Modes of the wintertime Arctic temperature variability

Vladimir A. Semenov[1] and Lennart Bengtsson[2]
Max Planck Institute for Meteorology, Hamburg, Germany

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[1] It is shown that the Arctic averaged wintertime temperature variability during the 20th century can be essentially described by two orthogonal modes. These modes were identified by an Empirical Orthogonal Function (EOF) decomposition of the 1892–1999 surface wintertime air temperature anomalies (40°N–80°N) using a gridded dataset covering high Arctic. The first mode (1st leading EOF) is related to the NAO and has a major contribution to Arctic warming during the last 30 years. The second one (3rd leading EOF) dominates the SAT variability prior to 1970. A correlation between the corresponding principal component PC3 and the Arctic SAT anomalies is 0.79. This mode has the largest amplitudes in the Kara-Barents Seas and Baffin Bay and exhibits no direct link to the large-scale atmospheric circulation variability, in contrast to the other leading EOFs. We suggest that the existence of this mode is caused by long-term sea ice variations presumably due to Atlantic inflow variability. *INDEX TERMS:* 1620 Global Change: Climate dynamics (3309); 3349 Meteorology and Atmospheric Dynamics: Polar meteorology; 9315 Information Related to Geographic Region: Arctic region. **Citation:** Semenov, V. A., and L. Bengtsson, Modes of the wintertime Arctic temperature variability, *Geophys. Res. Lett.*, *30*(15), 1781, doi:10.1029/2003GL017112, 2003.

1. Introduction

[2] The ongoing global warming during the last three decades exhibits highest trends in the Arctic [*Hansen et al.*, 1999; *Jones et al.*, 1999]. The surface air temperature (SAT) increase is accompanied by significant changes of the Arctic sea ice cover [*Johannessen et al.*, 1999] and atmospheric circulation [*Walsh et al.*, 1996]. The higher warming rate in the Arctic as well as its seasonality (most pronounced wintertime SAT increase) is in a general agreement with anthropogenic climate change scenarios simulated by climate models [*Räisänen*, 2002], although the observed high latitude warming pattern is usually different to the simulated ones. At the same time, the very strong early century warming anomaly in the Arctic, which has only recently been exceeded by the ongoing warming, does not support the polar amplification concept when century-long time periods are considered [*Polyakov et al.*, 2002]. The northern high latitudes are characterized by high natural variability, most pronounced during winter. It has been shown that a substantial part of the wintertime SAT variability in the Northern Hemisphere extratropics is related to atmospheric circulation regimes, in particular, to the Arctic Oscillation (AO)/North Atlantic Oscillation (NAO) and Southern Oscillation (SO) [*Hurrell*, 1995, 1996; *Thompson and Wallace*, 1998]. The AO is a dominant hemispheric atmospheric pressure variability pattern in the northern extratropics and it is closely linked to the NAO, a major regional pressure variability mode in the North Atlantic sector. A shift to the positive phase of the AO/NAO (enhanced mid-latitude westerlies over the Atlantic to Europe) was proposed as a reason for the recent high latitude warming [*Hurrell*, 1996]. A mechanism for the early 20th century warming is presently under debate. There are strong indications that this warming was a manifestation of internal variability [*Delworth and Knutson*, 2000; L. Bengtsson et al., The early 20th century warming in the Arctic - a possible mechanism, submitted to the *Journal of Climate*; O. M. Johannessen et al., Arctic climate change-observations and modeling of temperature and sea ice, submitted to *Tellus*]. It has also been suggested that the early 20th century warming may be a part of a low frequency oscillation, associated with variability in the thermohaline circulation [*Polyakov and Johnson*, 2000; *Delworth and Mann*, 2000]. However, no coupling mechanism has been proposed to link North Atlantic SST and Arctic SAT variations, nor do the length of the temperature records allow us to identify a particular multidecadal oscillation in the Arctic. Knowledge of spatial SAT variability patterns is important for attributing the variation to a particular physical mechanism. The analysis of the Arctic SAT variability has been usually restricted to the last 50 years, when reliable data and good spatial coverage exist (e.g., NCEP reanalysis). This time period does not include the early 20th century warming anomaly. In this study, we describe spatial patterns of the wintertime SAT variability between 40°N and 80°N during 1892–1999 using a gridded SAT dataset covering the high Arctic. Linkages between the main SAT patterns and atmospheric circulation are analyzed.

