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Extraordinary September Arctic sea ice reductions and their relationships with storm behavior over 1979–2008

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[1] Dramatic changes have been observed in Arctic sea ice, cyclone behavior and atmospheric circulation in recent decades. Decreases in September ice extent have been remarkable over the last 30 years, and particularly so in very recent times. The analysis reveals that the trends and variability in September ice coverage and mean cyclone characteristics are related, and that the strength (rather than the number) of cyclones in the Arctic basin is playing a central role in the changes observed in that region, especially in the last few years. The findings reinforce suggestions that the decline in the extent and thickness of Arctic ice has started to render it particularly vulnerable to future anomalous cyclonic activity and atmospheric forcing.

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1. Introduction

[2] Many aspects of Arctic climate have shown dramatic changes in recent decades [e.g., *Serreze et al.*, 2000]. These have been particularly marked in sea ice [*Stroeve et al.*, 2007; *Comiso et al.*, 2008] and temperature [*Overland et al.*, 2008], and are also apparent in cyclone behavior and atmospheric circulation [e.g., *Serreze et al.*, 2000; *X. Zhang et al.*, 2004, 2008; *Simmonds et al.*, 2008], and precipitation and river runoff. The changes in minimum Arctic sea ice extent (SIE) (in September) have been particularly remarkable in very recent times. In 2005 a new record low SIE was set (5.52×10^6 km^2), and this in turn was broken by a wide margin in 2007 (4.29×10^6 km^2). The September cover in 2008 (4.64×10^6 km^2) failed by only a small amount to break that new record. This investigation explores the extent to which changes in Arctic cyclonic activity are associated with these striking September trends over the last 30 years (1979–2008) and in the very recent past.

[3] The Arctic basin is a complex physical system with a myriad of interacting processes. The most important of these associated with the sea ice decline have yet to be clearly identified, but potentially include dynamical processes (changes in winds, ocean currents and cyclone behavior) and thermodynamic processes (changes in turbulent energy fluxes, ocean heat storage, air temperature and radiative effects) [*Deser and Teng*, 2008; *Kay et al.*, 2008; *Wang et al.*, 2009].

[4] In addition to being the time of minimum sea ice, September is of especial interest for many reasons. It is the month which displays the greatest SIE inter-annual variability, and is the first month after summer when the basin-wide average surface total heat flux becomes negative (i.e., away from the surface) [*Serreze et al.*, 2007]. Autumn is also a key season for ice-albedo feedback and is a time when the role of clouds in modifying the surface heat balance is of particular interest [*Schweiger et al.*, 2008a]. It has been argued that changes in perennial sea ice are crucial to the overall mass balance of Arctic ice [*Nghiem et al.*, 2007].

[5] Cyclones play a central role in the interaction between the surface and atmosphere and are a key component in the climate mix in the Arctic basin. Studies have shown strong relations between cyclone behavior and Arctic sea ice [*Murray and Simmonds*, 1995; *Sorteberg and Kvingedal*, 2006] and it is known that these systems (as distinct from the mean flow) are the dominant means by which moisture is transported into and over the Arctic basin, thus influencing cloud cover and precipitation [*Groves and Francis*, 2002].

[6] In this work we test some physical hypotheses as to the connections between September SIE in the Arctic basin (here defined as all ocean points north of 65°N) over the last three decades and aspects of cyclone behavior, with a view to obtaining a more integrated picture of Arctic variability. Septembers with low SIE correspond on average with greater basin-wide surface enthalpy fluxes. (For the data used in this paper the temporal correlation over 1979–2008 between the September SIE and the enthalpy flux is -0.31 ($p = 0.10$); the flux is dominated by the latent heat flux (LHF), which has a correlation of -0.37 ($p = 0.046$) with SIE (see Table 1).) From these considerations we suggest that Septembers with low SIE provide increased energy for cyclonic systems, and hence would be associated with the enhanced development of already-existing cyclones. Note also that more energetic cyclones will exert greater mechanical forcing on the ice, with the potential during this month of minimum extent and thickness to disperse ice (moving some into warmer waters) and result, in turn, in less SIE. From these reflections we form the hypothesis (HA1) that reduced September SIE is associated (through mutual interactions) with stronger and larger Arctic basin cyclones. As to the number of summer cyclones, a significant proportion of these originate outside the Arctic basin [*Serreze and Barrett*, 2008; *Löptien et al.*, 2008]. A second hypothesis is formed (HA2) of no relationship between Arctic September cyclone counts and SIE.

