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Reprint 783

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WU, M C , YEUNG, K H, LEUNG, Y K

Bulletin Hong Kong Meteorological Society,

Volume 17, 2007. 23-35

SOME CHARACTERISTIC ON THE APPARENT CHANGES IN EAST ASIAN WINTER ATMOSPHERIC CIRCULATION

WU, M C   YEUNG, K H   LEUNG, Y K
Hong Kong Observatory
Hong Kong, China

Abstract

Against the background of global warming, this study attempts to find out if there has been any change in the East Asian winter atmospheric circulation in the last several decades by examining the trends of the characteristics of its eight components and their correlations. These eight components were the monsoon surges, the Siberia-Mongolia high, the Aleutian low and the equatorial monsoon trough in the lower troposphere; the western North Pacific subtropical high, the Eurasian westerlies and the East Asian trough in the mid-troposphere; and the subtropical jet aloft.

Trends are noted in the characteristics of all the components studied except the strength of the subtropical jet, indicating an apparent change in the atmospheric circulation pattern. With the exception of the intensifying Aleutian low, all trends found are consistent with the observed rising winter temperatures in southern China which has been attributed in part to global warming.

Moving correlation analysis with a 29-year sliding window applied to time series showed that the degree of correlation between the Eurasian westerlies index and the three different subtropical high indices is declining. This decreasing covariability between the tropical circulation (i.e., the subtropical high) and the mid-latitude circulation (i.e., the Eurasian westerlies) is another indication of the climatic change in the East Asian winter atmospheric circulation. Whether such changes were due to global warming requires further investigation.

Keywords
Global warming, East Asian winter atmospheric circulation, Trend, Covariability

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) has recently concluded that global warming is unequivocal [IPCC, 2007]. Observed to occur concurrently are changes in the regional climate in different parts of world. The trends of regional temperature variations are important aspects of the baseline against which the potential effects of climate change should be assessed [IPCC, 1998].

A rising trend has been found in the winter temperature in Hong Kong between 1947 and 2003 [LEUNG et al, 2004a,b]. At the regional scale, LIANG et al [1999] suggested that both global warming and local urbanization effects are among the reasons for the winter warming in the Guangdong Province of China, and WANG et al [2003] described the warming over southern China as a whole. From the perspective of regime shifts, WU et al [2006] related the recent rise in winter temperature in Hong Kong, as part of a regional phenomenon, with the weakening of the East Asian winter monsoon. Many model simulations have suggested a weakening of the East Asian winter monsoon under global warming [HU et al, 2000; BRANDEFLT, 2006; HORI et al, 2006 among others].

This study attempts to find out if there has been any change in the East Asian winter atmospheric circulation in the last several decades (1958-2005) by examining the trends of the characteristics of its major components and their correlations. Their relationships with the winter temperature in Hong Kong are examined. Finally, the modulating effects of the Arctic Oscillation (AO) and the Pacific Decadal Oscillation (PDO) on the East Asian winter atmospheric circulation are also analyzed [GONG et al, 2001; JHUN et al, 2004; CHAN et al, 2005].

2. Data and Methodology

2.1 Data and definitions

Northern Hemisphere (NH) winter surface temperature anomaly data (December to February, DJF) are obtained from the National Climatic Data Center of NOAA (http://lwf.ncdc.noaa.gov/). Global atmospheric and sea surface temperature (SST) data in 1958-2005 comes from the monthly reanalysis of the National Centers for Environmental Prediction and the National Center for Atmospheric Research (NCEP-NCAR) [KALNAY et al, 1996]. NCEP-NCAR data prior to 1958 are not used because the quality is low [TRENBERTH et al, 2000]. In the computation of indices related to sea level pressure (SLP), Trenberth's monthly gridded northern hemisphere SLP data [TRENBERTH et al, 1980] are used (http://dss.ucar.edu/).

Winter temperatures of Hong Kong are computed from hourly temperatures recorded at the Hong Kong Observatory Headquarters. In the present study, temperature variation in Hong Kong is taken as a proxy for that of southern China because of the very high correlation between the two [LEUNG et al, 2004b].

Values of the Pacific Decadal Oscillation (PDO) index and the Arctic Oscillation (AO) index are obtained from the Joint Institute for the Study of the Atmosphere and Ocean of the University of Washington (http://jisao.washington.edu/) and the Climate and Global Dynamics Division of the Earth and Sun Systems Laboratory at NCAR (http://www.cgd.ucar.edu/) respectively. Values of the El Nino-Southern Oscillation (ENSO) index is calculated from the monthly SST in Nino region 3.4 (5°N-5°S, 170-120°W) data from the Climate Prediction Center of NOAA (http://www.cpc.noaa.gov/).

Published data from the National Climate Center (NCC) of the China Meteorological Administration

(CMA) are also used, including values of the Subtropical High indices, the Eurasian Westerlies index and the East Asian Trough (position) index.

Eight major components of the East Asian winter monsoon have been identified [WU, 2003], namely the monsoon surges, the Siberia-Mongolia high, the Aleutian low and the equatorial monsoon trough in the lower troposphere; the western North Pacific subtropical high, the Eurasian westerlies and the East Asian trough in the mid-troposphere; and the subtropical jet aloft. Table 1 summarizes the definitions of the related indices and the data used in their computation.

