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INTRA-SEASONAL VARIABILITY OF WINTERTIME TEMPERATURE OVER EAST ASIA

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ABSTRACT

There has been a profound warming over East Asia during the winter months (November through to March) over the past few decades. The goal of this study is to address the question of whether the daily temperature has become more variable in conjunction with this warming by using observed temperature data obtained from 155 Chinese and Korean stations. Prior to the analysis, the annual cycle is removed to obtain daily temperature anomalies for each winter for each station. Results show that the intra-seasonal variance generally decreases, implying that the daily temperatures are becoming less variable. Considering all stations as a whole, the rate of change is $-0.49\,^{\circ}C^2$ per decade (equivalent to -3.59% per decade). The changes are more robust in the northeastern portion of China. In contrast, there are no dominant trends for the skewness coefficients, except for clear negatively skewed trends in northeastern China. These results are consistent with an increase in the number of extremely cold events. Over the region, the frequency of low-temperature extremes (as low as below minus two standard deviations) increases at a rate of change of 0.26 days per decade, significant at the 95% confidence level. Both the Siberian high and Arctic oscillation (AO) exert a notable influence on the temperature variance. Intra-seasonal variance of the Siberian high and AO are significantly correlated with the temperature variance, whereas the seasonal mean state of the AO affects the temperature variance by modulating the high-frequency components of the Siberian high. The intra-seasonal variance of the Siberian high tends to decline at a rate of change of -10.7% per decade, significant at the 99% level; meanwhile, the mean wintertime AOs have strengthened in the last few decades. These two climate features together make a considerable contribution to the changes in intra-seasonal temperature variance in East Asia. Copyright © 2004 Royal Meteorological Society.

KEY WORDS: East Asia; intra-seasonal variance; skewness coefficient; extremes; trend

1. INTRODUCTION

Global warming is a challenging subject in climate research (Houghton *et al*., 1990, 1996). Observations show that the global-mean surface air temperature has risen by 0.6 °C during the 20th century; much of the increase has occurred in the last three decades, most significantly in winter and spring over the Northern Hemisphere continents (Houghton *et al*., 2001). Many research investigations focusing on climate change have been based on monthly or seasonal mean-temperature data. However, it should be noted that global or nationwide averages disregard the spatial distribution of climatic change and its variability. In addition, such averaging also ignores the occurrence of high-frequency extreme events. For example, whereas there are often years with very similar monthly average temperature, the frequency of extremely hot or cold days and/or their magnitude might be vastly different. The variations of high-frequency extreme events in association with monthly-to-seasonal fluctuations exert a tremendous influence on the natural environment and human

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activity, thus attracting considerable attention (Katz and Brown, 1992; Karl *et al*., 1995; Houghton *et al*., 2001).

East Asia is a region showing strong temperature variability in terms of both high-frequency and long-term trends. Observations for China indicate that there are substantial long-term temperature rises with magnitudes comparable to the global mean (Wang and Gong, 2000; Wang *et al*., 2001). In addition to the secular trends in annual and seasonal mean-temperature, a great deal of attention has also been focused on the variability of daily extreme temperature events in recent years. Of particular importance are the frequent drastic temperature decreases over short-term weather time scales caused by winter monsoon cold surges manifested over China (Ding, 1994). The mean daily temperature drop would typically be 10 °C or even greater occurring within 1 or 2 days in northern China (Zhang and Lin, 1992). Some studies indicated that there are long-term changes evident in daily temperature variability. For example, Yan *et al*. (2001a,b, 2002) analysed the variability of temperatures based on daily mean data for approximately the last 100 years, although, owing to lack of data availability, their investigation is limited only to a couple of stations, such as Beijing and Shanghai. Zhai and Ren (1997) and Zhai *et al*. (1999) investigated extreme temperature events and found a significant reduction of cold days in northern China during the past several decades.

Given the significant warming over the Eurasian continent, a question has arisen as to whether the daily temperatures have become more variable or not over East Asia where the winter monsoon prevails. To address this problem, in the present study we analyse the variability of daily mean temperature, emphasizing the intra-seasonal variance and higher order moments for the period 1954–2000. Higher order moments of the statistical distribution of temperature are expected to be capable of providing more detailed information on the variability (e.g. Vinnikov and Robock, 2002). In the present study, apart from the second moment (standard deviation), we also analyse the third moment (skewness coefficient; e.g. Garreaud, 2001).

The season we are concerned about here is the winter months from November to March. Daily temperatures from 1 November to 31 March of the following year (non-leap years) or 30 March (leap years), a total of 151 days for each winter, are considered.

Data sets for 155 stations and the method for computing daily anomalies are presented in Section 2. We examine the changes in intra-seasonal variance and skewness coefficients in Sections 3 and 4 respectively. Analysis of the relationship between intra-seasonal temperature and high-frequency variation of atmospheric circulation is presented in Section 5. Section 6 summarizes the results.

2. DATA PREPARATION

2.1. Mean daily temperature

The mean daily temperature data for Chinese stations used here are derived from the China Meteorological Administration (CMA) observation archives. There are long-term records for several stations, such as Beijing and Shanghai, dating from the late 19th century. However, most areas of the country have insufficient observations prior to the 1950s, and the early data for these limited stations also contain inhomogeneities and uncertainties (Yan *et al*., 2001a,b). Modern nationwide networks of weather observing stations in mainland China have operated since the mid-1950s. Here, we select 150 stations with data available for the period 1 January 1954 through to 31 December 2001, for which less than 4 days' wintertime data are missing throughout the whole period.

Five Korean stations belonging to the Korea Meteorological Administration are also employed in this study. They are Daegu (35.88 °N, 128.62 °E), Jeonju (35.82 °N, 127.15 °E), Kwangju (35.17 °N, 126.88 °E), Pusan (35.1 °N, 129.03 °E), and Kangnung (37.75 °N, 128.9 °E). All missing daily temperature records are simply filled by the mean temperatures of the 10 neighbouring days (five before and five after the missing day).

