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TELLUS

The recent Arctic warm period

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ABSTRACT

Arctic winter, spring and autumn surface air temperature (SAT) anomalies and associated sea level pressure (SLP) fields have decidedly different spatial patterns at the beginning of the 21st century (2000–2007) compared to most of the 20th century; we suggest calling this recent interval the Arctic warm period. For example, spring melt date as measured at the North Pole Environmental Observatory (2002–2007) is 7 d earlier than the records from the Russian North Pole stations (1937–1987) and statistically different at the 0.05 level. The 20th century was dominated by the two main climate patterns, the Arctic Oscillation/Northern Annular Mode (AO/NAM) and the Pacific North American-like (PNA*) pattern. The predominately zonal winds associated with the positive phases of these patterns contribute to warm anomalies in the Arctic primarily over their respective Eastern and Western Hemisphere land areas, as in 1989–1995 and 1977–1987. In contrast, SAT in winter (DJF) and spring (MAM) for 2000–2007 show an Arctic-wide SAT anomaly of greater than +1.0°C and regional hot spots over the central Arctic of greater than +3.0°C. Unlike the AO and PNA*, anomalous geostrophic winds for 2000–2007 often tended to blow toward the central Arctic, a meridional wind circulation pattern. In spring 2000–2005, these winds were from the Bering Sea toward the North Pole, whereas in 2006–2007 they were mostly from the eastern Barents Sea. A meridional pattern was also seen in the late 1930s with anomalous winter (DJFM) SAT, at Spitzbergen, of greater than +4°C. Both periods suggest natural atmospheric advective contributions to the hot spots with regional loss of sea ice. Recent warm SAT anomalies in autumn are consistent with climate model projections in response to summer reductions in sea ice extent. The recent dramatic loss of Arctic sea ice appears to be due to a combination of a global warming signal and fortuitous phasing of intrinsic climate patterns.

1. Introduction

Climate change in the Arctic is of particular concern as major shifts have occurred during the last decade, affecting physical and biological systems as noted by international reviews and indigenous observations (Krupnik and Jolly, 2002; ACIA, 2005). Of particular interest is the 40% reduction of sea ice extent in summer 2007 compared with climatology (Comiso et al., 2008). This retreat is faster than the expected value of sea ice loss projected by the climate models from the Intergovernmental Panel on Climate Change, 4th Assessment Report (IPCC-AR4, Overland and Wang, 2007; Stroeve et al., 2007). Along with other investigators, we anticipate that the future Arctic will be influenced by global warming with an Arctic amplification effect and subject to large interannual, decadal and regional 'climate noise' (Holland et al., 2006; Serreze and Francis, 2006). We will not live through the 'expected value' for the Arctic but through a single time line (realization), which presently appears to be on a fast track for Arctic warming and early summer sea ice loss.

There is a consensus developing that part of the monthly and longer scale variance for the near surface atmospheric circulation north of 20°N in the second half of the 20th century is represented by two consistent large-scale climate patterns based on Empirical Orthogonal Function (EOF)/Principal Component Analysis or simple indices, the Arctic Oscillation (AO)/Northern Annular Mode (NAM) and a Pacific Pattern, in one study named Pacific North American-like (PNA*) (Quadrelli and Wallace, 2004; Wu and Straus, 2004; Trenberth et al., 2005). These authors note that part of the trend toward warmer temperatures in the Arctic for 1950–2000 is determined by positive trends in both of these atmospheric circulation climate indices. It is against this 20th century background that the analysis of the current atmospheric circulation in the Arctic is so interesting.

Of particular recent concern is the paradox that changes in Arctic temperatures, sea ice and associated ecological impacts continued their trends from the last decade into the present one, even though the AO became more variable. Recent winter and spring composite sea level pressure (SLP) fields do not resemble the zonal flow of major 20th century patterns, but more of a

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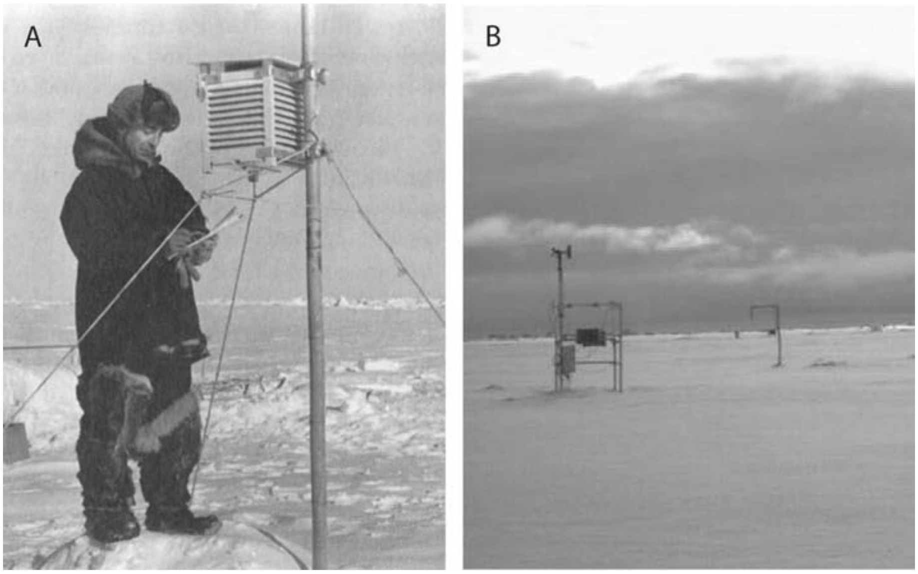

