Evolution of Arctic sea ice concentration trends and the role of atmospheric circulation forcing, 1979–2007

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[1] The retreat of Arctic sea ice in recent decades is a pre-eminent signal of climate change. What role has the atmospheric circulation played in driving the sea ice decline? To address this question, we document the evolution of Arctic sea ice concentration trends during the period January 1979–April 2007 in light of changing atmospheric circulation conditions, in particular an upward trend in the wintertime Northern Annular Mode during the first half of the record and a downward trend during the second half. The results indicate that concurrent atmospheric circulation trends contribute to forcing winter and summer sea ice concentration trends in many parts of the marginal ice zone during both periods. However, there is also an emerging signal of overall Arctic sea ice decline since 1979 in both winter and summer that is not directly attributable to a trend in the overlying atmospheric circulation. **Citation:** 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.

1. Introduction

[2] The accelerating retreat of Arctic sea ice in recent decades, evident in all months of the year, is one of the most dramatic signals of climate change worldwide. The physical mechanisms underlying the Arctic sea ice decline are not fully understood, but include dynamical processes related to changes in winds and ocean currents, and thermodynamic processes involving changes in air temperature, radiative and turbulent energy fluxes, and ocean heat storage [*Serreze et al.*, 2007; *Francis and Hunter*, 2006, 2007]. A better understanding of these mechanisms and their relationship to increasing greenhouse gas concentrations is an important step for assessing future predictions of Arctic climate change.

[3] What role has the atmospheric circulation played in driving the Arctic sea ice retreat? The consensus of numerous studies [e.g., *Deser et al.*, 2000; *Rigor et al.*, 2002; *Hu et al.*, 2002; *Rothrock and Zhang*, 2005; *Stroeve et al.*, 2007; *Serreze and Francis*, 2006; *Ukita et al.*, 2007] is that Arctic sea ice declines from the 1960s to the early 1990s were driven in part by a trend in the dominant pattern of wintertime atmospheric circulation variability over the high-latitude northern hemisphere known variously as the "Arctic Oscillation", "North Atlantic Oscillation", or "Northern Annular Mode" (collectively referred to hereafter as the "NAM"). In particular, the anomalous cyclonic wind circulation associated with the upward trend in the winter NAM flushed old, thick ice out of the Arctic via Fram Strait, causing the winter ice pack to thin which in turn preconditioned the summer ice pack for enhanced melt. However, the trend in the NAM has reversed sign since the early 1990s yet Arctic sea ice has continued to decline [*Overland and Wang*, 2005; *Comiso*, 2006; *Serreze and Francis*, 2006; *Maslanik et al.*, 2007]. This has led to speculation that the Arctic climate system has reached a "tipping point" whereby strong positive feedback mechanisms such as those associated with ice albedo and open water formation efficiency are accelerating the thinning and retreat of Arctic sea ice [e.g., *Lindsay and Zhang*, 2005; *Holland et al.*, 2006]. These positive feedback mechanisms leave the ice pack more vulnerable to forcing from other processes, natural and anthropogenic. For example, enhanced downward longwave radiation associated with increases in air temperature, water vapor and cloudiness over the Arctic Ocean [*Francis and Hunter*, 2006] has become a dominant factor driving summer sea ice extent declines since the mid-to-late 1990s. There is also evidence that the winter atmospheric circulation has continued to impact the winter sea ice distribution since the mid-1990s [*Comiso*, 2006; *Maslanik et al.*, 2007; *Francis and Hunter*, 2007].

[4] The purpose of this study is to revisit the issue of Arctic sea ice trends since 1979 in the context of evolving atmospheric circulation conditions, in particular trends in the NAM. How have the pattern and magnitude of winter and summer Arctic sea ice concentration trends changed from the first half (1979–1993) of the record when the trend in the NAM was positive to the second half of the record (1993–2007) when the trend in the NAM was negative? What is the nature of the association between trends in Arctic sea ice concentration and atmospheric circulation for the period 1979–2007 as a whole?