2. Data

[3] Air temperature observations in the Arctic and adjacent regions include a number of records from land-based weather stations, several of them extending back to the 19th century, drifting polar stations, buoys and dropsondes [*Przybylak*, 2000; *Serreze et al.*, 2000, for a review]. Due to different temporal-spatial coverage and measurement techniques, analyses of these data usually embrace only recent decades. Global SAT datasets [*Jones et al.*, 1999; *Hansen et al.*, 1999], which have been widely used for climate research, have major gaps over the high northern latitudes. This complicates an adequate analysis of the SAT spatial-temporal variability in the Arctic during the 20th century.

[1]Also at the Oboukhov Institute of Atmospheric Sciences, Moscow, Russia.
[2]Also at the Environmental System Science Center, Reading, UK

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[4] Here, we analyze a century-long gridded SAT dataset that is focused on the high latitudes of the Northern Hemisphere [*Alekseev and Svyaschennikov*, 1991; O. M. Johannessen et al., Arctic climate change - observations and modeling of temperature and sea ice, submitted to *Tellus*]. The dataset was compiled in the Arctic and Antarctic Research Institute, St. Petersburg. It consists of monthly mean values at $5^\circ \times 10^\circ$ lat./long. resolution and comprises land- and drifting station meteorological observations. The data cover the extratropical part of the Northern Hemisphere (generally north of 20°N) for 1892–1999.

[5] Principal component analysis has been performed on the SAT anomalies averaged for the winter half of a year (November through April) between 40°N–80°N. The Empirical Orthogonal Functions (EOFs) presented are computed for the period 1892–1999. The analysis was also performed for different subperiods. A statistical method described by *Kelly et al.* [1999] indicates that the first 4 EOFs bear meaningful information. These patterns are also found to be independent on the time period.

[6] In order to investigate relations between temperature variability and atmospheric circulation, principal component (PC) time series have been correlated with different Northern Hemisphere atmospheric teleconnection indices [*Barnston and Livezey*, 1987]. These indices are available from 1950 onwards from the NOAA/NCEP Climate Prediction Center http://www.cpc.noaa.gov/data/teledoc/telecontents.html). The correlations were also computed with the PCs of the wintertime (November–April) SLP between 25°N–80°N (1900–1999), referred below as SLP PC# (# spans from 1 to 6), using a century-long dataset [*Trenberth and Paolino*, 1980] as well as the NAO and SOI indices.

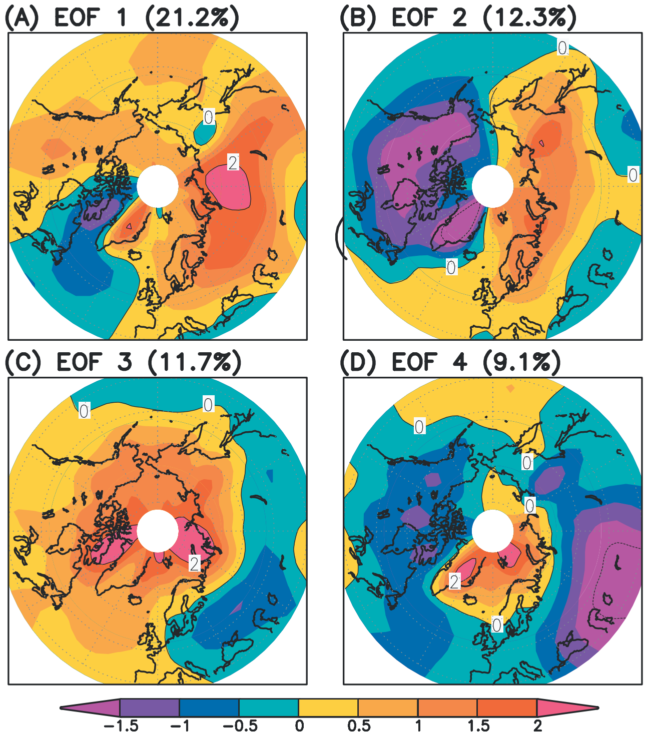

Figure 1. The four leading EOFs of the wintertime (NDJFMA) SAT variability (40°N–80°N) for 1892–1999. Contours are at −2, 0, 2.

3. Results

[7] Figure 1 shows the 4 leading EOFs of wintertime (November through April) SAT variability for 1892–1999 between 40°N–80°N. These modes explain 54% of the SAT variance during this period. The variances explained by each mode and the correlations with the atmospheric circulation indices are summarized in Table 1.

[8] The first EOF, which represents 21.2% of the variability, (Figure 1a) is related to NAO variability and has large positive temperature anomalies over northern Europe, eastern and central Eurasia, and negative anomalies over Baffin Bay. This mode looks very similar to the well known SAT-NAO regression pattern [Figure 3a, *Hurrell*, 1996]. The correlation between SAT PC1 and the NAO index is 0.60 for 1892–1999. For the 1951–98 period the highest correlation (0.58) is found with the Polar/Eurasia Pattern index (PE), which characterizes the polar vortex strength. The correlation with the NAO index for the same time period is 0.51. The highest correlation (0.77) is found with the SLP PC1, related to the AO [*Thompson and Wallace*, 1998].