Table 1. Definitions of indices characterizing the eight components of the East Asian winter monsoon.

	Component	Index	Definition of the indices and data used
Lower troposphere	Winter monsoon surge	WMI	Defined by YOUN [2005] as standardized SLP difference between (40°N, 135°E) and (45°N, 95°E) averaged for DJF and is calculated using Trenberth's SLP data. The more negative the WMI the stronger is the monsoon.
	Siberia-Mongolia high	SMH	Defined as SLP averaged over (45-55°N, 95-100°E)[1] and is calculated using Trenberth's SLP data. Larger value indicates a stronger Siberia-Mongolia high.
	Aleutian low	ALPI	The mean area (km^2) with SLP $\leq$1005 hPa [BEAMISH et al,1997]. A positive ALPI reflects a strong Aleutian low. Values of ALPI are downloaded from Fisheries and Oceans Canada at http://www.pac.dfo-mpo.gc.ca/.
	Equatorial monsoon trough	EMT	The outgoing longwave radiation (OLR) averaged over the region (10°S-10°N, 100-160°E). Larger values represent weaker convection and a weaker monsoon trough. NCEP-NCAR reanalysis data are used to calculate the values of this index.
Mid-troposphere	Subtropical high	SH_I	The intensity of the subtropical high. Data from NCC[2].
		SH_R	The ridge line position of the subtropical high. An increasing value refers to a northward shift of the subtropical high. Data from NCC.
		SH_W	The western position of the subtropical high. An increasing value refers to a eastward shift of the subtropical high. Data from NCC.
	Eurasian westerlies	EAW	It denotes the mid-latitude circulation condition in the Eurasia sector (45-65°N, 0-150°E). A positive value corresponds to the dominance of zonal flow in Eurasia. Data from NCC.
	East Asian trough	EAT	The longitudinal position of the East Asian trough. Data from NCC.
Aloft	Subtropical jet	JET	The areal average of the 200-hPa zonal wind over (30-35°N, 130-160°E) as defined by YANG et al [2002]. A larger value represents a stronger subtropical jet. NCEP-NCAR reanalysis data are used to calculate the values of this index.

[1] Region defined by WU et al [1997] to represent the Siberia-Mongolia high but using 1000 hPa geopotential height.
[2] See ZHAO [1999] for the detailed definitions of NCC indices.

2.2 Methods

In this study, the trend in a time series and its statistical significance are assessed using the non-parametric Mann-Kendall (MK) test. Since the MK test gives only the significance and the direction of the trend but not the trend itself, the non-parametric Sen's slope estimator [SEN, 1968] is used to obtain the magnitude of the trend. Both MK test and the Sen's slope estimator have the advantage of not being predicated upon the normal distribution, while able to be applied to data with linear or non-linear trends, and insensitive to outliers [SNEYERS, 1990; FU et al, 1992]. However, for simplicity, trends of surface temperature, SLP, 500 hPa geopotential height and 200 hPa zonal wind for different grid points in NH are determined using linear regression analysis [EASTERLING et al, 1997].

Moving correlation analysis [KUZNETS, 1928] with a 29-year sliding window is used to examine the temporal variability in the relationship between any two indices [MCCABE et al, 2006]. Unless otherwise stated, spearman rank correlation [WILKS, 1995] is used to minimize outlier influence, although Pearson's correlation produces essentially the same results.

The empirical orthogonal function (EOF) technique [von STORCH et al, 1999] is used to highlight the coherent modes of variability in NH winter atmospheric circulation, which are compared with the linear trends. The cumulative summation (CUSUM) technique is used to determine changes in the trend of a time series, to identify periods of regime reversal and to see whether changes in trends tend to match up across indices [HARE, 1996; LEUNG et al, 2005]. It is defined as the accumulating sum of anomalies (from the overall mean) of all preceding values.

3. Results

3.1 Overall changes in Northern Hemisphere winter atmospheric circulation

Figure 1 compares the pattern of the linear trend describing the overall change and the pattern of the first EOF (i.e., EOF 1) of NH winter surface temperature in the period 1958-2005. The similarity between the two indicates that the trend dominates the variability of NH winter temperature as a whole. It is also noted that the temporal score or principal component (PC) of the first EOF exhibits an increasing trend (not shown) suggesting that warming is the key feature of NH in this period. The north-south SLP gradient (Fig. 2a) and the East Asian trough in the vicinity of Japan (Fig. 2b) have been weakening, indicating a weakening of the East Asian monsoon. These changes are also found to be consistent with their respective leading mode of variability (Fig. 3a,b) with positive trends in the associated PCs.

Aloft, the most prominent features of the spatial trend of the 200 hPa zonal wind are the northward displacement and eastward extension of the subtropical jet (Fig. 2c). No significant trend is found in the first two EOFs (i.e., EOFs 1 and 2) of the 200 hPa zonal wind. Both the third and fourth EOFs have significant positive trends in the corresponding PCs, suggest a weakening (EOF 3) and an eastward shift (EOF 4) of the subtropical jet. These findings also suggest a weakening of the winter monsoon circulation over East Asia. Changes in the major components of the East Asian winter atmospheric circulation are examined in more details below.