2. Data and Methods

[5] Monthly sea ice concentrations (SIC) on a 25 km $\times$ 25 km grid for the period January 1979 – April 2007 were obtained from the National Snow and Ice Data Center (NSIDC). These data are derived from the Nimbus-7 Scanning Multichannel Microwave Radiometer (SMMR) and Defense Meteorological Satellite Program (DMSP) -F8, -F11 and -F13 Special Sensor Microwave/Imager (SSM/I) radiances using the NASA team algorithm [*Cavalieri et al.*, 1999]. Monthly sea level pressure (SLP) data are from the NCEP/NCAR Reanalysis Project [*Kalnay et al.*, 1996] on a $2.5^\circ \times 2.5^\circ$ latitude grid.

[6] Arctic sea ice undergoes a large seasonal cycle, with maximum extent in February–March and minimum extent in August–September [*Comiso*, 2006]. Because SIC trends are highly persistent from February–March to April, and

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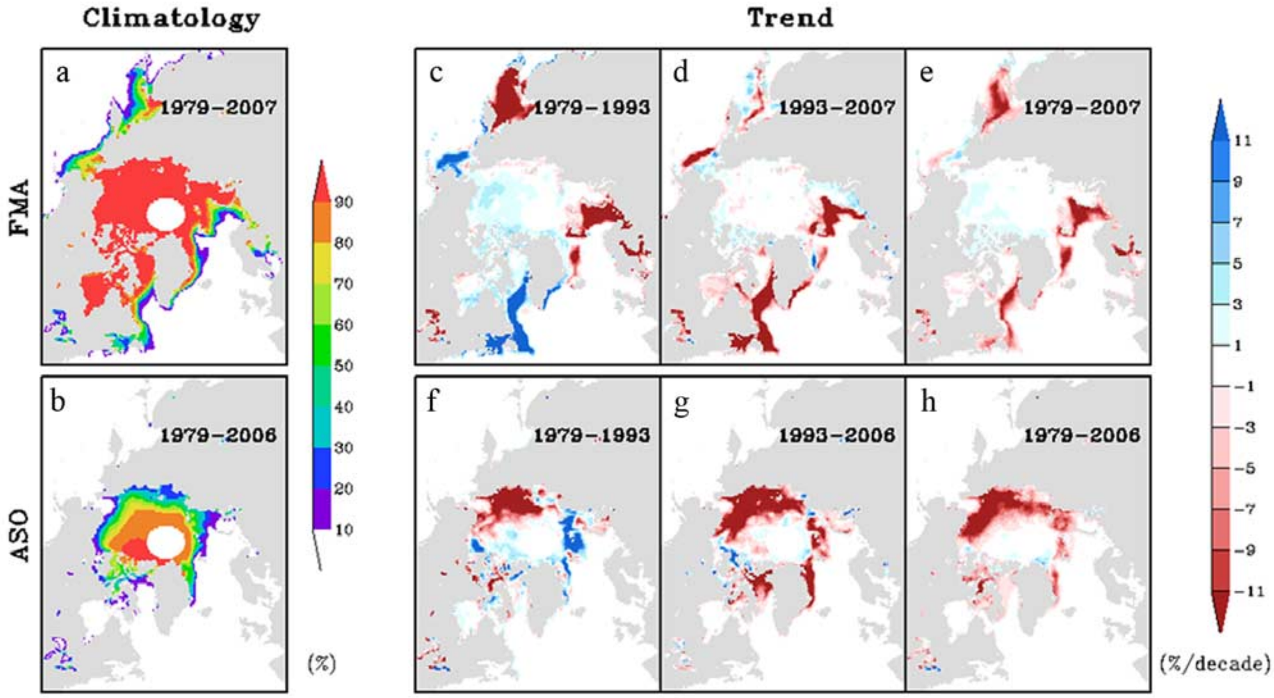