[9] The second mode is a dipole with a large positive anomaly over northern Eurasia and a negative anomaly over northern Canada and Greenland (Figure 1b). This mode is connected to circulation variability over the North Pacific, which is indicated by relatively strong correlations with the Pacific/North American (PNA) and West Pacific (WP) patterns (see the Table). A significant correlation (0.34) for the whole 1892–1999 period has been found with the SOI index. This mode is highly correlated with SLP PC2, which has the largest anomaly over the North Pacific.

[10] The third mode, responsible for 11.7% of the variability, exhibits no significant connection to any atmospheric circulation indices. The strongest correlations with TI or SLP PCs do not exceed 0.25. This third mode is highly correlated (0.79) with the averaged SAT anomalies over the Arctic, very closely describing the early century warming episode (Figure 2). The mode has its strongest positive SAT anomalies over the Kara and Barents Seas, the northern part of the Greenland Sea, and Baffin Bay (Figure 1c). This mode is very similar to the first leading mode described by *Kelly et al.* [1982] for annual mean Arctic SAT anomalies. In their study, the NAO-related mode stood out as the second one. This was also the case with our data when the 1892–1950 period was considered. As the third PC does not show any significant link to the large-scale atmospheric circulation and the strongest anomalies of the EOF3 are located in (or close to) the regions of the highest interannual to interdecadal variability of the sea ice concentrations (SIC) [*Venegas and Mysak*, 2000], it is suggested that this mode is related to the interdecadal variability of the wintertime SIC in the Kara-Barents Seas and Baffin Bay. A relatively short duration of reliable wintertime sea ice observations (basically starting from 1953 [*Walsh and Johnson*, 1979]) does not allow one to identify such a long fluctuation. However, regional sea ice records or reconstructed data show a similar long-term variation in the Barents and Kara Seas [*Zakharov*, 1997; *Polyakov et al.*, 2002].

Table 1. Variance Explained by the SAT PCs and Their Correlation With Atmospheric Teleconnection Indices (TI, 1950–1999) and PCs of Wintertime (NDJFMA) SLP Anomalies Between 25°N–80°N (1900–1999)

	Explained variance	Highest correlation, TI	Highest corr., SLP PCs
EOF1	21.2%	PE, 0.58; NAO, 0.51	PC1, 0.77
EOF2	12.3%	PNA, −0.49; WP, −0.44	PC2, −0.57
EOF3	11.7%	Arctic SAT, 0.79 (1892–1999)	
EOF4	9.1%	SCA, 0.33	PC5, −0.45

Only the highest correlations are listed.

[11] The EOF4 pattern (Figure 4c) consists of a positive anomaly over the eastern part of the Arctic Ocean and Greenland, and a very strong negative anomaly over central Eurasia. The time series of the corresponding PC is correlated (0.33 for NDJFMA, and 0.51 for the DJF means) with the Scandinavia pattern (SCA) index. This PC is significantly correlated with the SLP PC5, which is associated with a corresponding SLP increase over central Eurasia and a decrease over the Atlantic sector of the Arctic.

[12] In order to demonstrate a contribution of the EOF patterns to the Arctic averaged SAT variability, the anomalies associated with EOF1, EOF3, and EOF1 combined with EOF3 (EOF1+3), respectively were subtracted from the SAT variability. The residual time series are shown in Figure 3 in comparison with the original data. These two EOFs were found to explain 94% of the Arctic SAT variability. EOF2, due to its asymmetrical structure, does not contribute significantly to the zonally averaged SAT. EOF4 makes a small contribution to the Arctic SAT (about 5%). No noticeable contribution of EOF1 (or the NAO related anomalies) is found prior to 1970, while afterwards the SAT upward trend is significantly reduced (Figure 3a). The residual trend is 0.31°C/decade against 0.58°C/decade observed for 1971–1999. These trends become 0.14°C/decade against 0.45°C/decade respectively for the 1971–1995 period, which excludes the NAO downward trend during 1995–1999 (coinciding with the rapid increase in the PC3, Figure 2). As could be expected, the residual Arctic temperature after the EOF3 subtraction exhibits no early 20th century warming, and leaves the recent warming trend almost unchanged (Figure 3b). Subtraction of the combined patterns (EOF1+3) results in a total disappearance of interdecadal variability and trends (Figure 3c). This analysis also indicates that the most rapid Arctic warming in the second half of the 1990s is related to the fast increase of PC3 despite the decrease in PC1 (or the NAO index).

