



Recent radical shifts of atmospheric circulations and rapid changes in Arctic climate system

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[1] Arctic climate system change has accelerated tremendously since the beginning of this century, and a strikingly extreme sea-ice loss occurred in summer 2007. However, the greenhouse-gas-emissions forcing has only increased gradually and the driving role in Arctic climate change of the positively-polarized Arctic/North Atlantic Oscillation (AO/NAO) trend has substantially weakened. Although various contributing factors have been examined, the fundamental physical process, which orchestrates these contributors to drive the acceleration and the latest extreme event, remains unknown. We report on drastic, systematic spatial changes in atmospheric circulations, showing a sudden jump from the conventional tri-polar AO/NAO to an unprecedented dipolar leading pattern, following accelerated northeastward shifts of the AO/NAO centers of action. These shifts provide an accelerating impetus for the recent rapid Arctic climate system changes, perhaps shedding light on recent arguments about a tipping point of global-warming-forced climate change in the Arctic. The radical spatial shift is a precursor to the observed extreme change event, demonstrating skilful information for future prediction. **Citation:** 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.

1. Introduction

[2] The Arctic climate system change has conspicuously switched onto a fast track since the beginning of the 21st century. In particular, an extreme sea-ice coverage loss occurred in summer 2007 [e.g., Comiso *et al.*, 2008]. Although these changes have been largely attributed to the greenhouse-gas-emissions-induced radiative forcing, the atmospheric circulation is the route by which global-warming-forcing exerts dynamic effects by driving sea-ice motions and exports, ocean currents and heat transport. The atmospheric circulation also determines formation and distribution of cloudiness as well as critically modulating surface radiative heat budgets. Accordingly, substan-

tial Arctic climate system changes have been tightly associated, under conditions of global warming forcing, with the positively-polarized trend of the atmospheric circulation leading pattern, the Arctic/North Atlantic Oscillation (AO/NAO) [e.g., Rigor *et al.*, 2002; Zhang *et al.*, 2003].

[3] However, the AO/NAO has gone to neutral in the latest decade, clearly shifting away from the fast track of the changes, and unexpected from previous studies and global-warming-forced climate simulations [e.g., Thompson and Wallace, 1998; Osborn, 2004]. The driving role of the AO/NAO trend in underlying cryospheric, hydrospheric, and terrestrial subsystem changes has been substantially weakened [e.g., Maslanik *et al.*, 2007]. Therefore, the rapid climate change signature in atmospheric circulations and its connection to other subsystem changes remain unclear.

2. Methodology and Data Sets

[4] To gain insight into the rapid change signature and untangle the broad spectrum of complex atmospheric circulations, we take advantage of the Empirical Orthogonal Function/Principal Component (EOF/PC) technique, which seeks spatiotemporally-coordinated structures that explain maximum variance and identifies centers of action (centers of maximum variance) of climate variability. Conventionally, the EOF/PC analysis provides simple representations of spatial state of atmospheric circulations, which do not evolve with time. This restricts the EOF/PC technique for investigating trends presented as shifts of or changes in spatial pattern (e.g., spatially-varying decadal-scale trends by Deser and Teng [2008]), and filters out rapid change signals which usually occur in relatively short time periods. So, we employ the EOF/PC technique with a new strategy of using a running time window, leading to a Running-EOF/PC (Rn-EOF/PC) analysis. Specifically, we use a 30-month running wintertime window (five consecutive years with each containing six months from October-March) from 1958/59-2006/07.

[5] Data are monthly mean sea level pressure (MSLP) from the National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) reanalysis [Kistler *et al.*, 2001]. A geographic domain of poleward 20°N is chosen for consistency with AO [Thompson and Wallace, 1998]. Results are compared with surface air temperature (SAT) from NCEP-NCAR reanalysis and meteorological stations north of 60°N from 1958-2007; the monthly sea-ice concentration (SIC) derived from 1978-2006 passive microwave satellite data [Comiso *et al.*, 2008]; and the recently-measured 1997-2006 North

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Atlantic warm water heat flux across the Barents Sea Opening (BSO) [Skagseth *et al.*, 2008].

