**3**
2006	0.35	**0.72**	**1**
2007	**2.20**	**−1.40**	**3**
2008	**0.62**	**−1.05**	**3**

[a] The value of 0.6 is selected for the threshold, over which the indices are significant (in bold). The record low years are in italic and bold.

spring wind anomalies with the summer wind anomalies by a scatter plot with the summer DA index as the x-axis and the winter-spring mean DA index as the y-axis (Figure 3). Most years (1995, 2002, and 2007) with previous record low ice extent including the second lowest ice extent ever in 2008 (though not a record low relative only to 2007) were attributed to +DA-induced wind anomalies that were persistent from winter-spring to summer, while in 1999 and 2005, although the winter-spring mean DA was negative, the strong summer +DA contributed to the ice minima. By contrast, the other years with no record low ice extent belong to either states 2 or 4, in which −DA retains the sea ice inside the Arctic Ocean [*Wu et al.*, 2006; *Watanabe et al.*, 2006], while during 1997 (state 3) and 2006 (state 1), DA was not statistically significant, although the AO index was in 2006.

[10] Did the DA alone drive the 2007 summer ice minimum? Certainly not. In the winter of 2006/07, there was a “preconditioning” of thin ice in the western Arctic [*Comiso et al.*, 2008]. The anomalously thin ice at the end of the winter is at least partly associated with a multidecadal downward trend in ice thickness (more than 1-m decrease from the 1950s to 1990s) [*Yu et al.*, 2004; *Rothrock and Zhang*, 2005; *Nghiem et al.*, 2007; *Zhang et al.*, 2008] due to accumulated ocean heat storage by the increasing trend in the Arctic air temperature [*Thompson and Wallace*, 1998]

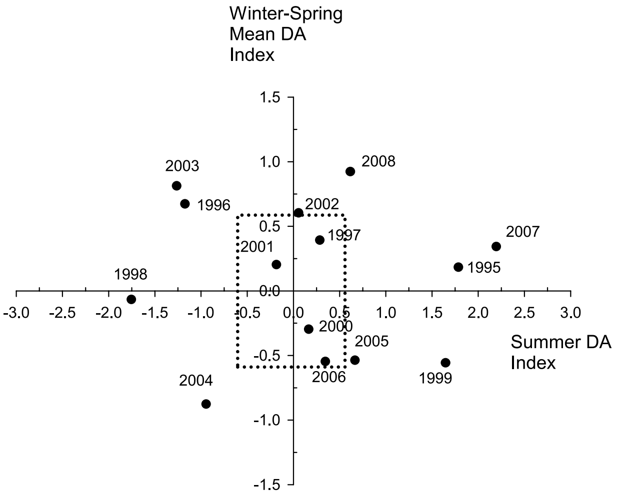

Figure 3. Scatter plot between the summer DA index (x-axis) and winter-spring mean DA index (y-axis) from 1995 to 2008. The box outlined by dotted lines indicates the 0.6 index threshold; the indices greater than 0.6 are considered significant DA years.

Table 3. Annual Northward Heat Flux Via the Eastern Bering Strait in TW

Year	TW
2000	3.87
2001	3.44
2002	2.57
2003	3.72
2004	5.40
2005	4.82
2006	5.43
2007	5.96
Mean	4.40

and the so-called ice/ocean-albedo feedback process during the strong positive AO period in the 1990s [*Ikeda et al.*, 2003; *Wang et al.*, 2005]. Enhanced absorption of solar radiation during summer favors a later freeze-up of sea ice and less sea ice growth during the cold season. A thinner ice cover retreats faster in the following summer, leading to more open water than the previous summer. Because this process continued, it led to a cumulative heat storage in the ocean, resulting in a long-term downward trend [*Yu et al.*, 2004; *Wang et al.*, 2005; *Rothrock and Zhang*, 2005]. This ice/ocean-albedo feedback has an amplified effect that created the thin ice in the 2006/07 winter, upon which the DA-induced wind anomaly in the 2007 summer drove the minimum ice episode [*Zhang et al.*, 2008].