[7] Testing basin-wide hypotheses such as these has the potential to reveal much in an integrated sense about the complex interactions taking place over the basin. However, when analysed over key sub-regions the associations between climate variables highlight regional processes. Many studies have uncovered climate connections within sub-

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Table 1. Temporal Correlations Between September SIE and Mean Cyclone Characteristics and Latent Heat Flux[a]

Parameter	Correlation (and p Value) (Entire Arctic Basin)	Correlation (and p Value) (Eastern Arctic Basin)
Number	0.19 (0.33)	−0.07 (0.69)
Depth	−0.52 (0.003)	−0.55 (0.002)
Radius	−0.65 (0.001)	−0.53 (0.003)
LHF	−0.37 (0.046)	−0.24 (0.20)

[a] The correlations are calculated over the period 1979–2008 for the Arctic basin averages and the east Arctic (20°W to 160°E) averages. The numbers in parentheses are the p values.

domains of the Arctic but one must be cautious of interpreting a posteriori the results of statistical analyses. One is on more defensible grounds by framing hypotheses over regions which have been identified as key in independent investigations. The recent insightful work of *Wang et al.* [2009] provides a framework for forming regional hypotheses in connection with ice-cyclone links. Their analysis revealed that the polarity of the summer Arctic Dipole Anomaly sea level pressure (SLP) pattern was strongly related to Arctic sea ice coverage. The larger loadings of this mode [*Wang et al.*, 2009, Figure 2d] lie in the eastern Arctic (approximately between 20°W and 160°E), and their results strongly suggest that the eastern Arctic is a key region with respect to the connections between ice and cyclones. (This is consistent with the work of, e.g., *Bengtsson et al.* [2004] and *Sorteberg and Kvingedal* [2006], which emphasised the importance of these connections in the Barents Sea.) We form hypotheses similar to those above, of negative associations between the anomalies of East Arctic (defined as all ocean points north of 65°N, and between 20°W and 160°E) September SIE and cyclone size and strength (HEA1), and of no association with SIE and cyclone counts (HEA2). We test these four hypotheses using quality sea ice and cyclone data sets, with an especial interest in the very low September sea ice and strong cyclones in the last few years.

2. Methodology and Data Sets

[8] The atmospheric analyses we use are the Japanese JRA-25 global reanalysis [*Onogi et al.*, 2007] over 1979–2008, a period corresponding to that of comprehensive satellite coverage. The spatial resolution of the model used in its construction is the highest (T106L40) of any reanalysis which extends up till 2008. The data are available every 6 hours on a 2.5° × 2.5° latitude-longitude grid. The catalog of Arctic surface cyclones and their properties has been determined from the SLP fields in JRA-25 using The University of Melbourne cyclone identification scheme [*Simmonds et al.*, 2003]. This analysis diagnoses many key features of cyclone structure, including Radius (R) and Depth (D) (the difference in the pressures at the center and the 'edge' of a cyclone). Cyclone size is an important characteristic of storms [*Simmonds*, 2000]. Depth is a particularly insightful statistic which is related to the overall influence of a cyclone (e.g., via its net eddy meridional transport [*Simmonds and Keay*, 2000]), and is approximately proportional to the square root of the total surface kinetic energy of a cyclone (and the surface stress). The exact relationship can be easily established for the case of an axisymmetric cyclone whose pressure assumes a parabolic shape between the center and the (circular) edge, i.e.,

$$p(r) = p_c + ar^2, \tag{1}$$

where p (r) is the SLP at distance r from the center and a is a constant (in fact the Laplacian of pressure divided by 4). The Depth can then be written as

$$D \equiv p(R) - p_c = aR^2 \tag{2}$$

The net kinetic energy of the cyclone per unit vertical distance is

$$KE = \frac{1}{2} \int_{\mathit{area\ of\ cyclone}} \rho v^2 dA$$

where ρ is the density and v the speed. Assuming geostrophy this can be expressed as

$$KE = 2a^2 \int_{\mathit{area\ of\ cyclone}} \frac{1}{f^2 \rho} r^2 dA$$

and f denotes the Coriolis parameter. Making the reasonable simplification that $f^2\rho$ is constant across the cyclone this can be evaluated as

$$KE = \frac{\pi a^2}{f^2 \rho} R^4 \tag{3}$$

From (2) and (3) we can write

$$KE = \frac{\pi}{f^2 \rho} D^2$$

Hence Depth provides a direct measure of the square root of the total kinetic of the system (without any reference to its intensity or size). (Note the constant of proportionality depends on latitude (*via* the Coriolis parameter).)