3. Radical Spatial Shift of Atmospheric Circulations

[6] Considering the different nature of the extreme event in summer 2007, we first apply the Rn-EOF/PC before 2007. The Rn-EOF/PC analysis not only captures the atmospheric circulation leading spatial pattern and its amplitude evolution in each time window, but also tracks movements of its centers of action throughout the entire time period. The first EOF/PC patterns of MSLP are outstandingly robust, exhibiting statistical and physical significance in sampling error assessments, Monte Carlo simulations, and composite analysis (auxiliary material Table S1 and Figure S1).¹ These patterns primarily represent the AO/NAO throughout the analysis period except for the last wintertime window (2001/02-2005/06). Most interesting are non-stationary behaviors of the centers of action (Figure 1a). The poleward center, originally over the Icelandic Sea, shifted conspicuously northeastward in the last 20 years of the 20th century. This shift is obviously consistent with, and could be an integrative manifestation of poleward shift of storm tracks and intensification of Arctic storm activity, given the correspondence between the centers of action and the maximum storm activity [e.g., Zhang *et al.*, 2004].

[7] The atmospheric circulation pattern shift is not always in a stable state. The poleward center of action shifted continuously northeastward from 65.0°N, 18.0°W to 67.5°N, 7.5°E during 1983/84-1997/98, and eastward from 7.5°E to 27.5°E at around 72.0°N during 1998/99-2002/03. However, a pronounced northeastward jump occurred between these two periods, resulting in a changed average position of the center of action from south to northeast of the Nordic Seas and an unprecedented entry of the center into the Barents Sea in the early 2000s. North Atlantic and North Pacific centers of action also shifted. The former showed a pronounced northward shift from the mid-1990s to early 2000s of about 8°, from 42°N to 50°N.

[8] Instability in the position shift of the poleward center of action strikingly occurred during 2001/02-2005/06. We observe a sudden great jump of the poleward center of action from the northeastern Nordic Seas to the Eurasian Arctic coast.

[9] At this time, the first EOF/PC spatial pattern experienced an abrupt distortion. Examining each time window, we found AO/NAO robustly represented the predominant variance (>20%) of atmospheric circulation variability; its tri-polar spatial pattern was retained until the early 21st century (Figure 1b). However, this persistence ended in 2001/02-2005/06. The previous tri-polar AO/NAO was transformed into a totally different dipole structure between the Eurasian Arctic coast and North Pacific. We propose that this new atmospheric circulation leading pattern – the Arctic Rapid Change Pattern (ARP) – represents an unprecedented climate change signature, and plays a decisive role in driving recent rapid Arctic climate change.

[10] Along with statistical significance, the ARP has a real-world expression in MSLP variability and change (AM Figure S1). It changes conventional means by which Arctic and sub-arctic interact, and increases the efficiency of poleward atmospheric and oceanic heat transport compared to AO/NAO, because the MSLP isobars associated with the centers of action are aligned across the central Arctic Ocean (Figure 1b). The ARP amplitude time series or index, which is defined by the projection of the monthly MSLP anomalies onto the ARP spatial pattern, shows an obvious polarity toward its negative phase from the late 1980s to 2006 with considerable amplifications in 2002/03 and 2005/06, while at the same time the AO/NAO index assumed neutral and slightly negative values (AM Figure S2). The ARP replaced the AO/NAO, playing the leading role in the last 5 years (Figure 1b). During ARP's negative phase, an anomalous Eurasian Arctic coast high and North Pacific low occur, resulting in strengthened poleward atmospheric heat transport directly reaching the central Arctic and enhanced North Atlantic warm water intrusion into the Arctic Ocean and Barents Sea.

4. ARP: An Accelerating Impetus for the Recent Arctic Climate Changes

[11] The increased atmospheric and oceanic heat supplied to the Arctic by ARP is clearly evident in SAT regression onto the ARP index (Figure 2a); North Atlantic Arctic SAT significantly increases with a maximum centered over the northern Barents Sea, and also extends into the central Arctic Ocean and the Beaufort and Laptev seas. In concert with Arctic warming, the Eurasian continent becomes colder due to southward cold polar air transport, and possibly enhanced outgoing longwave radiation associated with the anomalous high. The SAT linear trend distribution (Figure 2b) generally resembles the regression results in spite of the magnitude differences over a number of geographic locations, such as the Greenland Sea, suggesting that ARP explains much variance of rapid SAT increase. Results also suggest that the recent central Arctic warm anomaly in the freezing season is mainly attributable to enhanced heat transport associated with the ARP negative phase. The warmed atmosphere and accordingly thinned sea-ice would enhance the following melting season ice-albedo feedback.