Figure 1 shows the positions of these 155 stations. A large number of stations are located in the eastern regions (east of 100 °E) and a few in the west. A major feature of the winter mean temperature during the last few decades is the notable positive warming trend predominant at most stations. Taking all 155 stations as a whole, the trend is 0.34 °C per decade. The strongest warming occurs at the northern stations; averaging over stations north of 30 °N, the trend is 0.4 °C per decade; for those north of 40 °N the value increases to 0.5 °C

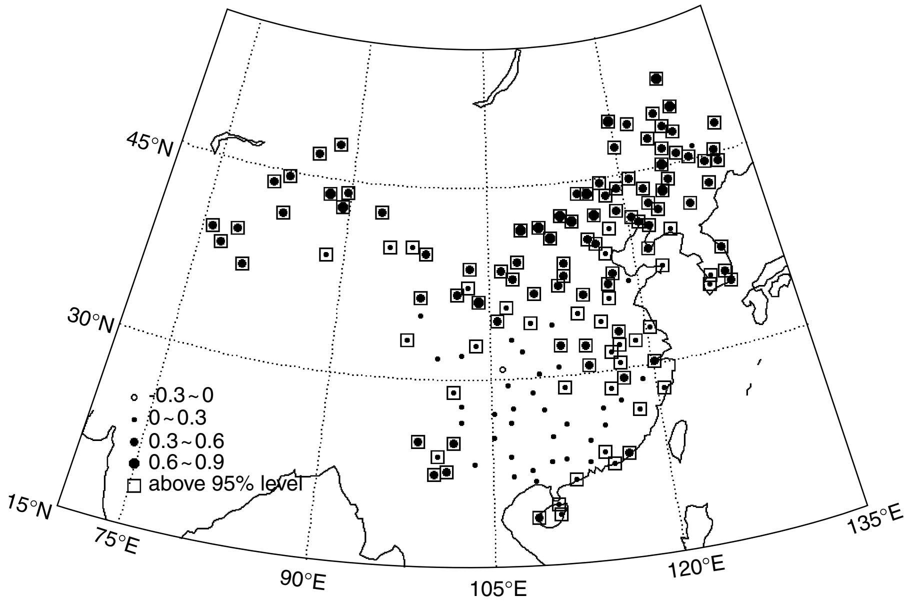

Figure 1. Linear trends of winter temperature (November through to March) for 155 stations, estimated using the ordinary least-squares method. The units are °C per decade. Stations where a linear trend is significant at the 95% confidence level are denoted as squares

per decade. These warming rates are all statistically significant above the 99% confidence level, supporting previous studies mentioned in Section 1 (e.g. Wang and Gong, 2000).

2.2. *Temperature anomaly*

To obtain the mean daily temperature anomaly T' we first removed the annual cycle from the observations. Some authors have derived the annual cycle by harmonic estimation (e.g. Epstein 1991). Taking Beijing station as an example, however, the results from the harmonic analysis do not match the annual course very well (see Figure 2). The values are a little higher than the raw data in winter and summer, but lower in autumn and spring; they show a slight phase lag in summer. Some researchers have used the simple mean average for the climatological base period as the normal course. We calculate the simple average of daily temperature for each of the 365 days for the period 1961 to 1990 (for simplicity we do not consider the value on 29 February for leap years). This 30 year mean does not remove the random noise satisfactorily either. Even using the entire period available for the station, the simple means do not show good smooth curves. Jones *et al*. (1999) used a centred 11-term binomial filter to eliminate the noise. Neverthless, the results still show considerable saw-toothed curve effects.

It is evident that the inter-annual variability of the mean daily temperature is frequently too large to be smoothed out by averaging the observations of the same calendar days for a base period. The means in the successive days are often very different. In order to overcome the above-mentioned drawbacks and to obtain a smooth curve for the annual cycle, here, we utilize running means as standard. Strong fluctuations in daily temperatures result from many weather systems. In the mid-latitudes, most weather systems have a lifetime shorter than 2 to 3 weeks. So, the running mean for calendar day d is obtained by averaging observations from $d - 10$ to $d + 10$ days for the entire period 1961–90, i.e. the mean is calculated based on 630 data points (30 years $\times$ 21 days = 630 days in total). Figure 2 compares the results of the different methods for Beijing. Clearly, the running means suppress the day-to-day fluctuations considerably and provide a reasonable annual cycle. In the present study, the annual cycles are estimated using the running means for each station. The value for 29 February in leap years is estimated by calculating the mean of 28 February and 1 March. Then, daily anomalies from the annual cycle are calculated for each station for the entire period.

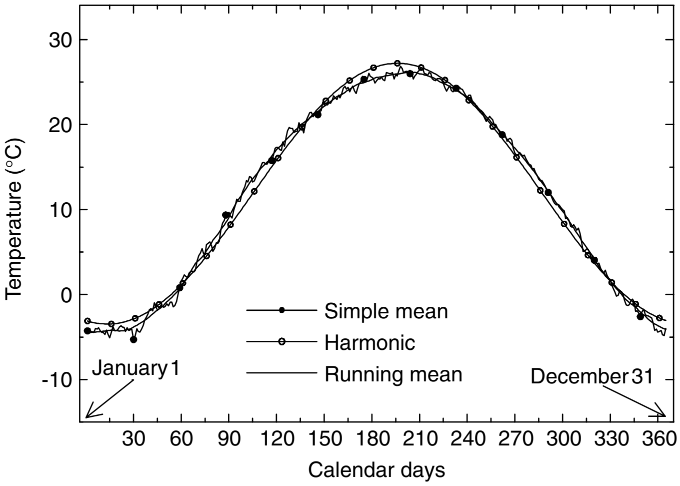

Figure 2. Comparison of temperature annual cycles resulting from different averaging methods for the period 1961–90. The 'simple mean' is calculated using the 30 years' worth of data for each calendar day. The 'running mean' is calculated using the adjacent 21 days (10 days before and 10 days after each calendar day are considered) for 30 years, i.e. the average of 630 days. The 'harmonic' is estimated based on the simple mean. Shown here is the example of Beijing (WMO No.54511)