Figure 1. (left) Long-term mean sea ice concentrations (%) for (a) winter (February–April) and (b) summer (August–October) based on the period January 1979 – April 2007. The white ellipse around the North Pole indicates missing data. (right) (c)–(e) Winter and(f)–(h) summer sea ice concentration trends (% per decade) during 1979–1993 (Figures 1c and 1f), 1993–2007 (Figures 1d and 1g) and 1979–2007 (Figure 1e and 1h). Note that 2006 is the last year of data in summer.

from August–September to October (not shown), we have defined winter and summer as February–April and August–October, respectively. Figure 1 (left) shows the long-term mean winter and summer SIC distributions based on the period January 1979 – April 2007. In winter, long-term mean SIC values between 10% and 90%, indicative of the location of the marginal ice zone, are found in the Labrador Sea, the Greenland and Barents Seas, the Bering Sea, and the Sea of Okhotsk. In summer, the marginal ice zone retreats northward to coastal regions of the Arctic Ocean and the Canadian Archipelago.

3. Results

3.1. SIC Trends

[7] The SIC trends over the first (1979–1993) and second (1993–2007) halves of the record, and over the period 1979–2007 as a whole, in (top) winter and (bottom) summer (note that 2006 is the last year of data for summer) are shown in Figure 1 (right). The magnitudes of the trends in each period may be directly compared as they are expressed in % per decade. The regions of largest SIC trends in each season correspond to the marginal ice zone as depicted in the left-hand columns. The pattern of winter SIC trends in the first half of the record (1979–1993) exhibits positive values in the Labrador and Bering Seas and negative values in the Greenland and Barents Seas and the Sea of Okhotsk. In contrast, winter SIC trends in the second half of the record (1993–2007) are negative throughout the marginal seas, with the largest declines in the Atlantic sector. The winter SIC trends over the full period of record (1979–2007) are also negative throughout the marginal seas, except in the Bering Sea where the trends are near zero. The change in pattern of winter SIC trends between the first and second halves of the record is notable and will be discussed further below in the context of evolving atmospheric circulation trends.

[8] In summer, SIC trends in the first half of the record are negative in the East Siberian Sea and positive in the Barents, Kara, and eastern Beaufort Seas, with the area of reduced SIC outweighing that of increased SIC. In the second half of the record (1993–2006), the area of negative SIC trends has expanded to cover almost all longitudes. The summer SIC trend over the full period of record (1979–2006) is similar to that for the second half of the record, with the largest declines extending from the Laptev Sea eastward to the Beaufort Sea.

[9] To investigate whether the SIC trend patterns shown in Figure 1 correspond to preferred structures of variability, we applied empirical orthogonal function (EOF) analysis to the covariance matrix of SIC anomalies over the full period of record, using a separate EOF analysis for winter and for summer. The results indicate that the two leading EOFs in each season closely resemble the trend patterns for the first and second halves of the record (see auxiliary materials[1]).

3.2. SIC Trends in the Context of SLP Trends

[10] Figure 2 shows the SIC trends in the context of the overlying trends in SLP (note the larger domain used in

[1]Auxiliary materials are available in the HTML. doi:10.1029/2007GL032023.