Fig. 1. Meteorological shelter for 2-m surface air temperatures from Russian North Pole (NP) station in 1937 and an autonomous station in 2003 from the North Pole Environmental Observatory (NPEO).

meridional flow pattern (Overland and Wang, 2005). As Arctic-wide warm surface air temperature (SAT) anomalies have persisted during 2000–2007 and are associated with their own characteristic pressure patterns, we assign it as the Arctic warm period. Deser and Teng (2008) also note such a decadal shift. This paper explores the relation of recent climate patterns to those of the 20th century and suggests that a contributing mechanism for recent rapid Arctic changes is the fortuitous phasing that these patterns represent. While acknowledging that sea ice, land and ocean processes and feedbacks are important in establishing the current state of the Arctic, we concentrate on the contribution from intrinsic changes in large-scale atmospheric circulation.

2. North Pole observations

To show that the central Arctic has changed we present evidence from in situ temperature observations taken north of 80°N. Long time-series are necessary to estimate trends relative to interannual variability. We have been part of the North Pole Environmental Observatory (NPEO), locating autonomous routine weather observation, radiation and ice thickness measurements in the vicinity of the North Pole with deployments in April 2002–2007 (Morison et al., 2006). Stations are placed on pack ice and slowly drift toward the Atlantic Ocean. For comparison, we have meteorological data from the Russian Arctic drifting stations (NP) from 1937 to late 1980s (Frolov et al., 2005). Figure 1 shows the 2-m air temperature shelter at NP-1 in 1937 and at NPEO in 2003.

We have chosen to use a pseudo melt date for comparison of the recent North Pole climate to earlier NP records. For each spring and autumn a 15 d running mean is applied to the 2-m air temperature time-series. This is necessary to remove short-term daily events from the record. Although melt should be defined as 0 °C, this is also the summer mean temperature for the Arctic and does not provide a clean break point. We have chosen a crossing value of -2.0 °C, which gives a clear signal for interannual comparison, although this event usually occurs 1–2 weeks earlier than surface snow melt, based on visual observations from a web camera. The left-hand side panel in Fig. 2 shows the day during the year (*X*-axis) that temperatures are above -2.0°C with the year on the *Y*-axis. There is considerable year-to-year variability in both the NPEO data and the Russian NP data. The mean pseudo melt date for NPEO is 11 June (Julian day 162) ± 3.3 d and for Russian NP stations is 18 June (Julian day 169) ± 4.6 d, a significant difference of 7 d at the 0.05 level based on a *t*-test statistic. Looking at the right-hand side of Fig. 2, we find no significant change in the mean pseudo freeze-up date, a result at odds with those of Belchansky et al. (2004) who investigated melt dates from passive microwave data. We proceed to investigate whether there may be an atmospheric circulation contribution to these North Pole changes.

3. Northern Hemisphere climate patterns

The AO/NAM and the PNA* pattern represent a portion of intermonthly and longer Northern Hemisphere variability in the second half of the 20th century (Quadrelli and Wallace, 2004). These authors use PNA* as their Pacific index based on Principal Component analysis of SLP to distinguish it from the classic 4-point, 500 hPa geopotential height definition of the Pacific North American (PNA) circulation index. Figure 3 shows

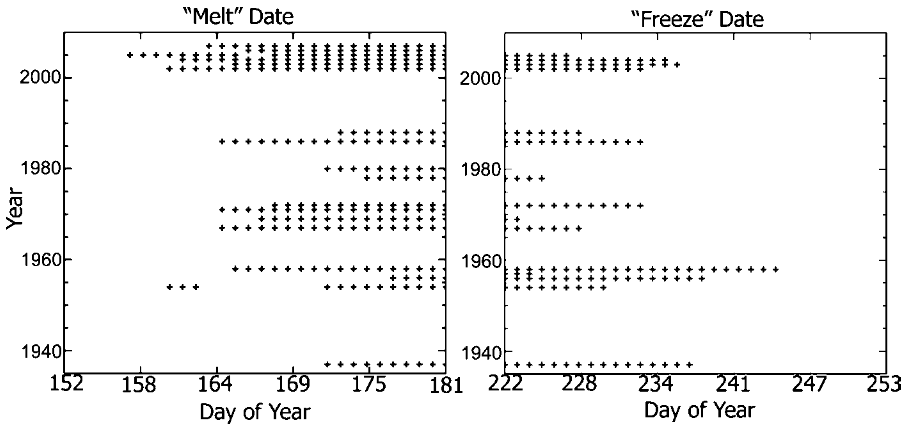

Fig. 2. Dates when NPEO SAT are above −2.0°C for recent years (2002–2007), in contrast to those date from the Russian NP Stations (1937–1988). The mean transition date for this pseudo melt date is 7 d earlier for the recent NPEO observations relative to the NP Stations.