3.2 Trends in components of the East Asian winter atmospheric circulation

Significant trends (at 5% level) are found in the indices of all the components studied except the strength of the subtropical jet (JET) aloft (Table 2), indicating a remarkable change in the East Asian winter atmospheric circulation particularly in the lower troposphere. Converting the trends to a common scale expressed in terms of a fraction of the standard deviation (Stdev) allows comparison of trends of different indices. It is found that the trend is most prominent in the Siberia-Mongolia high (SMH) in the lower troposphere and the East Asian trough (EAT) in the mid-troposphere respectively. The ratio of the standard deviation to the trend provides a measure of the time required for the trend to give a change equivalent to one standard deviation, and it ranges from ~ 20 to ~40 years for different indices.

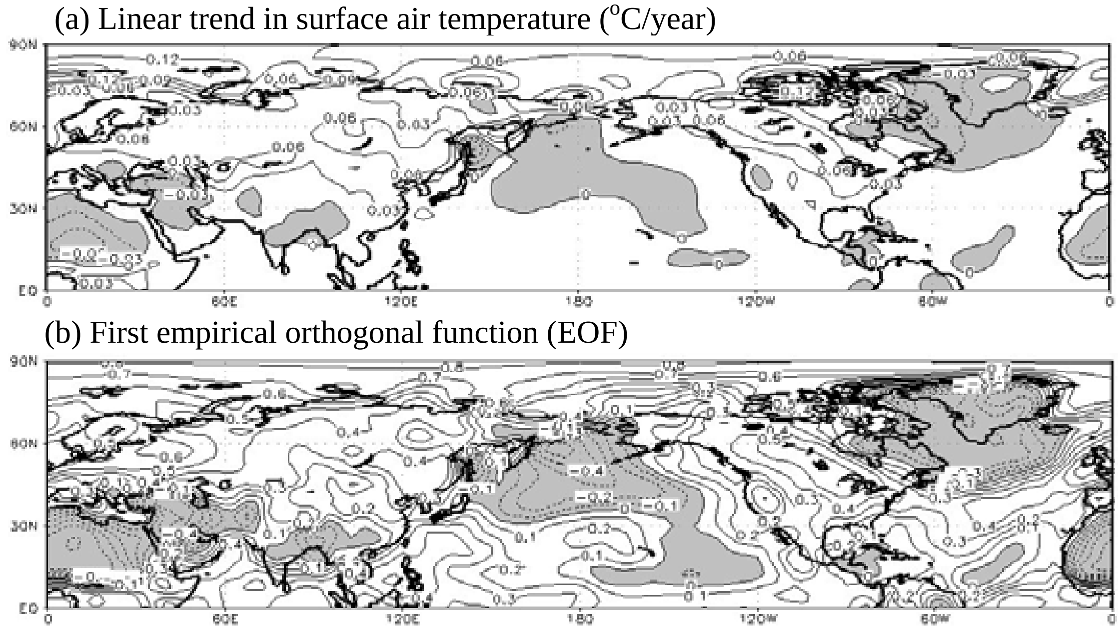


Fig. 1. (a) Linear trend (obtained by linear regression) of NH winter surface temperature. (b) First EOF of NH winter surface temperature which accounts for 16.6% variability. Negative values are shaded.

Table 2. Trend analysis of the components of the East Asian winter monsoon. Only trends significant at 5% level using MK test are given. Stdev is with reference to the period 1961-1990.

	Lower troposphere				Mid-troposphere					Aloft
	WMI	SMH	ALPI	EMT	SH_I	SH_R	SH_W	EAW	EAT	JET
Trend, (/decade)	1.67	-1.32	0.64	1.72	3.65	0.44	-6.06	0.04	1.28	-
Trend/Stdev	0.47	-0.53	0.22	0.34	0.31	0.33	-0.35	0.23	0.51	-
Stdev/Trend, (years)	21.5	18.9	45.2	29.8	32.2	30.5	28.4	43.6	19.7	-

Table 3 summarizes the change of each component of the East Asian winter monsoon circulation as revealed by the trend of the corresponding index. The average of Hong Kong's winter temperature corresponding to the 10 largest values of each index is compared with that corresponding to the 10 lowest values of the index to see how the winter temperature in Hong Kong vary with the index. With the exception of the intensifying Aleutian low, the trends of all indices are found to be consistent with the observed rising winter temperature in Hong Kong (and thus of southern China as discussed earlier [LEUNG et al, 2004b]) which has been attributed in part to global warming. The influences of the Aleutian low (ALPI) and the equatorial monsoon trough (EMT) are apparently slight as the difference in Hong Kong's winter temperature for large and small values of ALPI and of EMT are statistically not significant.