3. CHANGES IN VARIANCE

3.1. Mean condition

The temperature variance σ_T^2 is defined as follows:

$$\sigma_T^2 = \frac{1}{n-1}\sum_{i=1}^{n}(x_i - \overline{x})^2$$

where x_i is the daily temperature anomaly on the ith day, $n = 151$ days, and $\overline{x}$ is the mean value of daily temperature anomalies averaged over 151 days for each winter. Since $\overline{x}$ is based on each winter season's record, the results mainly measure the intra-seasonal variability of the daily temperature anomalies.

Figure 3 shows the spatial distribution of the mean variance averaged over 1961–90. The highest values appear in high latitudes. Another region with high standard deviations is located over southern China. Between these two regions there are stations showing relatively weaker intra-seasonal variability. This kind of distribution is different from that of the inter-annual variability in winter. As many studies have indicated, on the inter-annual time scale, the variance generally decreases from the north to the south monotonically. The high intra-seasonal variability in northern East Asia might have been caused by the active mid-latitude weather systems, and the high standard deviation in southern China could have resulted from the influence of both mid-latitude and tropical weather systems. In addition, the mountainous environments in central China also tend to reduce the impact from both high and low latitudes, hence yielding a smaller variance.

3.2. Linear trends

We calculated the linear trend of the variance for each station. The results are shown in Figure 4. Generally, the trends are negative: 141 of the 155 stations are becoming less variable. Only 14 scattered stations show positive values. It should be noted that although less than 15% of the stations (24 stations) show robust trends significant at the 95% confidence level, the tendency toward small variance is predominant throughout the whole study area. The northern regions show a slightly stronger trend than the southern stations. Averaging over stations north of 30 °N, where the mean temperature warming is the strongest, yields a rate of change of

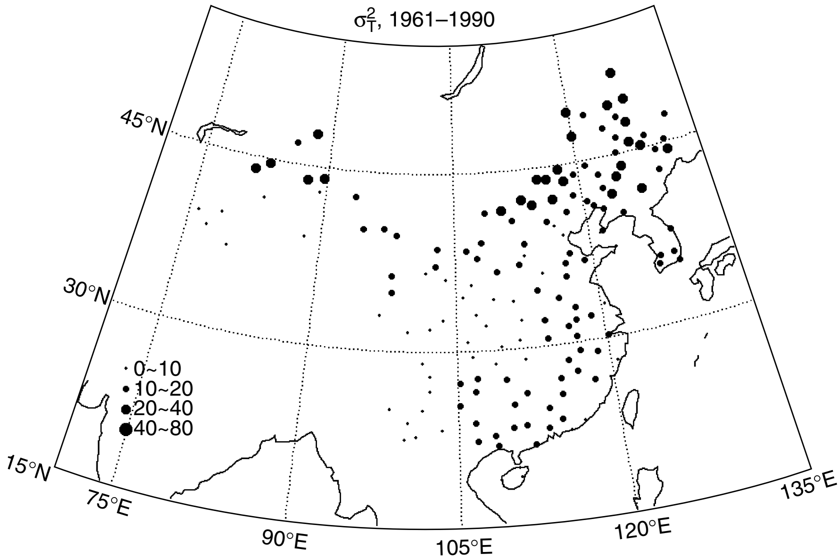

Figure 3. Mean intra-seasonal variance averaged for the period 1961/62–1990/91. The units are °C^2

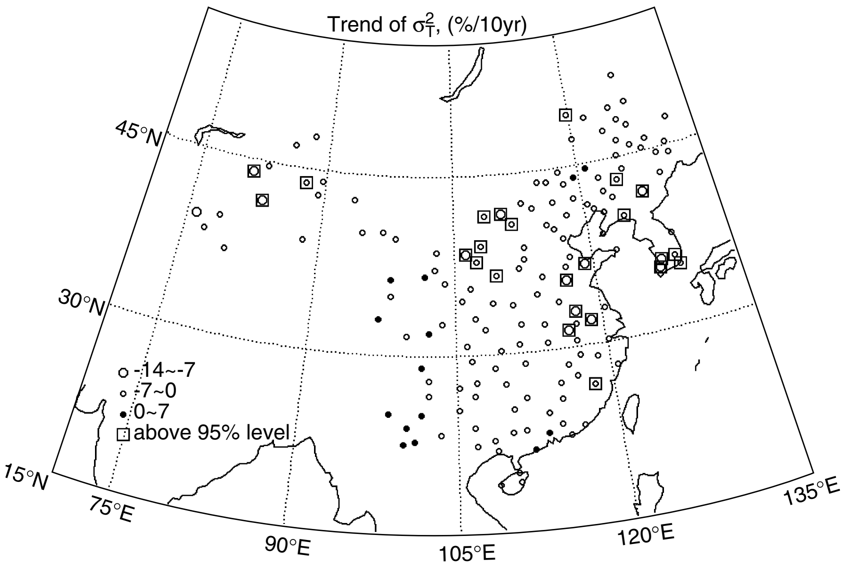

Figure 4. Linear trends of the intra-seasonal temperature variance. At each station, the σ^2_T is calculated for each winter, and then the trend is estimated for all 47 winters using linear regression. The units are percent per decade

$-0.58\,^\circ$C^2 per decade, equivalent to -3.85% per decade. For stations south of 30 °N the rate is $-0.27\,^\circ$C^2 per decade, i.e. -2.58% per decade, which is not significant. For the 155 stations taken as a whole, the variance trend is $-0.49\,^\circ$C^2 per decade, equivalent to -3.59% per decade, significant at the 90% confidence level.