[12] Lagged regression between summer (May-October) SIC and the ARP index demonstrates ARP's important driving role in the rapid shrinkage of summer sea-ice cover (Figure 2c); a large SIC decrease occurred in the Barents, Kara, and Laptev seas with ARP's shift to negative phase, changes largely congruent with winter SAT increases (Figure 2a). The reasonable argument is that higher winter temperatures lead to thinner spring ice, more prone to summer melting. In contrast, SIC noticeably increased in the North Pacific Arctic, the east Greenland shelf seas, and the Barents Sea marginal ice area, suggesting complex thermodynamic-dynamic interactions different from those associated with AO/NAO [e.g., Rigor *et al.*, 2002]. Nevertheless, comparing SIC regression and SIC linear change indicates that the shift of a positive center of action to the Eurasian Arctic accounts for much recent rapid sea-ice change (Figure 2c versus d).

¹Auxiliary materials are available in the HTML. doi:10.1029/2008GL035607.

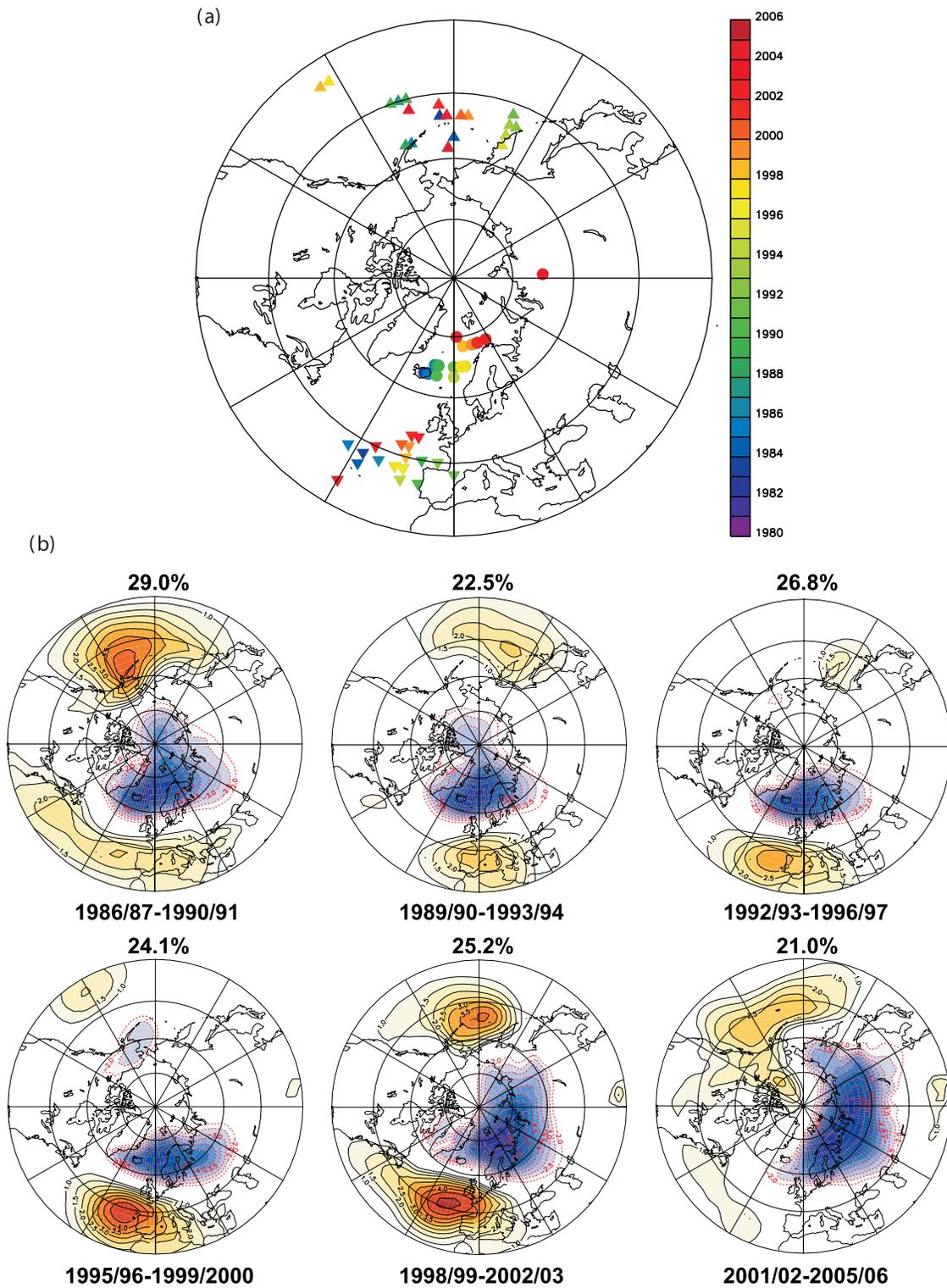


Figure 1. (a) Positions of the centers of action and (b) the first EOF/PC spatial patterns in the recent representative time windows. The circles and triangles represent positions of the centers of action for each time window centered in the year shown in the color bar over the Arctic, North Atlantic, and North Pacific.

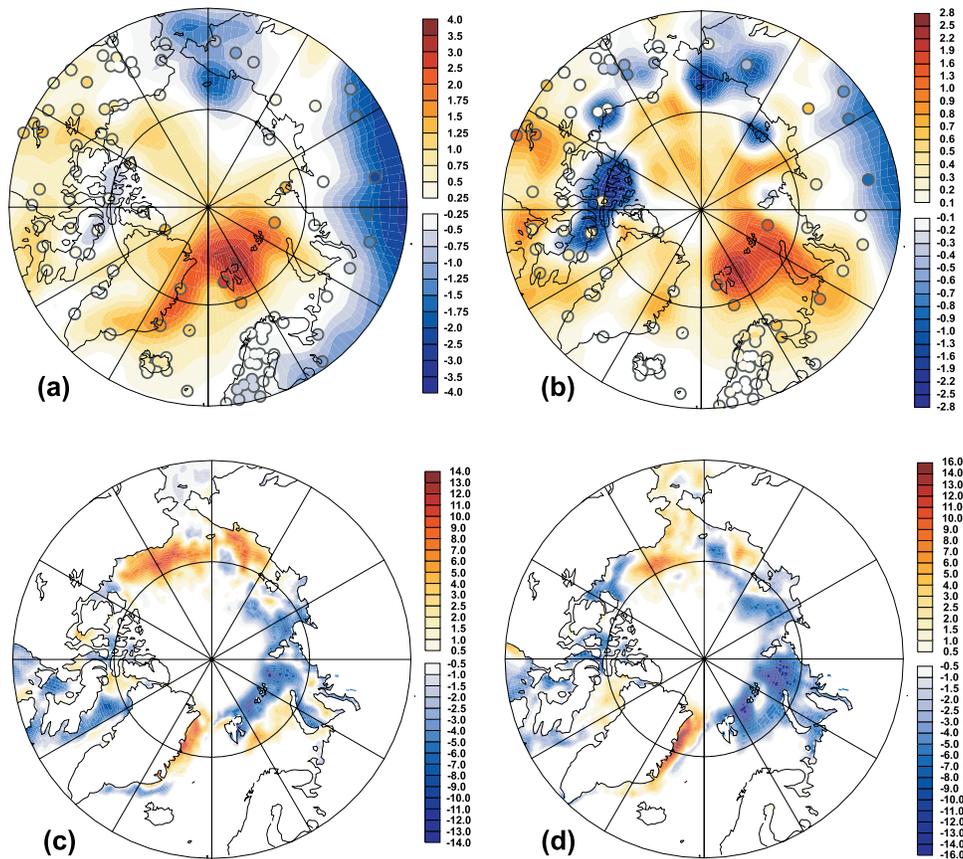


Figure 2. (a) Regression of winter (Oct-Mar) SAT onto the ARP index; (b) linear change rates of seasonal mean SAT during the 2001/02-2005/06 winters; (c) lagged regression of summer (May-Oct) SIC onto the ARP index; and (d) linear change rates of seasonal mean SIC during 2002-2006 summers. The SAT data from the meteorological stations are in circles. The regression sign in Figure 2a is reversed for convenience of interpretation. Units: $^{\circ}\text{C}$ for SAT and % for SIC.