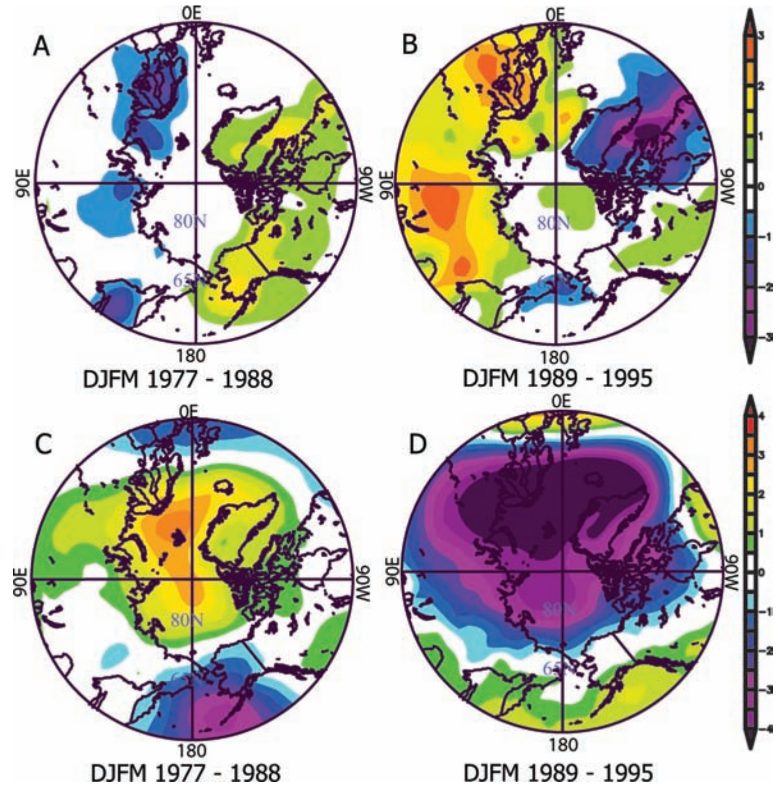

Fig. 3. Winter (DJFM) surface air temperature (SAT—top) and sea level pressure (SLP—bottom) anomaly fields for the period with a strong positive Pacific pattern (PNA*) during 1977–1987 (left-hand side) and the period with a strong positive AO pattern during 1989–1995 (right-hand side). Data and analysis software from the NOAA/ESRL Climate Diagnostics Centre. Contour interval is 0.5 °C for SAT (top) and 0.5 hPa for SLP (bottom).

examples of these two patterns for DJFM when they are in a strong positive phase, 1977–1988 for the PNA*, on the left-hand side and 1989–1995 for the AO, on the right-hand side. SAT anomalies are on top and SLP anomalies are at the bottom; contour ranges are ±3 °C for SAT and ±4 hPa for SLP with 0.5 contour intervals. Data and plotting software for these anomaly fields and those shown later are from the NOAA/ESRL web site, www.cdc.noaa.gov, based on the NCEP-NCAR Reanalysis. The base period for computing anomalies is 1968–1995. Typical of the positive AO, the lower right-hand side panel shows a negative SLP anomaly over the Arctic with the centre shifted towards the Atlantic sector. The upper right-hand side panel is the associated temperature anomaly plot with warm SAT anomalies over Eurasia and cold anomalies in eastern Canada/Baffin Bay. When the PNA* is positive (lower left-hand side panel), there are lower pressures in the Aleutian low region and warm SAT anomalies over most of the land area of North America (upper left-hand side panel). The AO and PNA* can be strong at the same time. The 1977–1988 period has, simultaneously, the AO in a negative phase while the PNA* was positive; thus, in addition to warm anomalies over North America, there were cold anomalies over Eurasia and the Barents Sea. A common characteristic of SAT