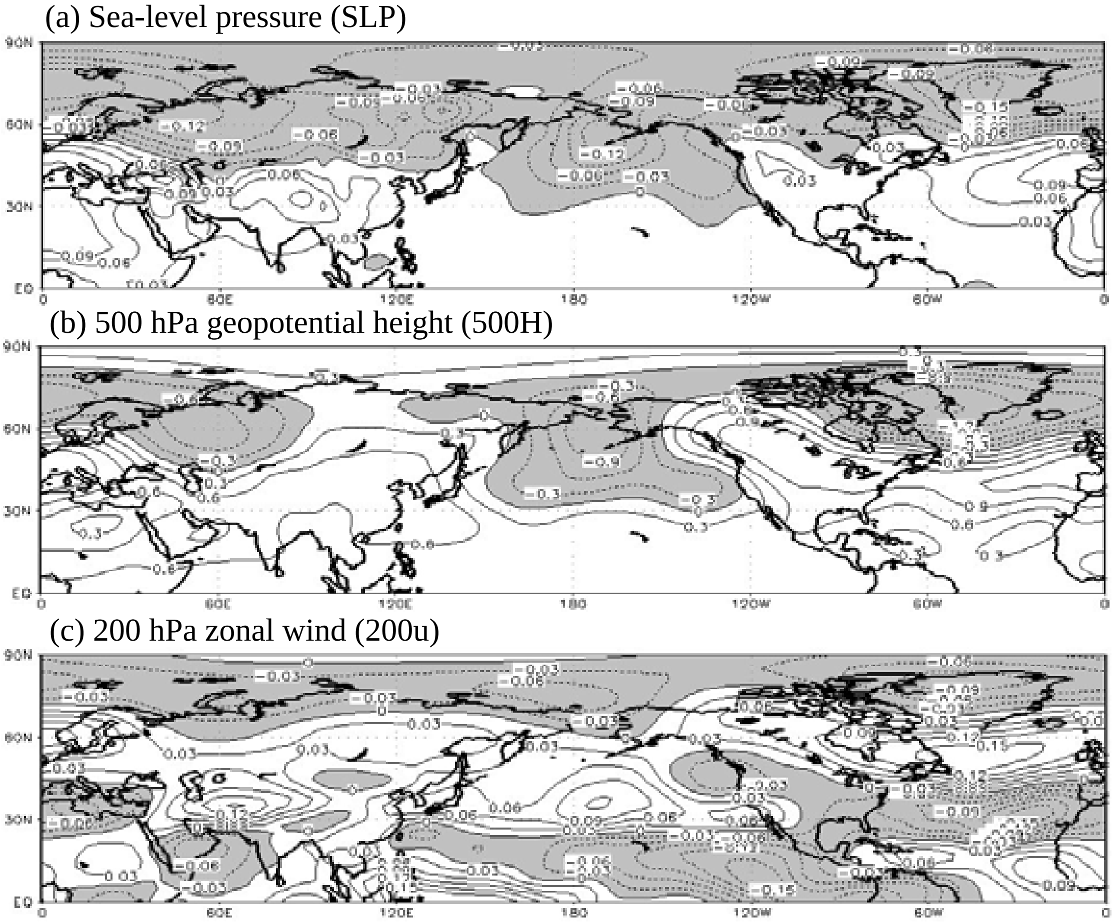


Fig. 2. As in Fig. 1a, but for NH winter (a) SLP, (b) 500 hPa geopotential height and (c) 200 hPa zonal wind. Negative values are shaded.

Table 3. The average of Hong Kong’s winter temperature corresponding to the 10 highest values of an index minus that corresponding to the 10 lowest values of the index. The significance of the difference is tested using the Kolmogorov-Smirnov (KS) test [SIEGEL et al, 1988]. * denotes significance at the 5% level.

Index		Difference (^{o}C)	Change correspond to the trend of each index
Lower troposphere	WMI	1.48*	Weaker monsoon surge
	SMH	1.49*	Weaker Siberia-Mongolia High
	ALPI	-0.13	Deepening of the Aleutian low
	EMT	0.66	Weakening of the Equatorial monsoon trough
Mid-troposphere	SH_I	1.04*	Stronger subtropical high
	SH_R	1.47*	Subtropical high shift northwards
	SH_W	1.14*	Subtropical high shift westwards
	EAW	1.26*	Zonal flow dominate in Eurasia sector
	EAT	0.81*	East Asian trough shift eastwards

The lack of a significant trend in JET is in line with the result given in Section 3.1, namely no significant trend being found for the PCs associated with the first two EOFs of the 200 hPa zonal wind. On the other hand, the eastwards shift of the subtropical jet as suggested by EOF 4 (Fig. 3d) is consistent with the significant trend in EAT (i.e., eastward shift of the East Asian trough).