This feature is, to some degree, similar to the spatial distribution of trends in mean temperature, except for the opposite sign. To check the existence of possible temporal relationships between the mean temperature and the variance during the last few decades, we investigated their variations on the basis of regional means time series. Here, we simply consider three cases: the first is the region north of 30 °N, where strong warming

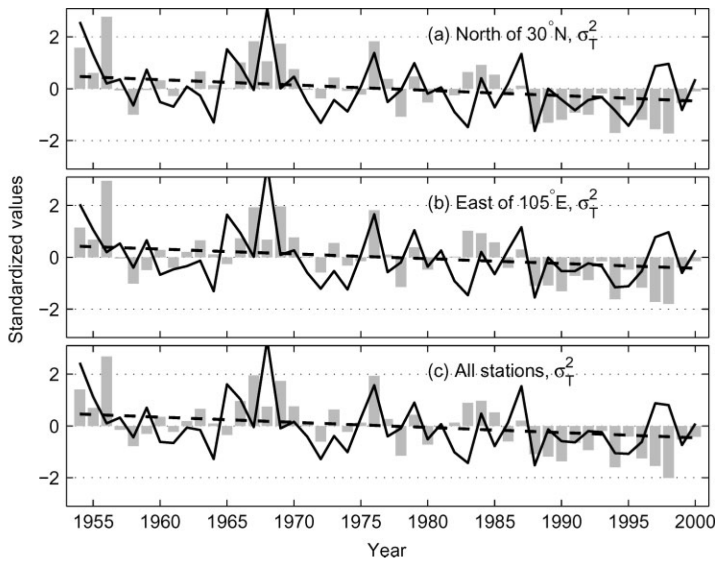

Figure 5. The intra-seasonal variance averaged for (a) 113 stations north of 30 °N, (b) 119 stations east of 105 °N, and (c) all 155 stations. Solid lines are for variance; dashed lines denote their linear trends. Shown in grey bars are the mean temperatures for the respective region. To facilitate comparison, all series are normalized. Temperature series are multiplied by −1

occurs; the second region covers the area east of 105 °E, where the climate is strongly influenced by the winter monsoon; the third includes all stations taken together as a whole. For each case, the regional mean temperature and variance are calculated and plotted as time series. As Figure 5 clearly displays, there are out-of-phase correlations between temperature means and the intra-seasonal variance. The correlations between them are −0.38, −0.28, −0.30 for each of the three cases respectively. Obviously, regions showing much stronger warming trends are generally the locations where a tendency toward weaker intra-seasonal variability is evident.

Thus, our results reveal that there is a substantial tendency toward weaker intra-seasonal variability in daily temperature anomalies in association with notable warming during the winter months. This implies that the winter weather might become more stable over East Asia in association with future climate warming.

3.3. High-frequency variance

Synoptic variability in wintertime over mid to high latitudes plays an important role in generating high-frequency variance. We examine the changes in synoptic variance (Figure 6(a)). Here, we consider only those components with a time scale shorter than 10 days. Daily temperature anomalies are high-pass filtered to remove the lower variations. On average the high-frequency synoptic variance accounts for about 30% of the total intra-seasonal variance in East Asia (Figure 6(b)). Trend analysis shows that the decrease of synoptic variance also dominates over most locations. Among the 155 stations, 146 show a tendency to smaller variance; only nine stations possess a contrasting drift. The trend for the whole region is $-0.17\,^{\circ}\mathrm{C}^2$ per decade, statistically significant at the 95% confidence level. This value is equal to −4.1% per decade, evidently stronger than the rate for the total variance. Even with the exclusion of the outlier of 1965, the trend is still as strong as $-0.13\,^{\circ}\mathrm{C}^2$ per decade, which is also significant. It is interesting to note that the ratio of synoptic variance to the total amount has not changed much during the last few decades. This indicates that the decrease in the synoptic variance makes a considerable contribution to the decrease in intra-seasonal variance.

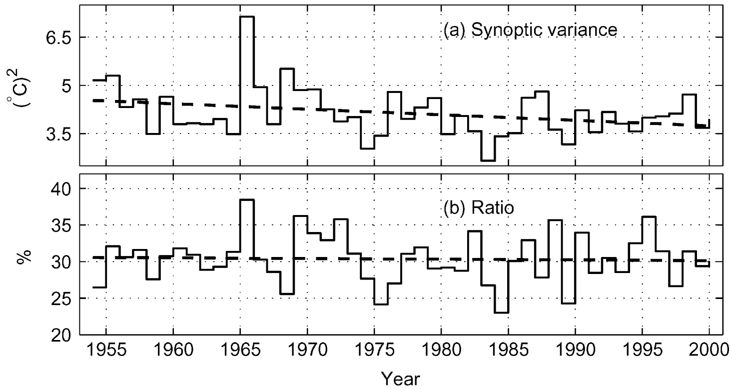

Figure 6. High-frequency variance (time scale ≤10 days) and their ratio with respect to the total intra-seasonal variance (%)

4. CHANGES IN SKEWNESS COEFFICIENT

4.1. Skewness coefficient

The skewness coefficient γ_T is defined as follows:

$$\gamma_T = \frac{1}{n-1} \frac{\sum_{i=1}^{n} (x_i - \overline{x})^3}{\sigma_T^3}$$

where σ_T is the sample standard deviation for 151 days, x_i is the daily temperature anomaly on the ith day, $n = 151$ days, and $\overline{x}$ is the mean for the 151 days. As seen in the formula, this parameter is the third moment of temperature distribution. All large deviations from the mean make a great contribution, since the deviation is cubed; therefore, the skewness coefficient provides, to some degree, a statistical measure for extreme events; a larger absolute value of the skewness coefficient indicates that there are stronger daily temperature anomalies and/or more frequent occurrences of them (Wilks, 1995). Since the σ_T and $\overline{x}$ used to estimate the skewness coefficient are based on each winter season's records, the results mainly measure the intra-seasonal variability of large or extreme daily temperature anomalies.