[9] The SIE was derived from remotely sensed Nimbus-7 Scanning Multichannel Microwave Radiometer (SMMR) and Defense Meteorological Satellite Program (DMSP) Special Sensor Microwave Imager (SSM/I) passive microwave data from the National Snow and Ice Data Center (NSIDC) [see, e.g., *Comiso et al.*, 2008]. This dataset includes daily sea ice concentrations at a grid cell size of 25 × 25 km. In computing the total sea ice extent, pixels must have an ice concentration of at least 15% to be included. The total SIE is then calculated by summing up the number of pixels which achieve this concentration multiplied by the total pixel area. To calculate monthly average SIE we determine the SIE on each day during the month and obtain an average of those values. This produces a slightly different value from the (often-applied) method of using the monthly mean concentration to determine monthly mean SIE.

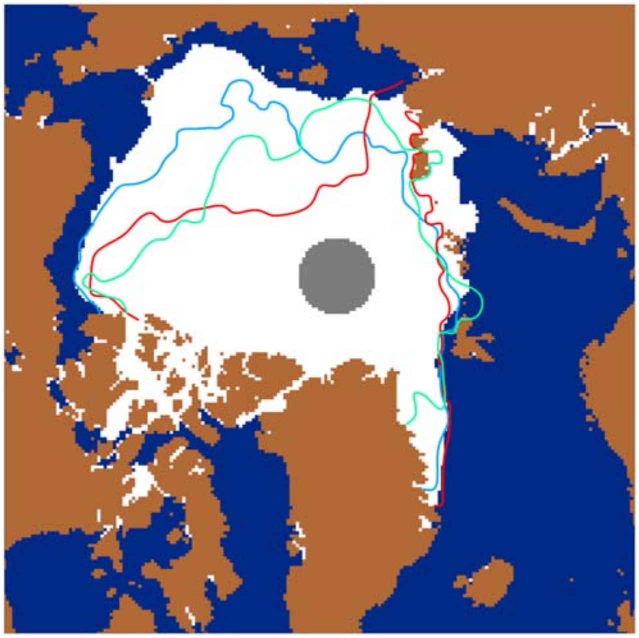

Figure 1. September Arctic sea ice coverage. The median ice cover (for 1979–2000) is presented in solid white. The blue, green, and red lines indicate the ice edges in 2005, 2008, and 2007, respectively.

[10] In our investigation we undertake correlation and (least squares) linear trend analyses. The statistical significance of these is quantified by the p-value obtained from appropriate two-sided t-tests (see, e.g., *von Storch and Zwiers* [2001] for the testing the null hypotheses of zero correlation and zero trend). Unless explicitly stated otherwise we use the 10% confidence level in the statistical significance tests.

3. Sea Ice and Cyclones

3.1. Trends

[11] The extraordinarily low September Arctic sea ice coverage over the last four years is shown in Figure 1, where the solid white indicates the 1979–2000 median coverage along with the ice edges for 2005 (blue), 2008 (green) and 2007 (red). All calendar months exhibit a significant SIE decline over the last three decades ($p < 0.001$), the greatest of these being -0.728×10^6 km^2 decade^{-1} in September. The nature of the September decline has been particularly marked this century (Figure 2a). Noteworthy variations in September synoptic activity have also occurred in the Arctic basin over the period. The mean number of cyclone counts per analysis is 5.04, and this has displayed no significant trend (Figure 2b). By contrast there are strong and significant positive trends in mean cyclone Depth (1.58 hPa century^{-1}, p = 0.037) and Radius (0.70°latitude century^{-1}, p = 0.001) (Figures 2c and 2d), and the last few years have witnessed extreme values of these cyclone characteristics. These basin-wide trends hint at links between SIE and cyclone vigor rather than frequency, consistent with the hypotheses formed above. The LHF (Figure 2e) exhibits a significant upward trend (7.02 Wm^{-2} century^{-1}, p = 0.066), and has displayed large values since 2002.