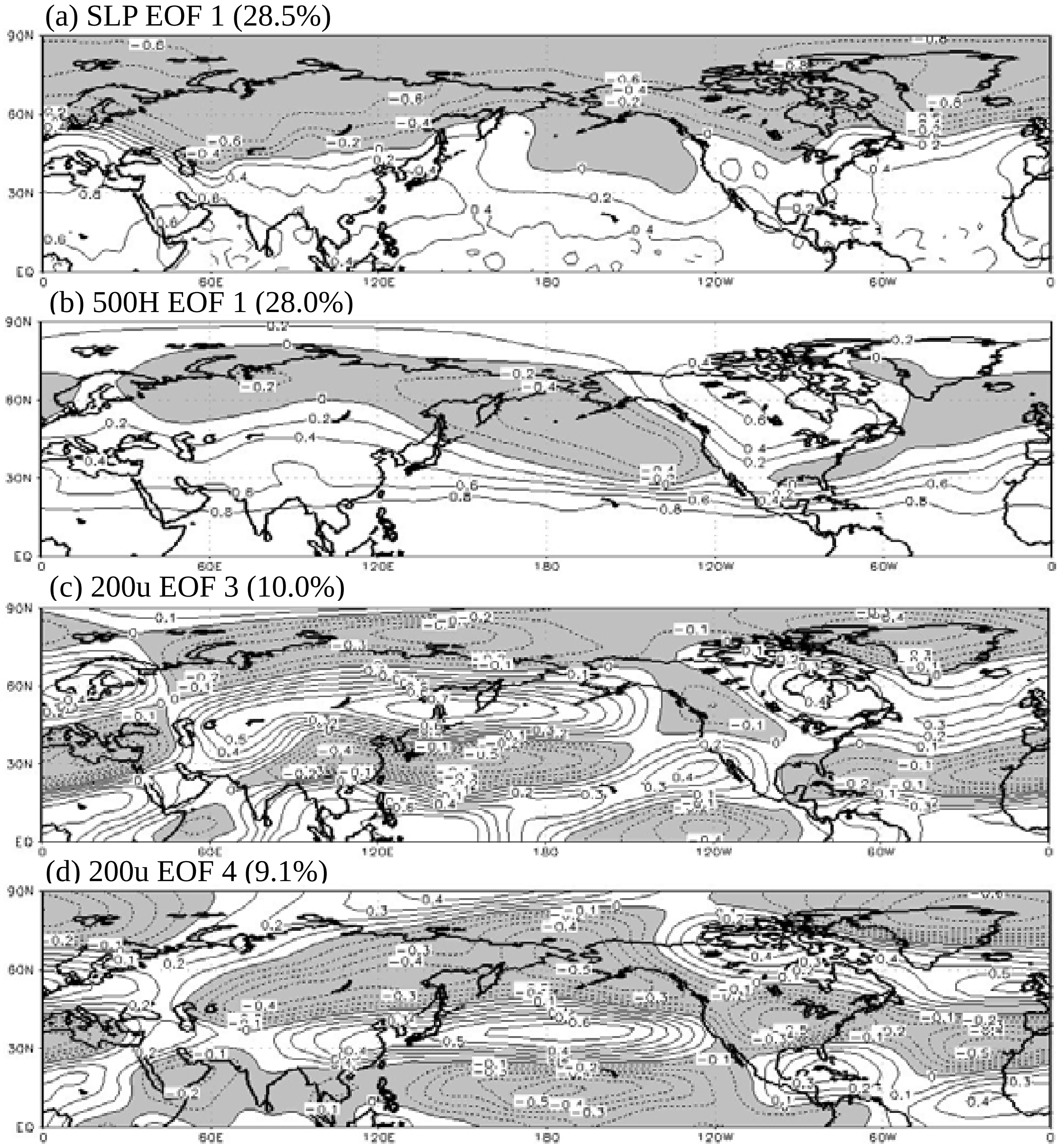
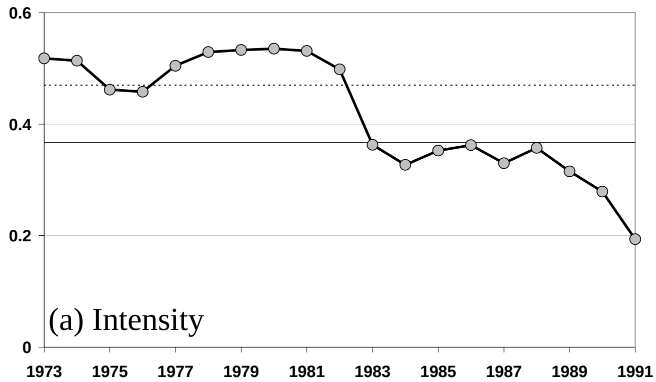


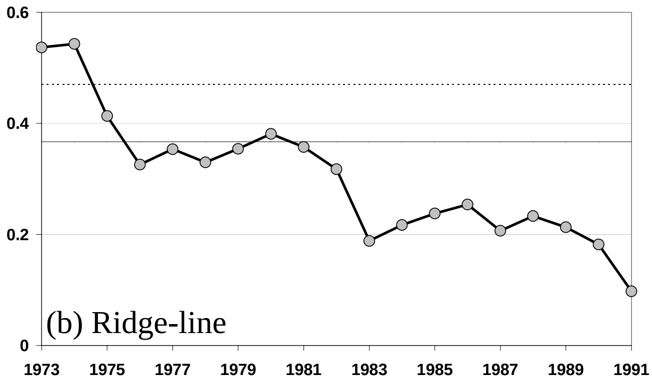
Fig. 3. The first EOF of NH winter SLP (a) and that of 500 hPa geopotential height (b), the third (c) and fourth (d) EOFs of winter 200 hPa zonal wind. Negative values are shaded. The bracketed value gives the total amount of field variance explained by each EOF. Note that no significant trend is found for the first two leading EOFs of 200 hPa zonal wind, and are therefore not shown.