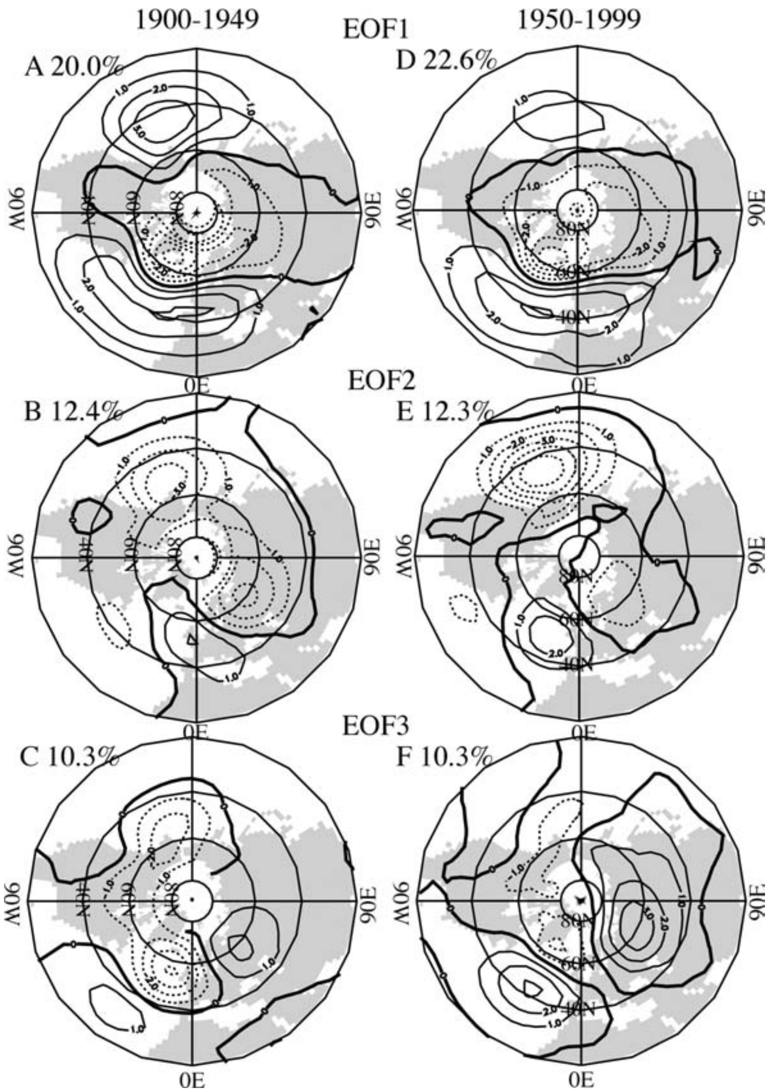

Fig. 4. Winter (DJFM) EOF patterns for the first and second half of the 20th century based on monthly SLP. The first two patterns (AO and PNA*) are spatially similar over time, whereas the third pattern has a more extensive low pressure trough from Alaska to western Europe in the early period. Numbers represent the percentage of SLP variance explained by each EOF pattern.

anomaly fields in the 20th century is that they often show simultaneous large geographical regions with opposite signs, as in Fig. 3.

Figure 4 shows an EOF analysis of SLP based on individual winter months (DJFM) for 1900–1949 (left-hand side) and 1950–1999 (right-hand side). The SLP fields we used are from Trenberth and Paolino (1980, updated). The spatial structure of the first two patterns, the AO (EOF1) and the PNA* (EOF2) are similar for both periods, but with increased amplitude of the Pacific action centre in the first half of the century for the AO and in the second half for the PNA*. The third pattern for 1900–1949 shows a dipole with an extended trough of low pressure in its positive phase spanning the Bering Sea to North America to the eastern North Atlantic, whereas for 1950–1999, the SLP ridge is greater over Asia. The third EOF represents a more meridional geostrophic wind pattern over the central Arctic.

The principal component time-series (actually the projections of individual years SLP onto the EOFs) for 1950–2007 (Fig. 5) show the well-known positive AO signal in 1989–1995 with mostly small or negative values before and variable values afterwards. The PNA* pattern shifts to more positive values (deeper Aleutian low) after the mid-1970s with single strong values in El Niño years such as 1983. PC3 has a run of negative values from 2001 to 2004. The principal component time-series for the AO during 1900–1949 (Fig. 6) has mostly positive values from 1903–1925 and notably negative values from 1940–1947, the war years. The amplitude of PNA* is mostly negative before 1925 and is positive from 1940 to 1946 when the AO is negative. The third pattern is mostly associated with a short positive event from 1926 to 1933 when the amplitudes of the other two patterns are small.

In the next section, we will look at recent departures from the AO and PNA* patterns. The only major departure in the 20th

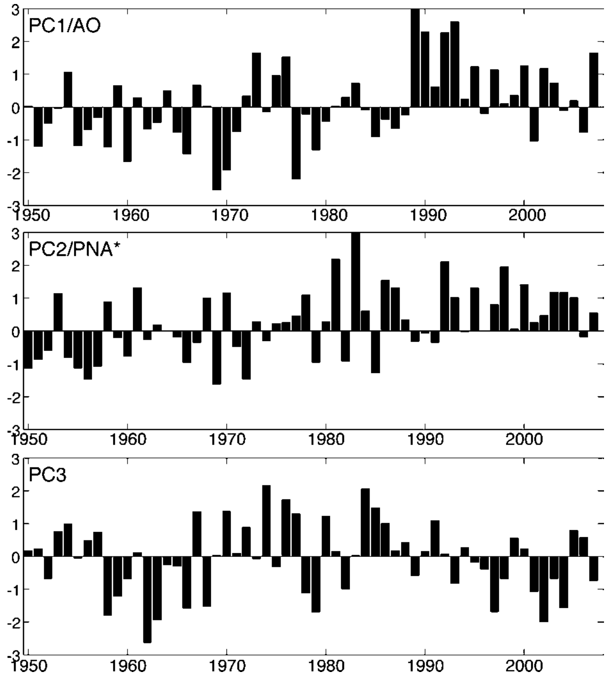

Fig. 5. Principal component time-series corresponding to Fig. 4 (right-hand side). Note the well-known positive AO (PC1) event in the early 1990s, the general shift in sign of the PNA* pattern (PC2) in the mid-1970s and the mostly negative values of PC3 from 1997–2004.