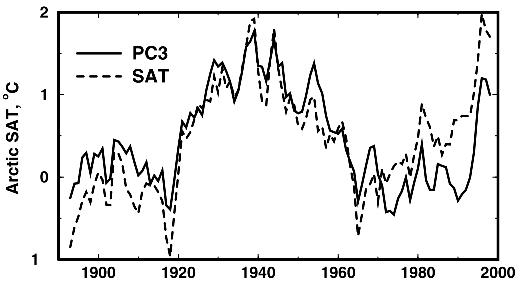

Figure 2. PC3 (solid) and averaged wintertime SAT anomalies north of 60°N (dashed, °C), 5 years running means.

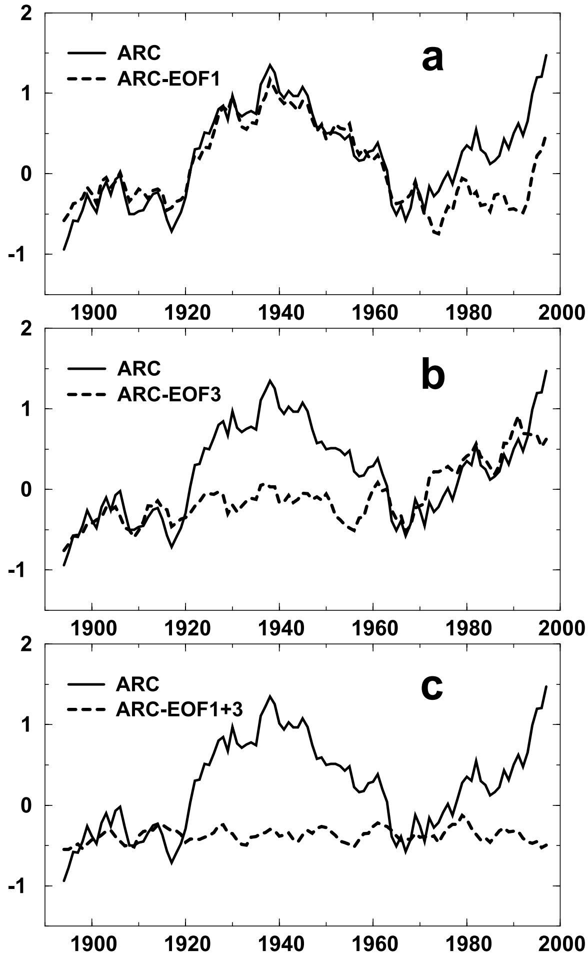

Figure 3. Arctic SAT (60°N–80°N, NDJFMA) anomalies (°C) with subtracted variability (dashed lines) related to the EOF1 (a), EOF3 (b) and EOF1+3 (c) and without subtraction (solid lines). 5 years running means.

4. Discussion

[13] The fact that two, presumably internal, modes of SAT variability describe the Arctic SAT variations in the 20th century, emphasizes the potential difficulties involved in detecting and attributing anthropogenic climate changes in the Arctic. This does not mean that greenhouse warming has not effected the recent Arctic SAT increase. Greenhouse warming can either manifest itself through intensification of an existing pattern or by generating a new pattern, which is similar to an internal mode. The first is likely the case for NAO-related variability, as many climate models simulate increased NAO with warmer climate [*Gillett et al.*, 2002 and ref. therein] and there is some evidence that the observed NAO increase is related to global warming [*Hoerling et al.*, 2001; *Schneider et al.*, 2003]. The second may happen because of the melting of arctic sea ice due to the greenhouse warming effect or the upward AO/NAO trend [*Rigor et al.*, 2002], and increased heat transport by warmer Atlantic waters. This melting during the wintertime takes place in the marginal arctic sea ice zone, which may

result in SAT anomalies similar to the EOF3 pattern. Although the PC3 was found to be uncorrelated with large-scale atmospheric circulation indices, it may be linked to regional atmospheric circulation changes [e.g., *Rogers*, 1985]. It was also shown [L. Bengtsson et al., The early 20th century warming in the Arctic - a possible mechanism, submitted to the *Journal of Climate*] that changes of the wintertime SLP gradient between Spitzbergen and Norway could produce the early 20th century warming by enhanced wind-driven Atlantic inflow into the Barents Sea with a subsequent sea ice retreat.

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V. A. Semenov and L. Bengtsson, Max Planck Institute for Meteorology, Bundesstr. 55, 20146 Hamburg, Germany. (semenov@dkrz.de)