The mean condition of the skewness coefficients displays well-defined features (Figure 7). There are 73 positively skewed stations and 82 negatively skewed stations. The main negatively skewed region covers about 30 to 45 °N, including most of the northern plains and northwestern China. On the other hand, there are two positively skewed regions, one located in southern China and the other in northeastern China. This suggests that there are more frequent cold extreme events in the northern plains and northwestern section of China, whereas the other areas suffer less from extremely cold events in the context of daily temperature anomalies. The positively skewed values in northeastern and southern China might be due to small numbers of cold days during each winter season. These results are consistent with those of Zhang *et al.* (1997), who demonstrated that cold surges mainly influence the regions north of about 30 °N.

4.2. Linear trends

We calculated the linear trends of the skewness coefficients (Figure 8). Results show that negatively skewed trends occur at most stations. There are 106 stations displaying negative trends; the other 39 stations show positive trends. However, statistically significant trends are found for only a few stations. As shown in Figure 8, over a large part of the analysis domain, the trends show no spatially coherent pattern. Comparison of the linear trends in the skewness coefficient with those in mean temperatures shows that there are no comparable spatial features (Figure 1 versus Figure 8). The features differ much from each other. Generally

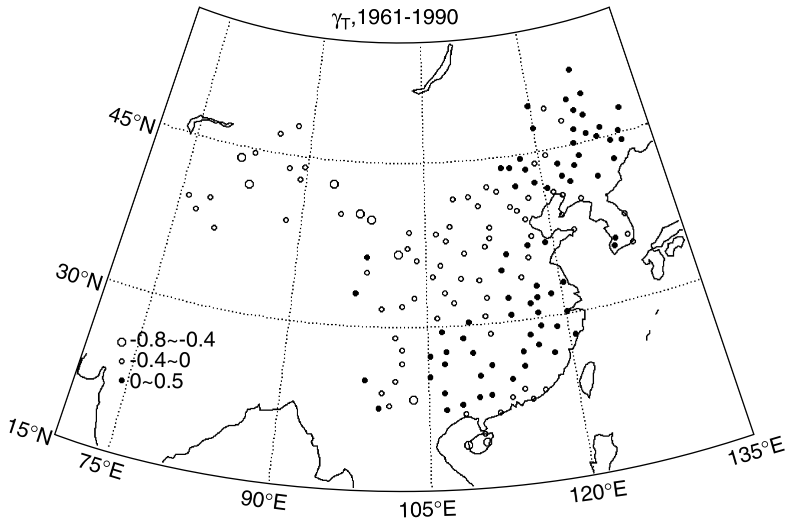

Figure 7. Mean skewness coefficients for the period 1961/62–1990/91

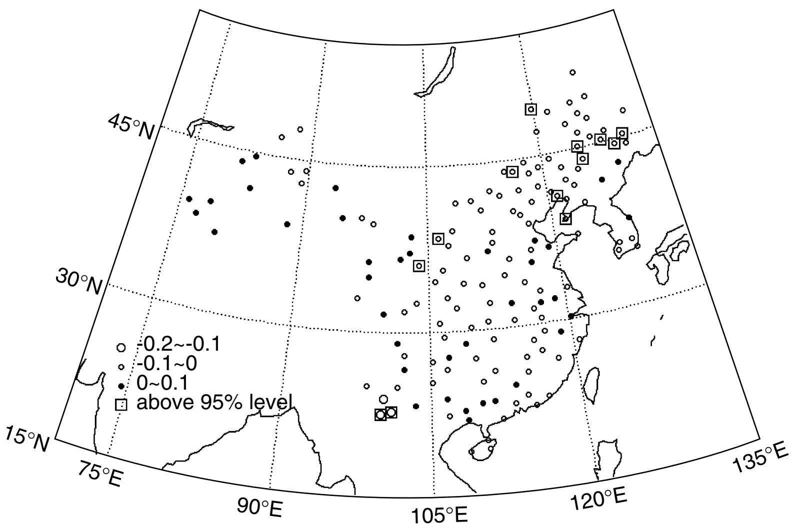

Figure 8. Linear trends of skewness coefficients. The units are reciprocal decades

speaking, the sensitivity of high-order intra-seasonal variability to mean temperature increases is not uniform over East Asia.

However, as can be seen in Figure 8, in the eastern area (east of about 105 °E), the negative values are apparently quite consistent. In particular, in northeastern China the signs of the changes show rather consistent features. Over this region (east of about 115 °E and north of about 40 °N), 36 of the 38 stations display negative trends, with only two stations located in Changbai Mountains exhibiting a positive trend. On average, there is a rate of change of −0.04 per decade, significant at the 90% confidence level. This rate of change is much more rapid and more significant than that of the entire region. Averaged over all 155 stations, the rate of change is −0.02 per decade; for southern stations, east of 105 °E, it is −0.017 per decade; neither are significant. This indicates that there is an obvious tendency toward more numerous and/or stronger cold events in northeastern China.