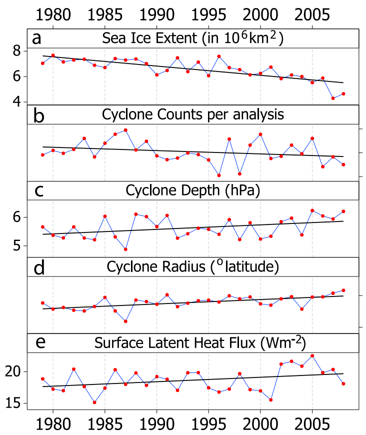

Figure 2. September Arctic basin mean time series 1979–2008. (a) Sea ice extent (in 10^6 km^2), (b) cyclone counts per analysis, (c) cyclone Depth (hPa), (d) cyclone Radius ($^{\rm o}$latitude), and (e) surface latent heat flux (Wm^{-2}). The solid black lines denote the line of best fit (least squares).

3.2. Temporal Associations Between Sea Ice Extent and Cyclone Properties

[12] We are now in a position to test HA1 that years of low September Arctic SIE are associated with stronger and larger cyclones. We undertake this by correlating the raw time series of SIE with those of the cyclone properties displayed in Figure 2, and the results are shown in Table 1. The analysis allows us to accept HA1 (at very high confidence levels); mean September Depth is correlated with SIE with a coefficient (r) of -0.52 ($p = 0.003$), while $r = -0.65$ ($p = 0.001$) for monthly mean Radius. Our examination also leads us to accept the null hypothesis (HA2) of no relationship between SIE and cyclone numbers.

[13] To complement these basin-wide relationships we test the hypotheses formed above in connection with the East Arctic region. The time series of the September means of the relevant climatological parameters over this domain are presented in Figure 3. There is considerable similarity with the basin-wide series shown in Figure 2. The 30-year trend in SIE (over this smaller area) is -0.278×10^6 km^2 decade^{-1} ($p < 0.001$). The trends in mean Depth, Radius, and LHF are significant and approximately double those for the entire basin (3.52 hPa century^{-1}, 1.27°latitude century^{-1}, and

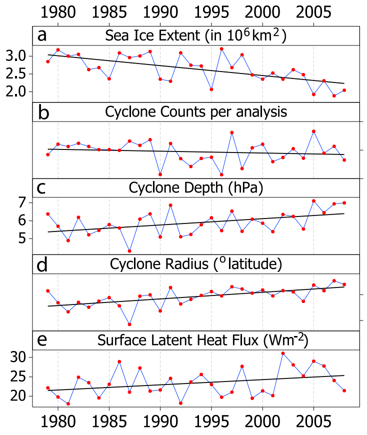

Figure 3. As in Figure 2, but for the east Arctic basin.

13.37 Wm^{-2} $\mathrm{century}^{-1}$, respectively). Recent years have seen extreme values in this sector also. Table 1 shows that the negative correlations between SIE and both Depth and Radius are rather similar to those for the entire Arctic basin, and highly significant, and thus we accept HEA1. As far as the total number of cyclones is concerned we accept the null hypothesis in the eastern region also (HEA2).

[14] Overall, then, the hypotheses framed in section 1 have been accepted and reveal a relationship between reductions in September SIE and increases in cyclone strength and size, but little change in frequency. In contrast to the Arctic-wide signal, it would appear that anomalies of LHF play only a minor role in these associations in the eastern Arctic (Table 1). While it is not addressed here, it is suggested that, in part, in that sector changes in SIE are associated with cyclone properties through other mechanisms such as changes in baroclinicity [see, e.g., *Glowienka-Hense and Hense*, 1992; *Serreze and Barrett*, 2008].

4. Discussion and Conclusion

[15] We have documented some remarkable changes in September mean cyclone properties which are partially associated with the dramatic decreases in SIE. In particular we have seen that informative September Arctic cyclone properties (such as Depth) are related to changes in the Arctic ice in a much more consistent manner than are variations in cyclone counts. We have taken the perspective here that to help us understand these changes it is important to consider as long a record as possible, rather than just focus on individual (extreme) years, in which one specific mechanism may be fundamentally responsible for the extreme. This view is consistent with that of *Wang et al.* [2009] who commented there has been no convincing explanation which accounts for all the low SIE events over the last two decades.