3.3 Changing covariability between different components

The covariability between different components of the East Asian winter atmospheric circulation in the mid-troposphere has been examined. Moving correlation analysis with a 29-year sliding window applied to time series reveals that the degree of correlations between the Eurasian Westerlies index (EAW) and the three different subtropical high indices (SH_I, SH_R and SH_W) are declining (Fig. 4).

This decreasing covariability between the low latitude circulation (i.e., the subtropical high) and the mid-latitude circulation (i.e., the Eurasian westerlies) is another indication of the change in the East Asian winter atmospheric circulation [BRAGANZA et al, 2004]. While the correlation between the East Asian Trough index (EAT) and Subtropical High Intensity index (SH_I) is also declining and becoming insignificant, no significant correlation is found between the East Asian Trough index (EAT) and the Subtropical High Ridge Line index (SH_R) and between EAT and the Subtropical High Western Position index (SH_W) in any time slices (not shown). In contrast, the correlation between the East Asian trough (EAT) and the Eurasian westerlies (EAW) is increasing and the covariability among the subtropical high indices remains significant and robust throughout the period (not shown). Figure 5 summarizes schematically the change in the interrelationship among the components of East Asian winter atmospheric circulation in the mid-troposphere.





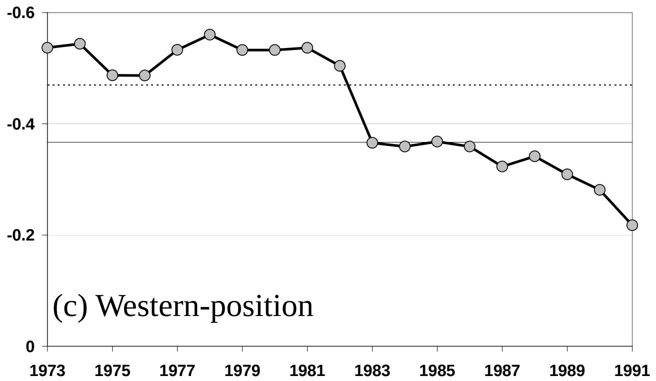


Fig. 4. Variations of the correlation coefficient between the Eurasian Westerlies index (EAW) and the subtropical high's (a) intensity (SH_I), (b) ridge-line index (SH_R) and (c) western-position index (SH_W). In each case the correlation "window" covers 29 years centred at the mid-year of the interval. Dashed (dotted) horizontal line shows the 5% (1%) significance level.

To see if the above decline in covariability between the low latitude circulation and the mid-latitude circulation could possibly be related to global warming in terms of the rising trend of NH winter temperature, the time series of EAW, SH_I, SH_R and SH_W are first grouped into 2 slices, each consisting of 29 years, according to the ranking of the detrended (using linear regression for simplicity and convenience) NH winter temperature. Each group with 29 years therefore corresponds to the relatively warmer (Group W) and colder (Group C) winters after the linear trend had been removed. The purpose of detrending is to ensure that one looks at the relationship between temperature and the index, not just the time variation of the index which had already been addressed earlier, in view of the increase in temperature with time under global warming. Table 4 compares the correlations among indices between the 2 groups. Apparently, with warmer NH winters, there is a decline in correlation between the Eurasian Westerlies index (EAW) and the subtropical high indices, most evident for SH_I and SH_W.

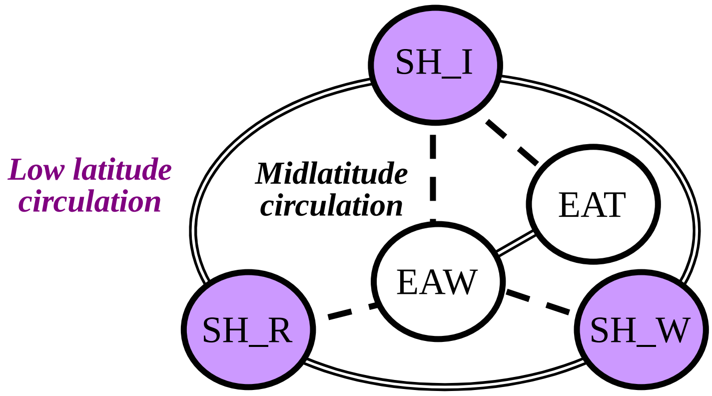
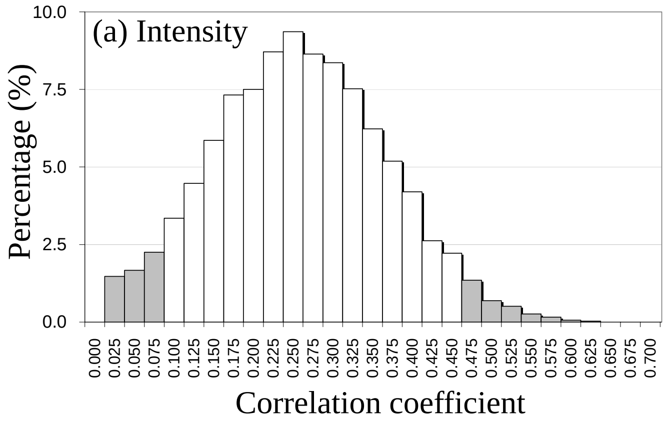


Fig. 5. Schematic diagram showing the interrelationships among the components of the East Asian winter atmospheric circulation in the mid-troposphere. Double line denotes significant correlation in recent decades. Dashed line represents a declining correlation from significant to insignificant.