[13] To examine year-by-year modulations of climate change and variability by ARP beyond the aggregated regression relationship, we selected representative parameters for further comparisons. Coincident interannual fluctuations and linear relationships among these parameters can be visually recognized (Figure 3); among these, the Longyearbyen (78.22°N , 11.88°E) SAT is correlated well with the ARP index, showing a correlation coefficient of -0.58 at the 99.9% level of significance (Student's *t*-test). With ARP changing to negative phase, SAT increased substantially during 2001-06. The SAT anomaly reached 12.0°C in the 2005/06 winter relative to the 1958-97 average. Under atmospheric circulation associated with ARP, Longyearbyen sits directly in the warm air flow pathway; its SAT varies accordingly.

[14] Consistent with the tendency of the ARP index, North Atlantic heat transport into the Barents Sea through BSO intensified by 3.4 TW per year during 2001/02-05/06 winters (Figure 3), compared with 2.5 TW per year for 1997-2006. Due to a relatively slow adjustment and long memory, the ocean has a delayed, reddened response to atmospheric forcing. However, a readily identifiable year-by-year heat flux fluctuation follows the ARP index at various time lags. Peak 2002/03 and 2003/04 winter heat transport events apparently correspond to negative 2001/02

and 2002/03 winter ARP index extremes. Remarkably, a drastic 2005/06 winter heat flux increase showed excellent coherence with the ARP index amplification toward the negative phase. Corresponding heat transport reached an extreme high of about 90 TW, while the long-term averaged 1997-2006 transport was about 48 TW [Skagseth *et al.*, 2008]. An increase in the Atlantic Water core temperature was found in Fram Strait in 2006 [Walczowski and Piechura, 2007], consistent with negatively-amplified ARP forcing.

[15] Sea-ice area over the entire Arctic Ocean and its sub-region, the North Atlantic Arctic shelf Seas (NAAS, AM Figure S3), decreased significantly from 2001-06; superimposed fluctuations generally coincided with the ARP index (Figure 3). Their similarity suggests the latter's leading contribution to total sea-ice area change. Interestingly, a negative sea-ice anomaly persisted in 2005-2006 summers due to combined slowly-responding sea-ice and prolonged ocean heat release. Despite mixed time scales and fluctuating phase shift, these two domains' sea-ice areas still quantitatively and identifiably demonstrate correlation coefficients of 0.37 and 0.34 with the ARP index at the 95.0% significance level at a 4-month lag. Sea-ice area changed oppositely over the North Pacific Arctic shelf Seas (NPAS), showing a 1-month lagged correlation coefficient of -0.42 with the ARP index at the 97.5% signifi-

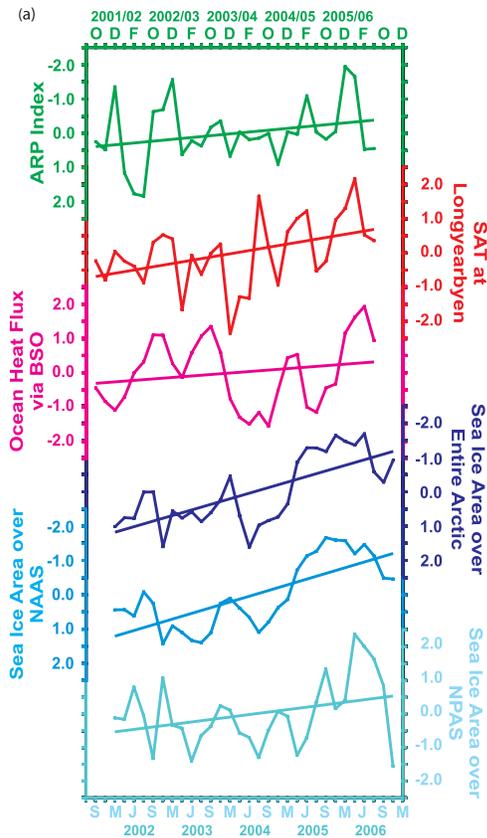


Figure 3. The ARP index (green) and the selected representative parameters, including the SAT at Longyearbyen (red), North Atlantic warm water (defined by salinity and temperature greater than 35.0 psu and 3°C) heat transport (pink) through BSO between Bear Island (74.5°N, 19.0°E) and Fugloya (70.2°N, 20.0°E), and sea-ice area for the entire Arctic Ocean (dark blue), NAAS (light blue), and NPAS (cyan). For convenient comparison, data were standardized (standard deviations: 4.2°C for SAT; 22.4 Wm⁻² for ocean heat transport; 2.7×10^5 , 2.3×10^5 , and 6.2×10^4 km² for sea ice areas over the three domains) and vertical coordinates for the ARP index and the first two sea ice parameters were reversed. The top time coordinate (O: Oct.; D: Dec.; F: Feb.) is for the first three parameters; the bottom coordinate (M: May; J: July; and S: Sept.) is for the rest.