[16] A number of authors [e.g., *Wernli and Schwierz*, 2006, *Sorteberg and Walsh*, 2008; *Raible et al.*, 2008; *Ulbrich et al.*, 2009] have stressed the importance of using reliable techniques and data sets for cyclone identification when undertaking studies of this nature. One of the strengths, and source of confidence in the results, of our study is that it has been conducted with very reliable sea ice data and with a state-of-the-art cyclone identification scheme applied to 30 years of a quality reanalysis product. Having said that, we are fully aware that cyclone identification and tracking in the Arctic is subject to greater uncertainties than in the midlatitudes.

[17] We finally remark that in addition to the associations discussed above cyclonic activity can potentially co-vary with sea ice coverage through its associated cloud cover (and its influence on the surface radiation budget). Sea ice retreat has been linked to a decrease in low-level cloud during autumn and a simultaneous increase in mid-level clouds [*Schweiger et al.*, 2008a]. The net radiative effect of this change is small, and this strongly suggests that changes in cloud cover do not contribute to sea ice anomalies in autumn [*Wang and Key*, 2005; *Schweiger et al.*, 2008a]. Indeed, no significant trends have been observed in autumn Arctic cloudiness [*Schweiger*, 2004; *Wang and Key*, 2005] during the period of massive SIE reduction. This perspective is consistent with findings that the unusually (although not unprecedented) clear skies during the summer of 2007 did not contribute substantially to the record sea ice extent minimum [*Schweiger et al.*, 2008b; *Kay et al.*, 2008]. Our results are consistent with this perspective in that it is argued that the Arctic basin links between September SIE and cyclones properties are significantly influenced by the latter's association with surface fluxes of momentum and enthalpy, while other processes are clearly important over specific regions. Our study adds to the evidence which suggests that the decline in Arctic ice thickness [*Rothrock et al.*, 2008] and extent has started to render it particularly vulnerable to anomalous cyclonic activity and atmospheric forcing [*J. Zhang et al.*, 2008].

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References

Bengtsson, L., V. A. Semenov, and O. M. Johannessen (2004), The early twentieth-century warming in the Arctic: A possible mechanism, *J. Clim.*, *17*, 4045–4057, doi:10.1175/1520-0442(2004)017<4045:TETWIT>2.0.CO;2.

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.

Deser, C., and H. Teng (2008), Evolution of Arctic sea ice concentration trends and the role of atmospheric circulation forcing, 1979–2007, *Geophys. Res. Lett.*, *35*, L02504, doi:10.1029/2007GL032023.

Glowienka-Hense, R., and A. Hense (1992), The effect of an Arctic polynya on the Northern Hemisphere mean circulation and eddy regime: A numerical experiment, *Clim. Dyn.*, *7*, 155–163, doi:10.1007/BF00211157.

Groves, D. G., and J. A. Francis (2002), Moisture budget of the Arctic atmosphere from TOVS satellite data, *J. Geophys. Res.*, *107*(D19), 4391, doi:10.1029/2001JD001191.

Kay, J. E., T. L'Ecuyer, A. Gettelman, G. Stephens, and C. O'Dell (2008), The contribution of cloud and radiation anomalies to the 2007 Arctic sea ice extent minimum, *Geophys. Res. Lett.*, *35*, L08503, doi:10.1029/2008GL033451.

Löptien, U., et al. (2008), Cyclone life cycle characteristics over the Northern Hemisphere in coupled GCMs, *Clim. Dyn.*, *31*, 507–532, doi:10.1007/s00382-007-0355-5.

Murray, R. J., and I. Simmonds (1995), Responses of climate and cyclones to reductions in Arctic winter sea ice, *J. Geophys. Res.*, *100*, 4791–4806, doi:10.1029/94JC02206.

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.

Onogi, K., et al. (2007), The JRA-25 reanalysis, *J. Meteorol. Soc. Jpn.*, *85*, 369–432, doi:10.2151/jmsj.85.369.

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

Raible, C. C., et al. (2008), Northern Hemisphere extratropical cyclones: A comparison of detection and tracking methods and different reanalyses, *Mon. Weather Rev.*, *136*, 880–897, doi:10.1175/2007MWR2143.1.

Rothrock, D. A., D. B. Percival, and M. Wensnahan (2008), The decline in Arctic sea-ice thickness: Separating the spatial, annual, and interannual variability in a quarter century of submarine data, *J. Geophys. Res.*, *113*, C05003, doi:10.1029/2007JC004252.

Schweiger, A. J. (2004), Changes in seasonal cloud cover over the Arctic seas from satellite and surface observations, *Geophys. Res. Lett.*, *31*, L12207, doi:10.1029/2004GL020067.