[11] The +DA not only drove sea ice from the western to the eastern Arctic, but also strengthened inflow of the warm Pacific water since the 2000s [*Woodgate et al.*, 2006] that injected above-average heat flux from the Pacific, accelerating the drastic thinning of sea ice [*Steele et al.*, 2004; *Shimada et al.*, 2006]. To confirm that the Pacific water heat flux increased in the 2000s, in particular in summer 2007, we updated the calculation of the heat flux through the eastern Bering Strait from 2000 to 2007 during the June–October ice free seasons. Table 3 shows that since 2004, heat flux via the eastern Bering Strait has an annual average of 5.4 TW (1 TW = 10^{12} Watts), compared to the annual average of 3.4 TW during 2000–2003, representing a 45% increase. The heat flux in 2007 (5.96 TW) had a 35% increase compared to the average of 4.4 TW from 2000 to 2007. Therefore, the heat flux from the Pacific Ocean has two important impacts, direct and indirect, on sea ice in the western Arctic. The direct impact includes the bottom and lateral melting of sea ice when the warm Pacific enters the Chukchi Sea. The indirect impact involves a time-lag effect: the oceanic heat flux entering in the previous summer can survive winter [*Shimada et al.*, 2006] at the subsurface, which enhances the melting in the following spring and summer, amplifying the ice/ocean albedo process.

[12] To further confirm that the atmospheric forcing associated with +DA in the summer of 2007 (see Figure 4a) is the key, the PIOMAS [*Zhang et al.*, 2008] was used to simulate the sea ice and ocean circulation for the period 1978–2008 under daily NCEP forcing (Figure 4a and 4b). Figure 4c shows that the simulated sea ice area compares well against the satellite-measurements. The correlation between the observed and model results is 0.93 in September, while it is 0.92 for the January–September mean time series. In particular, the model reproduces excellent agreement with summer ice minima in 1995, 2002, 2005, and 2007, as well as 2008, though not for 1999.

4. Conclusions and Discussion

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

[14] 1) All five historical record lows fall into climate state 1 (+DA+AO; 1995 and 2002) or state 3 (+DA−AO; 1999, 2005, and 2007). Although September 2008 was not the record low relative to 2007, it was the second lowest year ever when compared to the other record lows. The cause for the 2008 event is similar to the 2007, since both belong to climate state 3 (+DA−AO). The difference is that the 2008 +DA and −AO indices are much weaker than the previous summer (see Table 2 and Figures 4a and 4b). It is clear that both the +DA and the +AO together enhance advecting sea ice out of the Arctic during climate state 1. During climate state 3, even though the −AO tends to converge sea ice inside the Arctic, the strong summer +DA is more dynamically important and effective than the −AO in advecting sea ice out of the Arctic by accelerating the TDS.

[15] 2) In terms of sea ice advection, the +DA-associated wind anomalies are the major driver to the record lows in Arctic summer sea-ice extent under the current thin ice