iceance level. The decreased time delay suggests quick response to dynamic forcing compared to the response to a mixed thermodynamic-dynamic interaction over NAAS.

5. Extreme Sea-Ice Coverage Loss in Summer 2007

[16] We extended the last time window to include 2007 in the Rn-EOF/PC analysis. The first EOF/PC pattern is exactly the same as ARP, suggesting that the anomalous atmospheric circulation in 2007 is an extremely-developed ARP snapshot, not a one-time event. To trace the cumulative impacts of ARP on the 2007 summer sea-ice minimum, we projected MSLP anomalies for all months onto the ARP loading pattern, and made a composite analysis of SIC and

MSLP in the ARP negative phase from 2001-2006 and the positive phase from 2006-2007 (Figure 4).

[17] Consistent with revealed above, the enhanced atmospheric and oceanic heat transport from the North Atlantic into the Arctic Ocean by the negatively-polarized ARP during 2001-06 suppressed sea-ice growth, reduced sea-ice aging, and increased marginal sea-ice from the North Atlantic side to the North Pacific side. Anomalously large areas of open water accordingly occurred in the North Atlantic Arctic (Figure 4b).

[18] Starting in summer 2006, ARP quickly transitioned to the positive phase that persisted until summer 2007 (Figure 4a). While a surface heat surplus is continually maintained by enhanced atmospheric and oceanic heat transport from the North Pacific, the changed wind patterns pushed sea-ice back to the previously-warmed and ice-reduced North Atlantic side (Figure 4c). The warmed ocean, increased solar radiation absorption in summer, and enhanced ice-albedo feedback due to previously-increased North Atlantic warm air and water intrusion and previously-reduced sea-ice cover maintained a persistent negative sea-ice anomaly over the North Atlantic Arctic (Figure 4c). The reversed wind pattern also increased perennial-ice loss through Fram Strait. Simultaneously, the wind-stress-forced sea-ice redistribution favoured to empty the North Pacific Arctic. The positive-ARP-steered clear sky intensified surface solar radiation and albedo-feedback by the increased open ocean, and, in turn, contributed to vanishing sea ice cover over the North Pacific Arctic, which has been manifested by the weather forecast product and ice mass balance buoy [Perovich *et al.*, 2008]. Taken together, the extreme loss of sea-ice area occurred.

6. Discussion and Summary

[19] The atmospheric circulation change identified here could be a mixed response to rising greenhouse-gas-emissions forcing or unexpected natural climate variability, or both. In particular, the exceptional northeastward invasion of the poleward center of action into the Barents Sea and the final formation of ARP have been detected for the first time which augments evidences of recently-observed drastic changes in Arctic climate system, perhaps implying a new era of global-warming-forced climate change and shedding light on recent arguments about a tipping point of Arctic climate system change toward a qualitatively different new state.

[20] The identification of atmospheric circulation change does not contradict existing knowledge of global-warming effects. Trends towards a long-term warming Arctic and declining sea-ice are generally attributable to global-warming-forced climate change. Nevertheless, extreme regional change events for a particular period are apparently impacted by both. A recent study suggested that changes in atmospheric heat transport may be an important cause of Arctic temperature amplification in 1979-2001, when AO/NAO dominated [Graversen *et al.*, 2008]. The ARP post-2001 obviously further strengthened poleward heat transport. A new study indicates that ocean circulation variability can mask global warming effects, holding down SAT increase [Keenlyside *et al.*, 2008]. By contrast, our results indicate that a spatial shift of atmospheric circulations can accelerate