Schweiger, A. J., R. W. Lindsay, S. Vavrus, and J. A. Francis (2008a), Relationships between Arctic sea ice and clouds during autumn, *J. Clim.*, *21*, 4799–4810, doi:10.1175/2008JCLI2156.1.

Schweiger, A. J., J. Zhang, R. W. Lindsay, and M. Steele (2008b), Did unusually sunny skies help drive the record sea ice minimum of 2007?, *Geophys. Res. Lett.*, *35*, L10503, doi:10.1029/2008GL033463.

Serreze, M. C., and A. P. Barrett (2008), The summer cyclone maximum over the central Arctic Ocean, *J. Clim.*, *21*, 1048–1065, doi:10.1175/2007JCLI1810.1.

Serreze, M. C., et al. (2000), Observational evidence of recent change in the northern high-latitude environment, *Clim. Change*, *46*, 159–207, doi:10.1023/A:1005504031923.

Serreze, M. C., A. P. Barrett, A. G. Slater, M. Steele, J. Zhang, and K. E. Trenberth (2007), The large-scale energy budget of the Arctic, *J. Geophys. Res.*, *112*, D11122, doi:10.1029/2006JD008230.

Simmonds, I. (2000), Size changes over the life of sea level cyclones in the NCEP reanalysis, *Mon. Weather Rev.*, *128*, 4118–4125, doi:10.1175/1520-0493(2000)129<4118:SCOTLO>2.0.CO;2.

Simmonds, I., and K. Keay (2000), Mean Southern Hemisphere extratropical cyclone behavior in the 40-year NCEP-NCAR reanalysis, *J. Clim.*, *13*, 873–885, doi:10.1175/1520-0442(2000)013<0873:MSHECB>2.0.CO;2.

Simmonds, I., K. Keay, and E.-P. Lim (2003), Synoptic activity in the seas around Antarctica, *Mon. Weather Rev.*, *131*, 272–288, doi:10.1175/1520-0493(2003)131<0272:SAITSA>2.0.CO;2.

Simmonds, I., C. Burke, and K. Keay (2008), Arctic climate change as manifest in cyclone behavior, *J. Clim.*, *21*, 5777–5796, doi:10.1175/2008JCLI2366.1.

Sorteberg, A., and B. Kvingedal (2006), Atmospheric forcing on the Barents Sea winter ice extent, *J. Clim.*, *19*, 4772–4784, doi:10.1175/JCLI3885.1.

Sorteberg, A., and J. E. Walsh (2008), Seasonal cyclone variability at 70°N and its impact on moisture transport into the Arctic, *Tellus, Ser. A*, *60*, 570–586.

Stroeve, J., M. M. Holland, W. Meier, T. Scambos, and M. Serreze (2007), Arctic sea ice decline: Faster than forecast, *Geophys. Res. Lett.*, *34*, L09501, doi:10.1029/2007GL029703.

Ulbrich, U., G. C. Leckebusch, and J. G. Pinto (2009), Extra-tropical cyclones in the present and future climate: A review, *Theor. Appl. Climatol.*, *96*, 117–131, doi:10.1007/s00704-008-0083-8.

von Storch, H., and F. W. Zwiers (2001), *Statistical Analysis in Climate Research*, Cambridge Univ. Press, Cambridge, U. K.

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.

Wang, X. J., and J. R. Key (2005), Arctic surface, cloud, and radiation properties based on the AVHRR Polar Pathfinder dataset. Part II: Recent trends, *J. Clim.*, *18*, 2575–2593, doi:10.1175/JCLI3439.1.

Wernli, H., and C. Schwierz (2006), Surface cyclones in the ERA-40 dataset (1958–2001). Part I: Novel identification method and global climatology, *J. Atmos. Sci.*, *63*, 2486–2507, doi:10.1175/JAS3766.1.

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.

Zhang, X., et al. (2004), Climatology and interannual variability of Arctic cyclone activity: 1948–2002, *J. Clim.*, *17*, 2300–2317, doi:10.1175/1520-0442(2004)017<2300:CAIVOA>2.0.CO;2.

Zhang, X., A. Sorteberg, J. Zhang, R. Gerdes, and J. C. Comiso (2008), Recent radical shifts of atmospheric circulations and rapid changes in Arctic climate system, *Geophys. Res. Lett.*, *35*, L22701, doi:10.1029/2008GL035607.

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