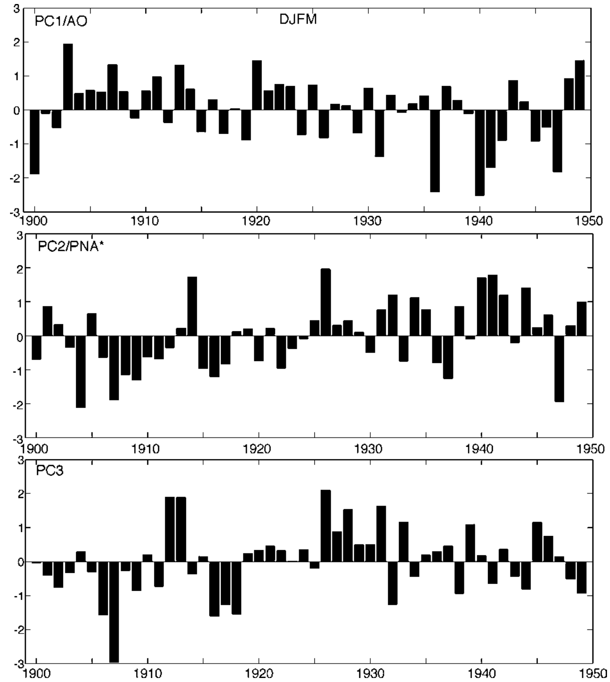

Fig. 6. Principal component time-series corresponding to Fig. 4 (left-hand side). Note the mostly positive AO from 1903–1925 and the general upward trend of the PNA*. PC3 has relatively large amplitudes from 1926–1933.

century was during the 1930s when SAT observations at Spitzbergen had an extended interval with winter (DJFM) anomalies above +4 °C relative to a 1912–2002 baseline (Fig. 7a). Maximum temperatures were toward the end of the decade with composite SLP anomalies for winter 1937–1939 showing strong meridional flow towards Svalbard (Fig. 7b). Major ice loss in the Barents Sea during this event and its eventual return are discussed by Bengtsson et al. (2004). The years of maximum Spitzbergen temperatures do not exactly coincide with the high amplitude periods of PC3 in Fig. 6. This may be because observed meridional circulation patterns are more regional and their longitudinal locations can vary, compared with more fixed hemispheric EOF patterns.

4. The Arctic warm period

The SAT and SLP patterns during the Arctic warm period (2000–2007) do not resemble the AO and PNA* patterns and their associated temperature impacts, especially during spring. Figure 8 shows plots of the Arctic-wide spring (MAM) SAT and SLP anomaly fields for 2000–2005 (left-hand side) and 2006–2007 (right-hand side). SAT anomalies greater than 1.0 °C cover most of the high Arctic (top), as indicated by yellow shading. The extensive area of warm anomalies shows up in every year, but the hot spot for 2000–2005 is north of eastern Siberia and the hot spot from 2006 to 2007 extents northeast from the Barents Sea. These hot spots are related to the orientation of the large-scale SLP pattern over the Arctic. The SLP anomaly field for MAM in 2000–2005 (lower left-hand side) has high pressure anomalies on the North American side and low pressure anomalies over Siberia, with anomalous geostrophic winds flowing from central Bering Sea to the North Pole and beyond. The geostrophic wind for MAM 2006–2007 has anomalous flow blowing over the eastern Barents Sea toward the North Pole and a continuing weak geostrophic wind anomaly across the Arctic (lower right-hand side).

If we look at the warm period in winter (DJF), the winters for 2000–2005 show composite warm anomalies (Fig. 9—upper left-hand side). In comparison with the winter PCs (Fig. 5), there is a contribution from both a positive PNA* and a negative PC3. The SAT pattern for 2006–2007 (Fig. 9—upper right-hand side) is similar to that of the following spring. The SLP pattern (Fig. 9—lower right-hand side) has a distinct dipole pressure pattern over the Arctic, but this is mostly contributed by 2006. As seen in the AO time-series (Fig. 5), there was a major return to a positive AO in winter 2007, with low SLP over most of the Arctic.

The loss of sea ice in 2000–2007 in the Pacific sector of the Arctic is well-known (Comiso et al., 2008; Deser and Teng, 2008). This loss of sea ice is consistent with a positive AO in the 1990s (Rigor and Wallace, 2004) followed by anomalous geostrophic winds coming from the Bering Strait and east Siberia regions during the Arctic warm period. Once the multi-year