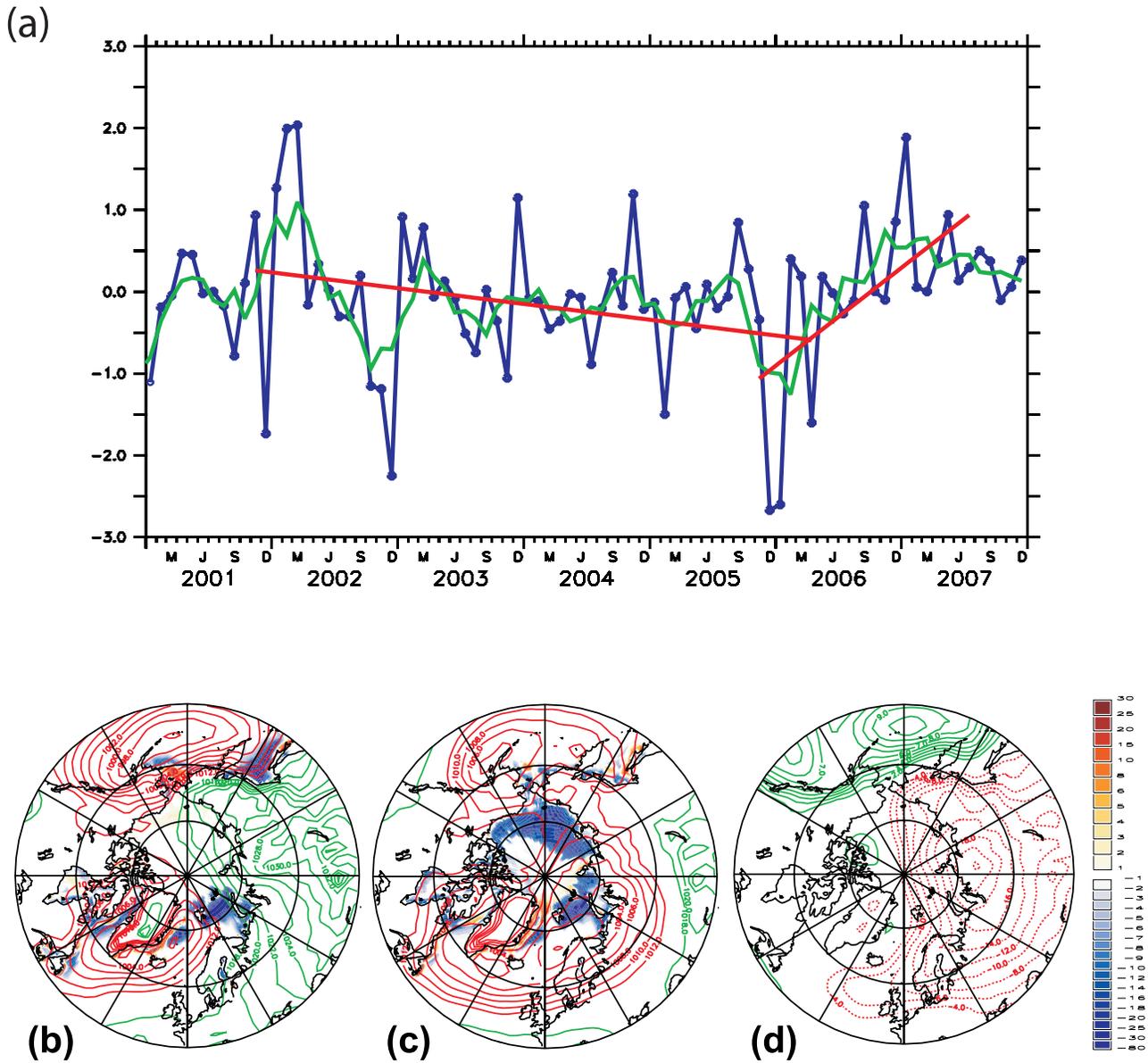


Figure 4. (a) Projected amplitude time series of ARP for all months during 2001-07 (blue: original data; green: 5-month smoothed data; and red: linear trend). Composite SIC anomalies and superimposed MSLP anomalies for the extreme (b) negative phase during 2001-2006 and (c) positive phase during 2006-2007. (d) The difference of composite MSLP anomalies is the same as ARP shown in Figure 1b. The selected months for the composite analysis are listed in AM Table S3.

global-warming-forced gradual changes, leading to a rapid change event.

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