4.3. Relation to extremes

From Section 4.2 we know that the variance is becoming smaller at most stations. Such a decrease in the variance is stronger and more significant in the northeastern section of the analysis domain than the other regions. According to a commonly held notion concerning the relationship between the variance and climate extremes, a smaller variance should be accompanied by a decrease in the frequency of cold temperature extremes (Katz and Brown, 1992; Houghton *et al*., 2001). However, the skewness coefficients in the northeastern stations show an evident tendency towards negative values, which implies that more cold extremes have been experienced, instead of a lower level of occurrence. This contradicts the understanding above.

In order to confirm this conclusion, we determined the frequencies of extreme daily temperature anomalies. Here, we define high and low extremes as those days with anomalies in excess of 2σ and below -2σ respectively. The counting is made locally and the standard deviation σ is defined for each given year. Then, all stations in the northeastern section of the study area are averaged to yield the regional mean time series. Both cold- and high-temperature extremes are shown in Figure 9 for comparison. The trend for the number of extremely high temperature anomalies is -0.19 days per decade, significant above the 90% confidence level. The trend for events with $T' < -2\sigma$ is much stronger than for high extremes, with a rate of change of $+0.26$ days per decade, statistically significant at the 95% confidence level. Clearly, the long-term changes in the frequencies of extremes support the above negative tendency in skewness coefficients. A further investigation shows that the changes in extremes have resulted from the changes in probability density functions (PDFs). One might infer that there would be a PDF shift to the negative anomaly side, since the cold extremes are becoming more frequent and the high-temperature anomalies are becoming less so. That inference is incorrect, as our results demonstrate. Figure 10 presents the PDF changes in two comparison periods from 1959–66 and 1989–94. The former period consists of consecutive years of low frequencies of cold extremes, and the latter period has high frequencies (see Figure 9). Prior to the analysis the daily temperature anomalies were normalized with respect to each winter period. PDFs are calculated locally in the form of relative frequency (in percent). Figure 10 shows the regional means. On the left-hand side, the frequency of $-2\sigma < T' < 0$ events has evidently decreased. But interestingly, the frequency of $T' < -2\sigma$ events has increased. On the far right-hand side, the frequency of high-temperature anomalies shows a very small decrease. These findings agree well with the rise in the number of cold extreme days and the considerable decreases in skewness coefficients. The change in the frequency distribution of daily temperature anomalies plays an important role in determining the features of intra-seasonal high-order moments and extremes.

It should be mentioned that the drastic day-to-day temperature falls are often caused by cold surges. The present analysis shows that there is a general decrease in skewness coefficients over East Asia, implying a tendency to a more common occurrence of cold extremes. However, it may be inappropriate to infer that there should be more cold surges or surges with stronger magnitude. There are a variety of definitions of

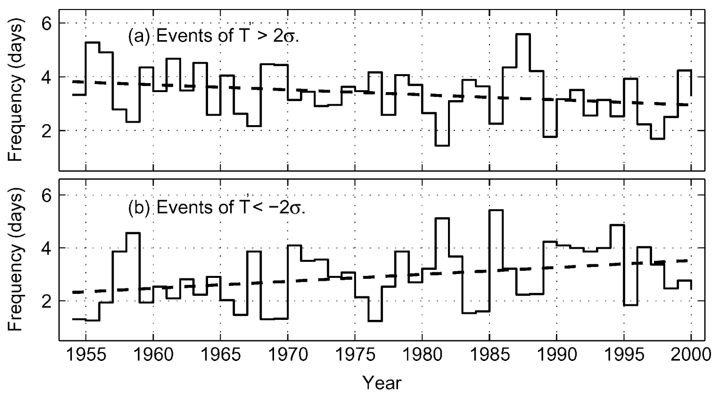

Figure 9. Frequencies of extremely high (upper panel) and low (lower panel) daily temperature anomalies in the northeastern section of the analysis domain (north of 40 °N and east of 110 °E)

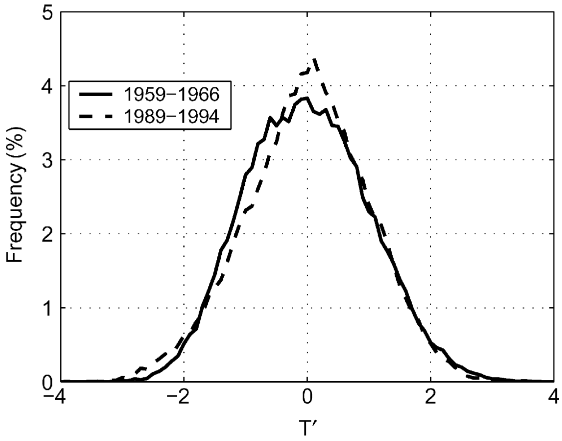

Figure 10. Histogram of daily temperature anomalies between the two periods 1959–66 and 1989–94. Temperature anomalies have been normalized with respect to each given winter

cold surges. A widely accepted definition used in routine daily weather forecasts was produced by the CMA, in which cold surges are defined by the magnitude of temperature drops, wind speed, and the absolute low temperature (Zhang and Lin, 1992). Some other definitions are also suggested, based on temperature, surface anticyclone activity, synoptic conditions, or a combination of these (e.g. Wu and Chan, 1995; Zhai *et al.*, 1999; Zhang and Chen, 1999). Evidently, the CMA definition is related to day-to-day temperature changes as well as the long-term variation of absolute temperatures. The significant warming trend on the annual to decadal time scales may result in the decreased absolute low temperatures. That will make the standard of a cold surge more difficult to meet, yielding a decrease in the cold surge frequency, as well as their magnitude (Zhai *et al.*, 1999; Yan and Yang, 2000). In the present study, we analysed only intra-seasonal variations; a modest increase in cold anomaly frequency does not necessarily mean a simultaneous rise in cold surge occurrence. The relationship with cold surges needs further analysis, which is, however, beyond the scope of the present study.