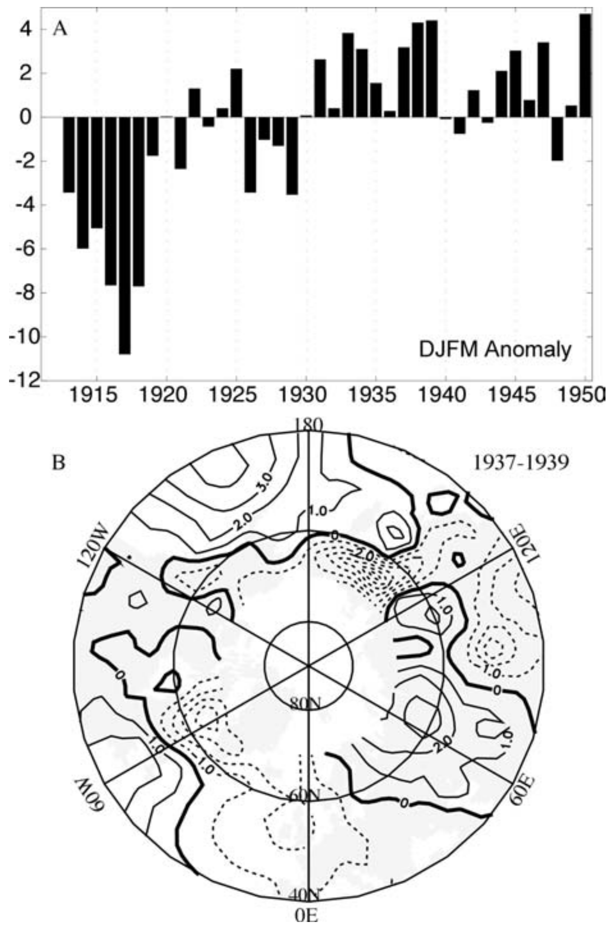

Fig. 7. (a) Winter (DJFM) SAT anomalies at Spitzbergen relative to a baseline period of 1912–2002. (b) Winter SLP anomalies for 1937–1939; Europe is in the lower margin of the figure with southerly geostrophic flow over northern Europe.

atmospheric flow pattern is set up, then other climate processes with multi-year memory can be established to help maintain below normal sea ice anomalies, such as sea ice advection and increased ocean heat as discussed by Shimada et al. (2006). At this point, we simply point out the co-occurrence of a multi-year anomalous southerly wind pattern and sea ice loss in the Pacific sector of the central Arctic, as a full Arctic heat budget is beyond the scope of this paper.

On an Arctic-wide basis, 2006–2007 winter and spring sea ice conditions contrast with the previous years due to different anomalous geostrophic wind directions. During February 2006, there were major negative sea ice anomalies throughout the Atlantic sector of the Arctic and increases in sea ice in the Bering Sea.

The return of the positive AO in winter 2007 is consistent with continued loss of multi-year sea ice (Rigor and Wallace, 2004). It is difficult to say whether the positive AO will be sustained. There are historical examples of both single strong AO years and years where the anomaly is the beginning of a multi-year event. Winter 2008 also has a positive AO.

The summer 2007 minimum ice extent was a major event. Its proximate cause was a SLP pattern with high pressure over the Beaufort Sea and low pressure on the Siberian side (Fig. 10—left-hand side), similar to the meridional geostrophic wind patterns in previous springs. As the Arctic pressure gradient in summer is nearly flat, we show the SLP field, rather than the anomaly field. This SLP pattern is a rare event in summer; the previous occurrences were in 1987 and 1977 (Fig. 10 right-hand side). Also see Ogi and Wallace (2007). We would argue, along with others, that the temporal sequence of the positive AO in the 1990s and the duration of anomalous meridional geostrophic winds during the Arctic warm period preconditioned the sea ice for the summer 2007 loss (Maslanik et al., 2007).

The subdecadal shifts of the AO, PNA* and the meridional pattern have the signature of natural internal variability of the atmospheric general circulation. However, due to recent summer sea ice loss, we are seeing an autumn warming signature in 2005–2007 (Fig. 11). SAT anomalies have extensive areas of greater than $+6\,^{\circ}$C. Thus autumn is also a signal of the Arctic warm period, and the warm temperatures are contributing to multi-year memory in the Arctic climate system. Because considerable multi-year ice has exited from the Arctic (Nghiem et al., 2007), we do not anticipate that it is possible to quickly return to ice conditions of the 1980s and expect warmer than normal autumn SAT anomalies to continue.

5. Discussion

One can hypothesize that natural variability in the large-scale atmospheric circulation, global response to anthropogenic forcing and a large contribution from ice/ocean feedbacks in response to these factors contribute to recent sea ice loss and continuing shifts in other Arctic physical and biological indicators. Like the study of Serreze et al. (2007), we see some evidence for an Arctic global warming pattern emerging from the background fields of the 20th century, but with superimposed large natural spatial and decadal variability. Our main evidence is the spatial uniformity of the $+1.0\,^{\circ}$C or greater background SAT anomalies across the Arctic in winter and spring as in Figs. 8 and 9, respectively, which are consistent with climate model projections from IPCC-AR4. Chapman and Walsh (2007) show annual Arctic temperatures approaching 1.0°C for 2000–2010 relative to 1981–2000 and a nearly uniform spatial distribution of temperature changes in winter and spring across the Arctic in 2010–2029, except for the Greenland and Labrador Sea. Other studies (Ulden and Oldenborgh, 2005) also suggest somewhat uniform spatial patterns of warming in the climate models that contributed to IPCC-AR4, rather than the warming patterns being associated with persistent shifts in dynamic climate patterns such as the AO (Palmer, 1999). Recent ice retreat contributes to extensive warm