Table 4. Comparison of the correlations between Group C and Group W. Group W (C) corresponds to 29 relatively warmer (colder) years for the detrended NH winter temperature. * denotes correlation significant at 1% level.

Indices	Correlation for group C	Correlation for group W
EAW vs SH_I	0.47*	0.07
EAW vs SH_R	0.29	0.26
EAW vs SH_W	-0.50*	-0.12

To consider the significance (in statistical sense) of the apparent decline in correlation between the Eurasian Westerlies index (EAW) and the subtropical high's intensity and western position index (SH_I and SH_W) with warmer NH winters, 29 years of the detrended EAT and SH_I are selected randomly (instead of according to the ranking of the detrended NH winter temperature) and the corresponding correlation coefficient is computed. This procedure is then repeated for 10,000 times so that we will have 10,000 correlation coefficients. Same consideration is also conducted between EAT and SH_W. Figure 6 shows the distribution of the 10,000 realizations of correlation coefficients between EAT and SH_I and that between EAT and SH_W. It is noted that the percentage to have correlation between EAT and SH_I to be $\leqq$ +0.075 (with reference to the 0.07 for group W given in Table 4) and $\geq$ +0.475 (with reference to the 0.47 for group C given in Table 4) is just ~5.4% and ~3.1% respectively. Likewise, the percentage to have correlation between EAT and SH_W to be $\leqq$ -0.50 and $\geq$ -0.10 is ~10.5% and $<$ 1%, respectively. In other words, the decline in correlation with warmer NH winters mentioned above could be rather significant.



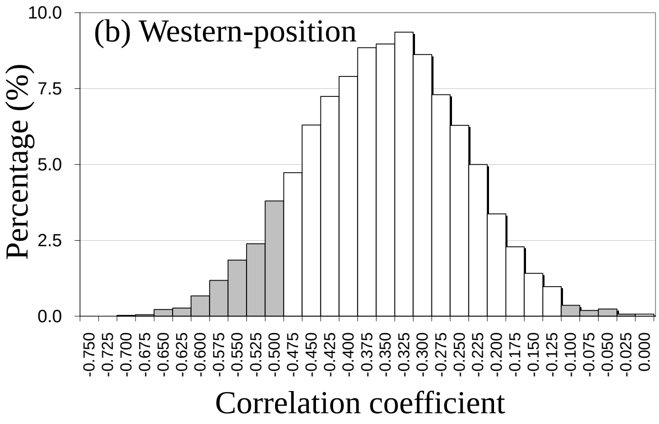


Fig. 6. Distribution of correlation coefficients between the Eurasian Westerlies index (EAW) and the subtropical high's (a) intensity (SH_I) and (b) western-position index (SH_W). With reference to the values of correlation given in Table 4 for EAT vs SH_I and EAT vs SH_W, correlation coefficients ≦ +0.075 and ≥ +0.475 for (a) and ≦ -0.50 and ≥ -0.10 for (b) are highlighted in grey.

Besides global warming, changes in the components of the East Asian winter atmospheric circulation are compared with some dominant modes of oscillations of NH oceanic and atmospheric circulations, namely PDO and AO, using the CUSUM method. The CUSUM graph helps to locate abrupt changes in the trend in a time series. Abrupt changes in the subtropical high indices (SH_I, SH_R and SH_W) as well as the ENSO index are found to coincide with the well-recognized climatic shift in the PDO [MANTUA et al, 1997] in the mid-1970s (Fig. 7). At the same time, it is clear that the subtropical high is more strongly influenced by PDO compared with the components in mid-latitudes (EAW and EAT).

Similar abrupt changes can be seen in the time series of the winter temperature of NH, winter temperature of Hong Kong, the Eurasian Westerlies and East Asian Trough indices (EAW and EAT) in the mid- to late 1980s, concurrent with the phase change in AO [OVERLAND et al, 1999]. As such, in line with the implication of the study by CORTI et al [1999], the observed changes of EAW, EAT and the three subtropical high indices SH_I, SH_R and SH_W could be a manifestation of some natural climate variability if AO and PDO are recognized as natural oscillations. However, CORTI et al [1999] has also pointed out that even if the observed change in a certain aspect of the climate is related to certain natural climate oscillations, the possibility of anthropogenic forcing of the former cannot be ruled out because the latter could have been affected. From Fig. 6(d), NH winter temperature exhibits an abrupt change around the mid-1980s, with a sharp increase in the rate of warming (though not as sharp as the change in AO, EAT, EAW or Hong Kong's winter temperature). As AO is strongly coupled with the surface temperature fluctuation over the Eurasian continent [THOMPSON et al, 1998] and thus the East Asian winter monsoon [GONG et al, 2001], it is therefore difficult to distinguish between natural variability and change due to anthropogenic forcing. For instance, while SHINDELL et al [1999] hypothesized that the change in AO is related to increase in greenhouse gases, COHEN et al [2005] recently argued that the global warming trend is largely independent of the AO.