5. ATMOSPHERIC CIRCULATION ASSOCIATED WITH THE CHANGING VARIANCE

5.1. Siberian high

The East Asian winter monsoon dominates the surface climate in the cold seasons over East Asia. The variations of monthly to seasonal mean temperature are strongly controlled by the monsoon systems; a strong seasonal Siberian high accompanies a cold winter over East Asia (Ding, 1994; Gong and Ho, 2002). There have been significant weakening trends in sea-level pressure over the middle–high continent of Eurasia, the Arctic Ocean and the surrounding regions during the last several decades (Walsh *et al.*, 1996; Serreze *et al.*, 1997). This has made a large contribution to the recent warming (Gong and Ho, 2002). On the intra-seasonal time scale, the day-to-day activity of a cold air mass from the interior continent often brings a drastic temperature change in regions where the cold air mass passes (Ding, 1990). However, a lower monthly–seasonal mean state of the Siberian high does not necessarily mean there is weaker day-to-day cold air mass activity and smaller temperature variance. In order to understand the changes in temperature variance better, we investigate the changes in intra-seasonal variance of the Siberian high.

We utilize daily sea-level pressure data taken from the National Centers for Environmental Prediction–National Center for Atmospheric Research reanalysis (Kalnay *et al.*, 1996). Daily pressure anomalies with respect to the mean of 1961/62–1990/91 are obtained by applying the same method as for daily temperature anomalies. The variance of pressure anomalies σ_P^2 is calculated for each given winter at each grid. This is a measurement of the intra-seasonal variability of the near-surface atmospheric circulation.

To check whether there is large-scale spatial structure, we first performed empirical orthogonal function (EOF) analysis based on the covariance matrix of σ_P^2. Here, the analysis domain is confined to the region of 70–150 °E and 15–65 °N. The leading EOF explains 48.5% of the total variance and is significant at the 95% confidence level when applied to the North *et al.* (1982) criteria among all EOFs. Interestingly, this mode shows a well-defined monopole structure (Figure 11). There is an overall single sign with a centre located in northwestern Mongolia; a contour line stretches southward to southern China along the east flank of the Tibetan Plateau. This pattern strongly suggests that the origin of intra-seasonal variance lies in the sea-level pressure in East Asia; the intra-seasonal variance in the Siberian high exerts a strong influence on high-frequency pressure variance over East Asia.

We then investigated the temporal features in the pressure variance. To focus on the Siberian high, we chose the central region of 45–55 °N and 90–110 °E in order to construct the time series of sea-level pressure, including the mean and variance. This is a measurement of the variance of the Siberian high and we refer to it as σ_{SH}^2 hereafter (Figure 12). There is a strong trend in σ_{SH}^2 with a value of −10.7% per decade, significant at the 99% confidence level. This agrees fairly well with the weakening temperature variance, too. It supports the above notion that the high-frequency variations, instead of the means, of the Siberian high play an essential role in the change of intra-seasonal temperature variance.

For comparison, we also calculated the mean sea-level pressure over the centre, representing the strength of the Siberian high ($\overline{P}_{SH}$). Correlation results show that the temperature variance in East Asia is strongly influenced by the variance of the Siberian high (Table I). The correlation coefficient between σ_{SH}^2 and σ_T^2 for the whole study area is as high as 0.66, significant at the 99% significant level. For the northern and eastern

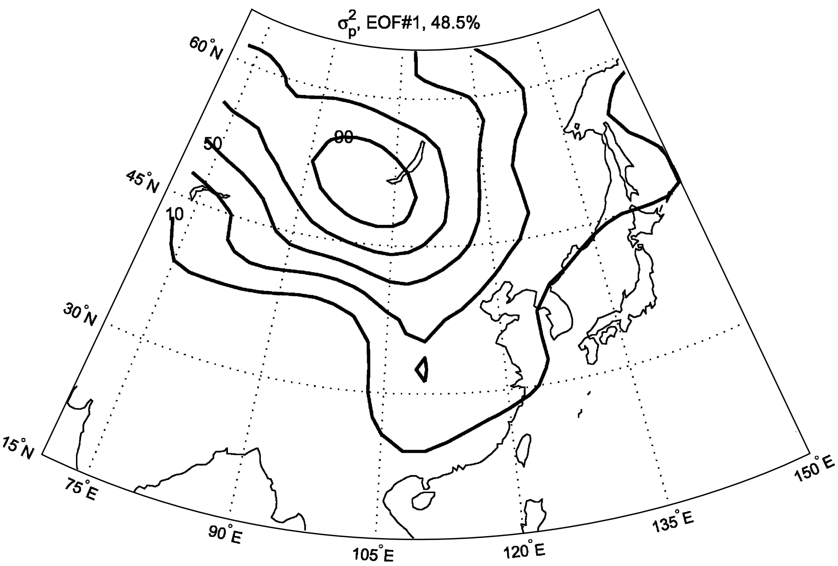

Figure 11. EOF1 of intra-seasonal variance of sea-level pressure based on daily sea-level pressure anomalies. The units are arbitrary

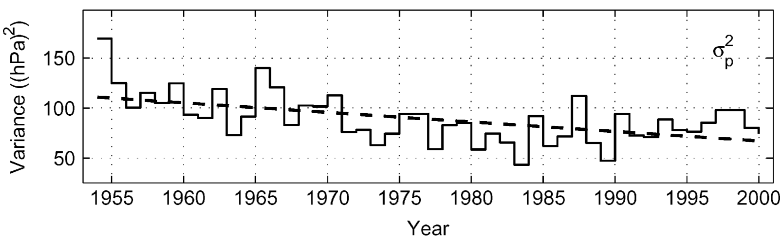

Figure 12. Intra-seasonal variance of the Siberian high (σ_{SH}^2) averaged over the region 45–55 °N and 90–110 °E