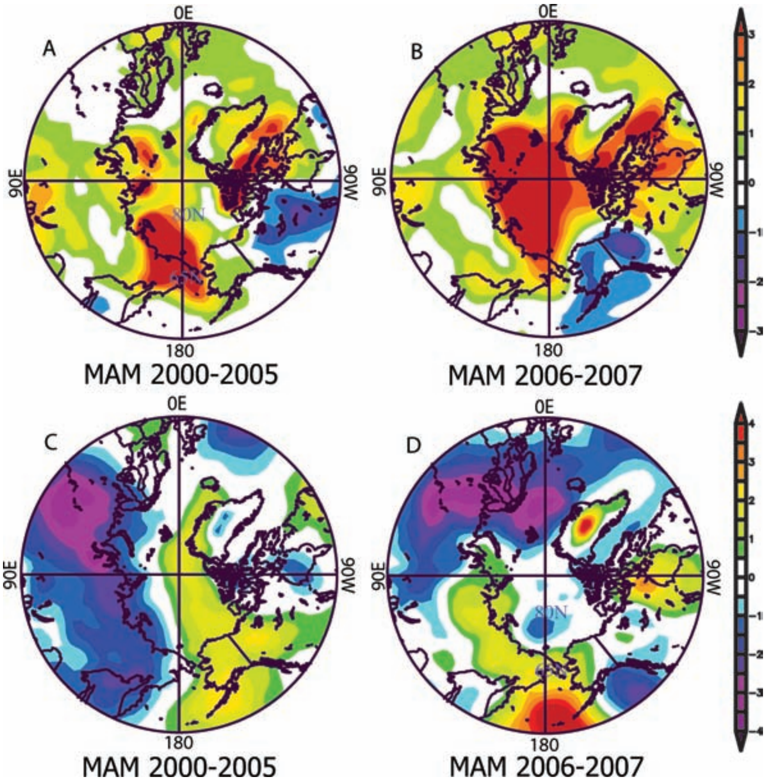

Fig. 8. Spring (MAM) SAT (top) and SLP (bottom) anomaly for 2000–2005 (left-hand side) and 2006–2007 (right-hand side). Note the large spatial extent of SAT anomalies >1.0 °C and meridional geostrophic wind anomalies over the central Arctic. We refer to 2000–2007 as the Arctic warm period. Contour interval is 0.5 °C for SAT (top) and 0.5 hPa for SLP (bottom). Fields are from the NOAA/ESRL Climate Diagnostics Center.

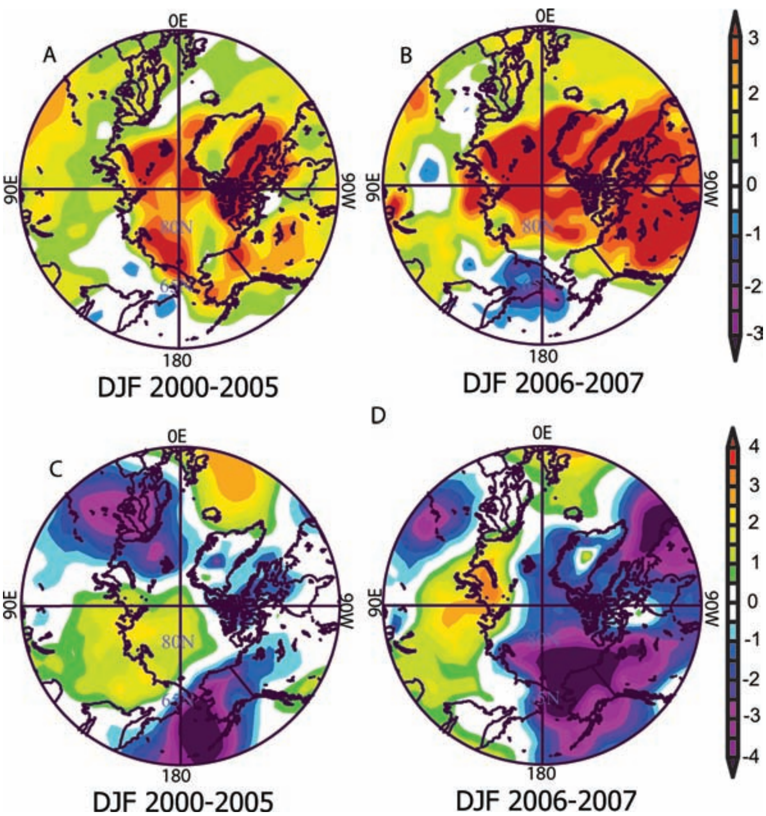

Fig. 9. Same as Fig. 8 but for winter (DJF) 2000–2007.