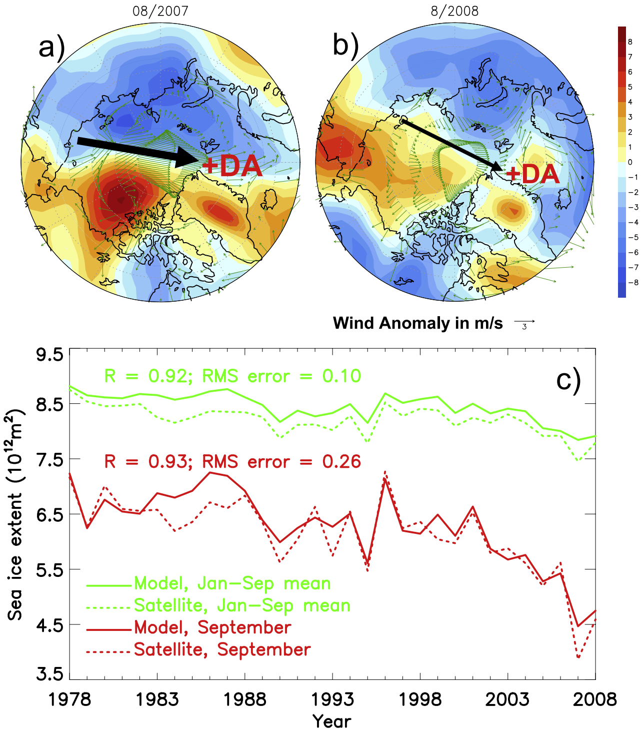

Figure 4. The (a) 2007 August and (b) 2008 August SLP (shaded) and wind (vectors) anomalies relative to the 1948–2008 mean (data from NCEP Reanalysis). Red/blue indicates the positive/negative anomalies in SLP. The green arrows indicate the +DA-derived anomalous wind velocity (in ms^{-1}). The DA-derived wind anomaly was the dominating driver for advecting sea ice toward the eastern Arctic, leading to the record minimum in the Arctic. (c) Comparison between the PIOMAS-simulated and SSM/I-observed ice extents for the period 1978–2008.

preconditioning that has been present for the last several decades, particularly during the early 1990s. In particular, when the +DA pattern persists from winter-spring to summer, the combined winter-spring mean and summer DA indices can be used to project a record low in the Arctic September sea ice extent (four out of six, including 2008). Nevertheless, the −DA in the winter-spring alone cannot project more ice in the western Arctic, because the summer +DA can drastically advect more ice out of the Arctic, such as in 1999 and 2005, leading to the record lows.

[16] Other low years (not yet minima) either fall into climate states 2 or 4, in which −DA-associated anomalous winds blow against and thus slow down the TDS (Figure 2), retaining sea ice inside the western Arctic. Even though some years fall into state 3, +DA is not statistically significant.

[17] Oceanic heat flux via the Bering Strait increases correspondingly since 2000 [*Woodgate et al.*, 2006], particularly in 2007 (see Table 3). A possible cause may be that the local southerly wind drives more warm Pacific water into the Arctic Ocean during the +DA summers. There is an association between the heat flux and +DA events, which need to be further investigated using long-term measurements. However, the orientation, bathymetry, and ocean boundary around the Bering Strait may be factors affecting the northward heat transport, which differs from the atmosphere without lateral boundary.

[18] Arctic sea ice has entered certain climate states that are particularly vulnerable to anomalous DA-associated atmospheric forcing [*Zhang et al.*, 2008]. Nevertheless, whether the 2007 summer record low is a tipping point that will cause a continued decline in Arctic sea ice toward an ice-free summer remains a challenging research topic for the 21st century.

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References

Comiso, J. C., C. L. Parkinson, R. Gersten, and L. Stock (2008), Accelerated decline in the Arctic sea ice cover, *Geophys. Res. Lett.*, *35*, L01703, doi:10.1029/2007GL031972.

Gascard, J.-C., et al. (2008), Exploring Arctic transpolar drift during dramatic sea ice retreat, *Eos Trans. AGU*, *89*(3), doi:10.1029/2008EO030001.

Ikeda, M., J. Wang, and A. Makshtas (2003), Importance of clouds to the decaying trend in the Arctic ice cover, *J. Meteorol. Soc. Jpn.*, *81*, 179–189.

L'Heureux, M. L., A. Kumar, G. D. Bell, M. S. Halpert, and R. W. Higgins (2008), Role of the Pacific-North American (PNA) pattern in the 2007 Arctic sea ice decline, *Geophys. Res. Lett.*, *35*, L20701, doi:10.1029/2008GL035205.

Maslanik, J., S. Drobot, C. Fowler, W. Emery, and R. Barry (2007), On the Arctic climate paradox and the continuing role of atmospheric circulation in affecting sea ice conditions, *Geophys. Res. Lett.*, *34*, L03711, doi:10.1029/2006GL028269.