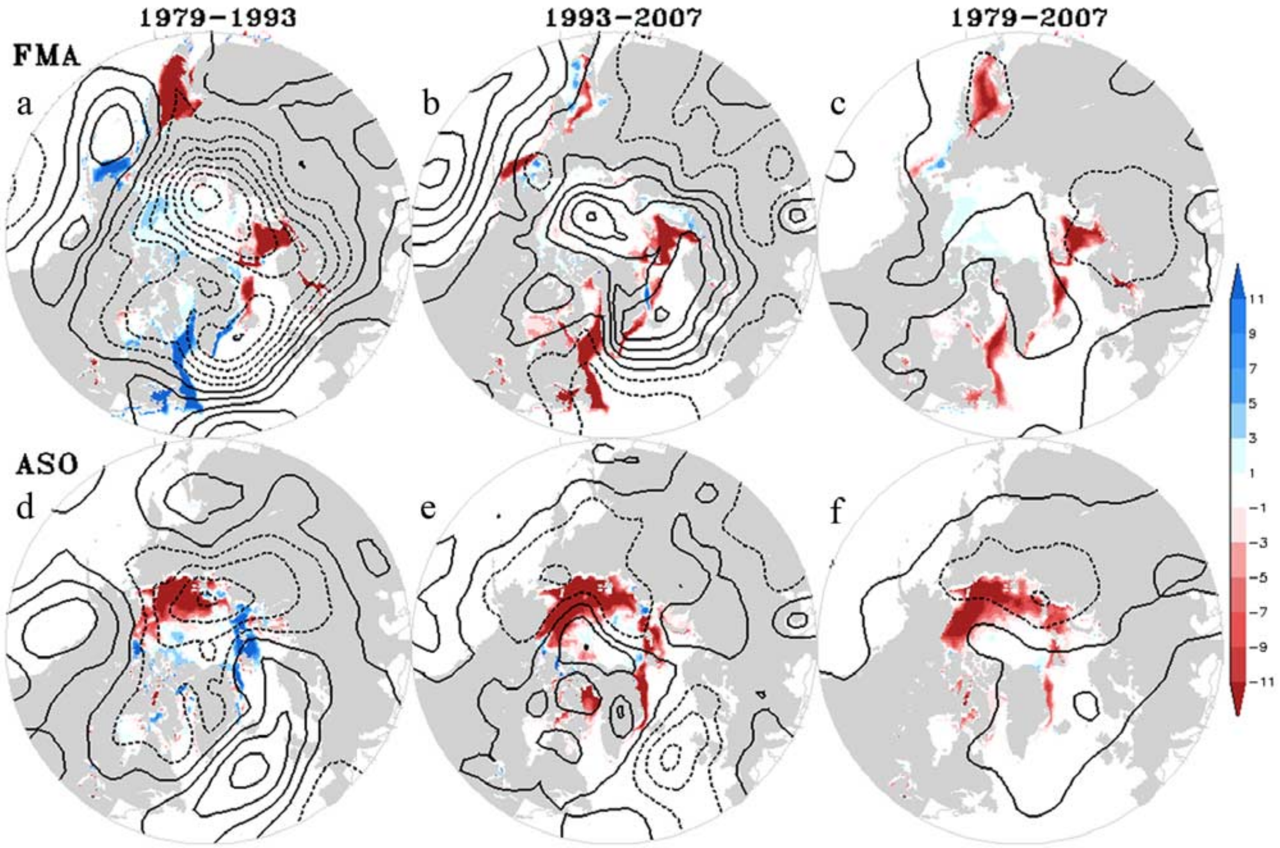

Figure 2. (top) Winter and (bottom) summer sea ice concentration (color shading; % per decade) and sea level pressure (contours; hPa per decade) trends during (a) and (d) 1979–1993, (b) and (e) 1993–2007, and (c) and (f) 1979–2007. The contour interval for sea level pressure is 1 hPa per decade, with negative values dashed, and the zero and positive values solid. Note that 2006 is the last year of data in summer.

Figure 2 compared to Figure 1). The SLP trends are based on the same seasonal definitions used for SIC, and are very similar to those leading by one month (e.g., January–March and July–September: not shown). The simultaneous (or 1-month lead) relationships between seasonal SLP and SIC trends provide an indication of the role of atmospheric circulation forcing of sea ice anomalies [*Fang and Wallace*, 1994]. However, there may also be a longer response time (e.g., seasonal and multi-year) associated with atmospheric forcing of sea ice thickness changes which in turn feedback upon SIC [*Rigor et al.*, 2002; *Rigor and Wallace*, 2004]. This component of the SIC response to atmospheric circulation forcing will not be addressed with our approach.