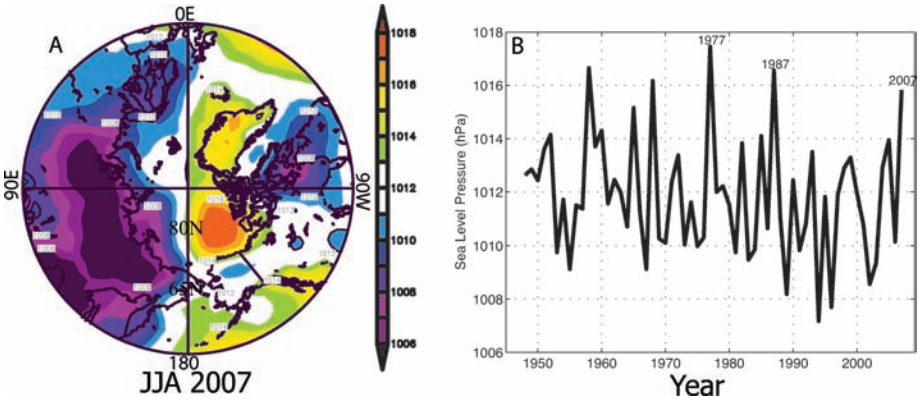

Fig. 10. (a) Summer (June–August) SLP field for 2007. Note the centre of high SLP over the Beaufort Sea. (b) Time history of summer SLP averaged over June–August for the area of 72.5–90 °N and 90–180 °W.

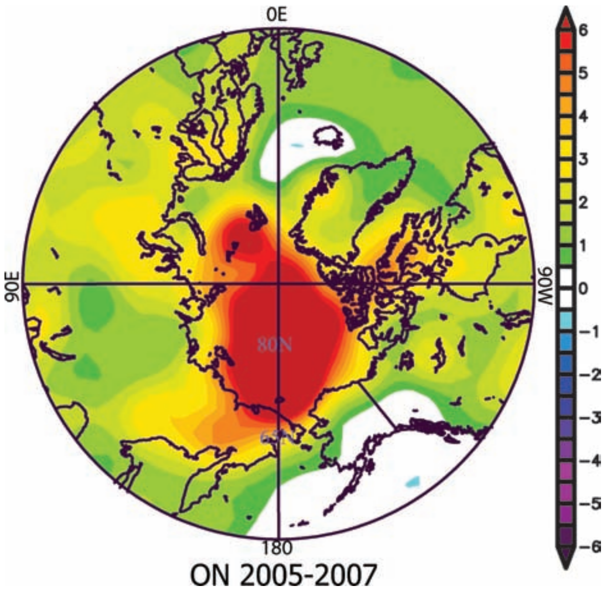

Fig. 11. Autumn (ON) SAT anomalies averaged for 2005–2007. Note the change in scale from previous figures with central Arctic values of greater than +6 °C.

autumn temperature anomalies, similar to projections by IPCC-AR4; compare observations in Fig. 11 with model projections for autumn (Chapman and Walsh, 2007, their fig. 14).

Recent atmospheric hot spots in the Arctic appear to be part of internal variability with the AO, PNA* and meridional wind patterns contributing in the late 20th and early 21st centuries. Major sea ice anomalies are regionally associated with the anomalous pressure fields, but are complex with potentially complicated multi-year memory from oceanographic and sea ice processes. This fast track for observed sea ice loss relative to the expected values for ice loss in the IPCC-AR4 climate models relates to the fortuitous timing of the positive AO, recent meridional wind anomaly patterns and ice/ocean feedbacks. As the expected time of major summer sea ice loss is near 2050 (Overland and Wang, 2007), a revised fast track estimate of summer sea ice loss before 2030 is reasonable (Stroeve et al., 2008).

6. Conclusions

The SAT and SLP patterns in the central Arctic at the beginning of the 21st century (2000–2007) were unique compared with most of the 20th century and are labelled the Arctic warm period. This was shown by earlier melt dates at the NPEO and the analysis of meteorological fields. The unusual patterns had two components, an Arctic-wide SAT anomaly consistent with IPCC-AR4 model projections based on anthropogenic forcing and a dipole pressure pattern giving anomalous meridional flow toward the North Pole with associated hot spots and loss of sea ice. This pressure pattern contrasts with the major Northern Hemisphere climate patterns of the 20th century, the AO and PNA*, whose positive phases influence positive SAT anomalies mostly over the continental areas of the Arctic. The winter/spring SLP anomalies for 2000–2007 often have a pressure dipole/meridional geostrophic wind pattern with some resemblance, but different orientation, to the pattern in the 1930s, when the AO and PNA* were also small.

What of the future? We project continued large positive and negative SAT anomalies in various regions of the Arctic as the AO and PNA* reassert themselves, as in winter 2007, in addition to a long-term Arctic-wide warming trend. For example, a slowing down of the recent major warming in the southeast Bering Sea and Alaska has begun. There is the realistic possibility, however, that the persistent minimum of sea ice extents from 2000 to 2007 have proceeded too far so that some Arctic warm anomalies such as those of recent autumns will be maintained; it would take many years to re-establish the sea ice fields of the 1980s even if the atmospheric climate patterns were favourable for ice growth. Thus, it is important to pursue long-term observational series, studies of large-scale Arctic atmospheric circulation patterns and the implications from consilient modelling studies with multiple runs to establish future climate scenarios.

7. Acknowledgments

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