Nghiem, S. V., I. G. Rigor, D. K. Perovich, P. Clemente-Colón, J. W. Weatherly, and G. Neumann (2007), Rapid reduction of Arctic perennial sea ice, *Geophys. Res. Lett.*, *34*, L19504, doi:10.1029/2007GL031138.

Ogi, M., I. G. Rigor, M. G. McPhee, and J. M. Wallace (2008), Summer retreat of Arctic sea ice: Role of summer winds, *Geophys. Res. Lett.*, *35*, L24701, doi:10.1029/2008GL035672.

Overland, J. E., M. Wang, and S. Salo (2008), The recent Arctic warm period, *Tellus, Ser. A*, *60*, 589–597.

Rigor, I. G., and J. M. Wallace (2004), Variations in the age of Arctic sea-ice and summer sea-ice extent, *Geophys. Res. Lett.*, *31*, L09401, doi:10.1029/2004GL019492.

Rothrock, D. A., and J. Zhang (2005), Arctic Ocean sea ice volume: What explains its recent depletion?, *J. Geophys. Res.*, *110*, C01002, doi:10.1029/2004JC002282.

Serreze, M. C., M. M. Holland, and J. Stroeve (2007), Perspectives on the Arctic's shrinking sea ice cover, *Science*, *315*, 1533–1536, doi:10.1126/science.1139426.

Shimada, K., T. Kamoshida, M. Itoh, S. Nishino, E. Carmack, F. McLaughlin, S. Zimmermann, and A. Proshutinsky (2006), Pacific Ocean inflow: Influence on catastrophic reduction of sea ice cover in the Arctic Ocean, *Geophys. Res. Lett.*, *33*, L08605, doi:10.1029/2005GL025624.

Steele, M., J. Morison, W. Ermold, I. Rigor, M. Ortmeyer, and K. Shimada (2004), Circulation of summer Pacific halocline water in the Arctic Ocean, *J. Geophys. Res.*, *109*, C02027, doi:10.1029/2003JC002009.

Stroeve, J., M. Serreze, S. Drobot, S. Gearheard, M. Holland, J. Maslanik, W. Meier, and T. Scambos (2008), Arctic sea ice extent plummets in 2007, *Eos Trans. AGU*, *89*(2), doi:10.1029/2008EO020001.

Thompson, D. W. J., and J. M. Wallace (1998), The Arctic Oscillation signature in the wintertime geopotential height and temperature fields, *Geophys. Res. Lett.*, *25*, 1297–1300.

Wang, J., M. Ikeda, S. Zhang, and R. Gerdes (2005), Linking the Northern Hemisphere sea ice reduction trend and the quasi-decadal Arctic Sea Ice Oscillation, *Clim. Dyn.*, *24*, 115–130, doi:10.1007/s00382-004-0454-5.

Watanabe, E., J. Wang, A. Sumi, and H. Hasumi (2006), Arctic dipole anomaly and its contribution to sea ice export from the Arctic Ocean in the 20th century, *Geophys. Res. Lett.*, *33*, L23703, doi:10.1029/2006GL028112.

Woodgate, R. A., K. Aagaard, and T. J. Weingartner (2006), Interannual changes in the Bering Strait fluxes of volume, heat and freshwater between 1991 and 2004, *Geophys. Res. Lett.*, *33*, L15609, doi:10.1029/2006GL026931.

Wu, B., J. Wang, and J. E. Walsh (2006), Dipole Anomaly in the winter Arctic atmosphere and its association with Arctic sea ice motion, *J. Clim.*, *19*, 210–225, doi:10.1175/JCLI3619.1.

Yu, Y., G. A. Maykut, and D. A. Rothrock (2004), Changes in the thickness distribution of Arctic sea ice between 1958–1970 and 1993–1997, *J. Geophys. Res.*, *109*, C08004, doi:10.1029/2003JC001982.

Zhang, J., R. Lindsay, M. Steele, and A. Schweiger (2008), What drove the dramatic retreat of arctic sea ice during summer 2007?, *Geophys. Res. Lett.*, *35*, L11505, doi:10.1029/2008GL034005.

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