[11] The pattern of winter SLP trends in the first half of the record resembles the positive phase of the NAM, with negative values over the Arctic and northern North Atlantic (maximum amplitudes ~4–6 hPa per decade) and positive values farther south with regional maxima over the central Atlantic and the Bering Sea. This pattern is physically consistent with the notion that the atmospheric circulation is driving the SIC anomaly trends, with anomalous northwesterly winds over the enhanced sea ice cover in the Labrador and Bering Seas, and anomalous southerly winds over the regions of reduced ice cover in the Barents Sea and the Sea of Okhotsk. Such wind anomalies affect SIC by altering the surface fluxes of latent and sensible heat through air temperature and wind speed changes, as well as by inducing ice drift and changes in sea surface temperatures and ocean currents.

[12] The pattern of winter SLP trends in the second half of the record is largely opposite to that in the first half over the Arctic and north Atlantic; the monopole of positive values over the north Pacific in the later period contrasts with the dipole pattern in the early period. The change in sign of the Arctic/North Atlantic SLP trends between the first and second halves of the record is consistent with the behavior of the winter NAM index which reached a relative maximum in 1993 (not shown). The inferred trends in the geostrophic wind field during the second half of the record are indicative of enhanced southeasterly (southwesterly) flow over the reduced SIC in the Labrador (Bering) Sea, consistent with the notion that the atmospheric circulation is driving the SIC trends as discussed above. Thus, the change in sign of the SIC trends in the Labrador and Barents Seas between the two halves of the record may be attributed to the change in sign of the overlying wind trends.

[13] The relationship between the SLP and SIC trends in the Greenland Sea and the Sea of Okhotsk in the second half of the record appears to be inconsistent with the notion of atmospheric forcing. In particular, negative SIC trends persist in the Greenland Sea beneath weak geostrophic wind trends; and a lack of SIC trends in the Sea of Okhotsk occurs despite geostrophic southwesterly wind trends. The continuation of negative SIC trends in the Greenland Sea

from the first half of the record to the second half despite the lack of wind forcing may indicate that other processes such as oceanic warming are starting to play a dominant role in this region [see also *Polyakov et al.*, 2005; *Francis and Hunter*, 2007; *Stroeve and Maslowski*, 2008]. In the Sea of Okhotsk, the cooling trend of autumn sea surface temperatures (not shown) may offset the impact of wintertime wind forcing and account for the lack of SIC trends in this region during the second half of the record [*Ogi and Tachibana*, 2006].

[14] Given the opposition of winter SLP trends in the first and second halves of the record, it is not surprising that winter SLP trends over the full period of record are weak (Figure 2c), with magnitudes generally less than 1 hPa per decade. The lack of pronounced SLP trends is in striking contrast to the negative SIC trends found throughout the marginal ice zone. This result strongly suggests that processes other than winter atmospheric circulation trends are controlling the long-term retreat of winter SIC, for example increased ocean heat transport and residual absorption of solar energy during summer.

[15] Summer SLP and SIC trends are shown in Figures 2d–2f. We note that SLP trends in spring (May–July) yield very similar geostrophic wind trends over the marginal ice zone to those in summer (not shown). The summer SLP trends in the first half of the record are indicative of southerly wind anomalies over the negative summer SIC trends in the East Siberian, Chukchi and Beaufort Seas, and northerly wind anomalies over the positive summer SIC trends in the Barents and Kara Seas, consistent with the notion that atmospheric circulation forcing contributes to the SIC trends as discussed previously. It is unclear to what extent summer atmospheric circulation trends play a role in the decline of summer SIC in the second half of the record. In particular, easterly rather than southerly geostrophic wind anomalies overlie the negative SIC trends in the East Siberian and Beaufort Seas, and northerly wind trends are found over the region of negative SIC trends between Greenland and Siberia: the latter is counter to the relationship expected if the atmospheric circulation were forcing these SIC trends.

[16] Summer SLP trends over the record as a whole (1979–2006) are small, with negative values (magnitudes $\sim$1 hPa per decade) over coastal Siberia and near-zero values elsewhere [see also *Ogi and Wallace*, 2007]. The weak amplitude of the SLP trends suggests that summer (and spring) atmospheric circulation anomalies are not the dominant factor driving summer SIC declines since 1979, although *Ogi and Wallace* [2007] have speculated that the implied increase in Ekman divergence may thin the summer ice pack and increase it's susceptibility to melt.