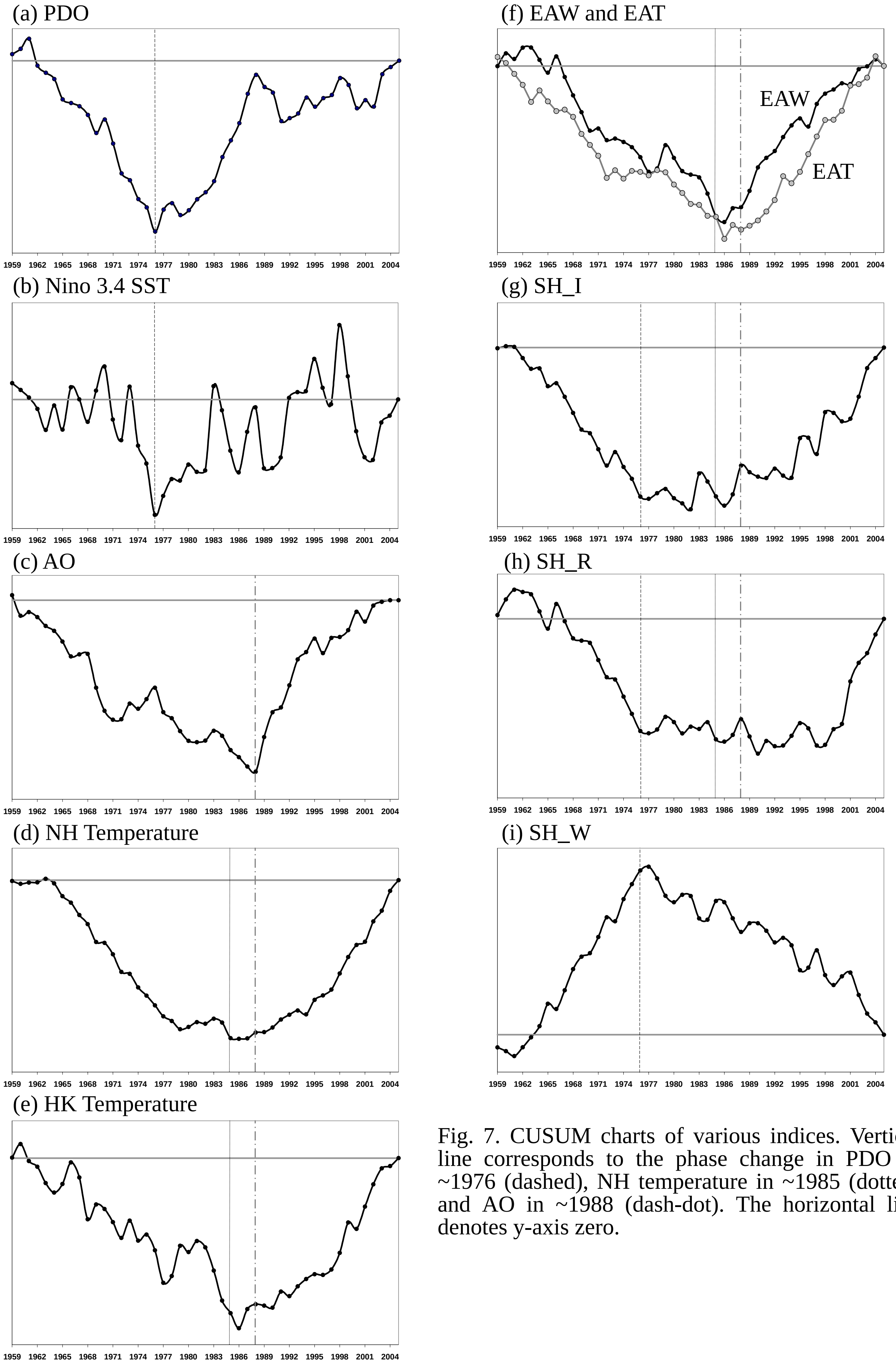


Fig. 7. CUSUM charts of various indices. Vertical line corresponds to the phase change in PDO in ~1976 (dashed), NH temperature in ~1985 (dotted) and AO in ~1988 (dash-dot). The horizontal line denotes y-axis zero.

4. Conclusion

Against the background of global warming, this study attempts to find out if there has been any change in the East Asian winter atmospheric circulation in the last several decades by examining the trends of the characteristics of its eight components and their correlations. Trends are noted in the characteristics of all the components studied except the strength of the subtropical jet aloft, indicating an apparent change in the atmospheric circulation pattern. With the exception of the intensifying Aleutian low, all trends found are consistent with the observed rising winter temperatures in southern China which has been attributed in part to global warming.

Changes in some components of the East Asian winter atmospheric circulation have been suggested to be related to global warming based on the results of coupled GCMs simulations. These include for examples, the weakening of the Siberia-Mongolia high [BRANDEFLT, 2006], the deepening of Aleutian low [HU et al, 2000] and the weakening of the East Asian winter monsoon [HORI et al, 2006]. These changes are consistent with the findings of this paper.

The covariability between the low latitude circulation and the mid-latitude circulation is declining which is another indication of the climatic change in the East Asian winter atmospheric circulation. Whether or not such changes were due to global warming requires further investigation.

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