[17] It is worth noting from Figure 2 that there is no robust relationship between SLP trends over the Arctic Ocean in summer and winter. Although Arctic SLP trends are negative in both seasons in the first half of the record, they are positive in winter but of mixed sign in summer in the second half

4. Summary and Discussion

[18] The purpose of this study was to document the evolution of Arctic SIC trends in summer and winter during the period January 1979 – April 2007 in light of changing atmospheric circulation conditions, in particular an upward trend in the NAM during the first half of the record (1979–1993) and a downward trend during the second half (1993–2007). The spatial patterns of the winter SIC trends in the two halves of the study period are distinctive, reflecting in part opposing trends in the overlying atmospheric circulation. These distinctive trend patterns correspond to the two leading EOFs of winter SIC anomalies during 1979–2007. In the earlier period, the winter SIC trends are characterized by positive values in the western Atlantic and eastern Pacific, and negative values in the eastern Atlantic and western Pacific, a pattern consistent with that due to atmospheric circulation forcing associated with a positive trend in the NAM. In the second half of the record, the winter SIC trends are negative nearly everywhere within the marginal ice zone. The change from positive to negative SIC trends in the western Atlantic (Labrador Sea) and eastern Pacific (Bering Sea) is physically consistent with the change in sign of the overlying atmospheric circulation forcing from the first to the second half of the study period. However, the continuation of negative SIC trends in the Barents and Kara Seas since 1993 is inconsistent with the notion of atmospheric circulation forcing.

[19] We also find a residual trend of declining winter SIC throughout the marginal ice zone over the period of study as a whole (1979 – 2007). Since the trend in the winter atmospheric circulation over this period is negligible, this implies that other factors are responsible for the residual winter SIC decline, for example enhanced ocean heat storage and transport [*Polyakov et al.*, 2005; *Shimada et al.*, 2006; *Stroeve and Maslowski*, 2008] as well as increased oceanic absorption of solar energy during summer associated with the decline in summer ice extent [*Perovich et al.*, 2007].

[20] The spatial patterns of summer SIC trends in the two halves of the record show modest differences compared to their winter counterparts, and resemble the leading EOF of summer SIC anomalies during 1979–2006. The 1979–1993 period is characterized by weak positive SIC trends in the Greenland, Barents, and Kara Seas, and larger amplitude negative trends in the East Siberian, Chukchi, and eastern Beaufort Seas. Summer atmospheric circulation trends contribute to forcing this dipole pattern of SIC trends. The periods 1993–2006 and 1979–2006 exhibit negative SIC trends throughout the marginal ice zone. The weak amplitudes of the concurrent summer and previous spring SLP trends suggest that the atmospheric circulation is not the dominant factor driving overall summer SIC declines since 1979 and 1993.

[21] *Francis and Hunter* [2007] examined some of the factors responsible for winter sea ice extent variability in the Barents and Bering Seas during 1979–2005, including satellite-derived estimates of downwelling longwave radiation, low-level winds, and sea surface temperatures (SSTs). Wind anomalies were found to be the dominant forcing mechanism in the Bering Sea, while a combination of wind and SST anomalies were the main factors in the Barents Sea. In a related paper, *Francis and Hunter* [2006] showed that downward longwave radiation was the primary cause of summer sea ice extent variations during 1979–2004 throughout the Arctic marginal ice zone. They also reported that wind anomalies played a role in forcing summer sea ice

extent anomalies in the Barents and Chukchi Seas before, but not after, 1991. The results shown here based on SLP trends are in general agreement with the findings of *Francis and Hunter* [2006, 2007], although we note that a direct comparison is not possible due to the different time scales of variability examined in the two studies (interannual and longer in the case of Francis and Hunter, and trends in our case). In future work, we plan to extend our analysis to include the forcing data sets of Francis and Hunter. A better understanding of the role of atmospheric circulation forcing of Arctic sea ice trends remains an important task with relevance to future predictions of Arctic climate change.

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