Table I. Correlation between atmospheric circulation indices and temperature time series for different regions

	Variance of temperature			Mean temperature		
	North of 30 °N	East of 105 °E	All stations	North of 30 °N	East of 105 °E	All stations
σ^2_{SH}	0.68**	0.62**	0.66**	−0.30*	−0.21	−0.25
$\overline{P}_{SH}$	0.14	−0.11	0.13	−0.30*	−0.31*	−0.32*
σ^2_{AO}	0.31*	0.39**	0.34*	−0.12	−0.08	−0.10
$\overline{AO}$	−0.47**	−0.46**	−0.46**	0.46**	0.42**	0.41**

* Significant at the 95% confidence level.
** Significant at the 99% confidence level.

sections of the domain, the situations are nearly the same. In contrast to this finding, the influence of σ^2_{SH} on the mean temperature is much weaker. Only the northern part correlates with σ^2_{SH} significantly. For all stations as a whole, there is no significant relationship. Similarly, the $\overline{P}_{SH}$ influences the mean temperatures significantly, while showing no evident relation to the temperature variance.

5.2. *Arctic oscillation*

In addition to the Siberian high at the surface, there are a variety of factors that influence surface temperature in East Asia, including, for example, the middle troposphere circulation (Lau and Li, 1984; Wu and Chan, 1997; Yin, 1999) and the planetary-scale North Atlantic oscillation (NAO)/Arctic oscillation (AO) (Wu and Huang, 1999; Gong *et al*., 2001; Wu and Wang, 2002). On the basis of the monthly-to-annual mean, there is a tight connection between NAO/AO and East Asian climate. A strong positive phase of the NAO/AO is associated with a weaker Siberian high and weaker winter monsoon. In addition, Thompson and Wallace (2001) reported that the AO exerts a strong influence on the high-frequency components near the surface, including the extremely cold events over the Northern Hemisphere. Some studies found a clear connection between weather regimes and the preceding variations in the north polar vortex (Baldwin and Dunkerton, 2001; Thompson *et al*., 2002). Some studies also found a tight connection between the AO and regional temperature variance and extremes in North America (Higgins *et al*., 2002; Wettstein and Mearns, 2002).

In spite of these findings concerning the AO–climate anomaly connection, it still needs to be clarified whether the AO variance or the AO mean condition relate to the changes in high-frequency variance of surface daily temperature in East Asia. We utilized the daily AO data to unravel this problem. Based on the daily AO time index (Thompson and Wallace, 2000), its winter mean ($\overline{AO}$) and intra-seasonal variance (σ^2_{AO}) are derived. Correlations indicate that σ^2_{AO} do significantly impact the temperature variance in East Asia, whereas no clear evidence of the influence on the mean temperatures is found. It is interesting to note that the state of $\overline{AO}$ significantly correlates to both temperature variance and temperature means (Table I). The good agreement in mean AO and temperature supports the previous findings concerning the AO–winter monsoon climate connection (Gong *et al*., 2001; Wu and Wang, 2002). Furthermore, the remarkable correlation between $\overline{AO}$ and σ^2_T provides a new perspective for understanding surface temperature variance and extremes in East Asia. One possible reason for this relation might be due to the AO itself altering σ^2_{AO}. However, our investigation suggests that this mechanism is not apparent. Though σ^2_{AO} generally tends to be smaller during the high-positive $\overline{AO}$ years, the change in σ^2_{AO} is not significant. The correlation between σ^2_{AO} and $\overline{AO}$ is −0.24. The second reason involves the Siberian high. The mean condition of the AO can influence not only the mean pressure in the lower troposphere, but also its variance. The $\overline{AO}$ is correlated with σ^2_{SH} at a rather high value of −0.45, significant at the 99% confidence level. A stronger positive phase of AO tends to generate a much smaller intra-seasonal variance in the Siberian high. Clearly, the background of hemispheric atmospheric circulation indicated by $\overline{AO}$ significantly modulates the high-frequency components of the surface pressure system and their variance. This mechanism may be the primary cause. The strong decreasing trend of σ_{SH}^2 should be, to a considerable degree, related to the increasing mean AO conditions during the last few decades.

6. SUMMARY

Intra-seasonal variability is often directly connected to extreme weather events. The changes in variability of daily temperature in the warming climate are of particular interest. We examined the intra-seasonal variability in daily temperatures over East Asia. The results are summarized as follows.

In association with the significant warming, the intra-seasonal variance is generally weakening. For all 155 stations as a whole, the variance trend is $-0.49\,^{\circ}C^2$ per decade (equivalent to -3.59% per decade, significant at the 90% confidence level). The decreasing trends are more robust in the northern regions of East Asia, particularly north of $40\,^{\circ}$N. This implies that in the future warming climate the winter weather might become more stable in East Asia.

The linear trends of the skewness coefficients experience a slight, general tendency toward negative values. But only a few scattered stations satisfy significance limits. In the northeastern section of the study area the negative trends display evident spatial consistency. The mean time series shows a considerable trend of -0.04 per decade, significant at the 90% confidence level. This is supported by the increasing frequency of extremely low daily temperature anomalies. The trend for events with $T' < -2\sigma$ is $+0.26$ days per decade, statistically significant at the 95% confidence level. The PDF for daily temperature anomalies has changed, causing corresponding changes in skewness coefficients and extremes.

The Siberian high and AO play essential roles in the variation of intra-seasonal temperature variance. Temperature variance in East Asia is strongly influenced by the variance of the Siberian high. The correlation coefficient between σ_{SH}^2 and σ_T^2 for the whole study area is as high as 0.66, which is significant above the 99% significance level. There is also a significant (at the 99% level) trend in σ_{SH}^2, with a value of -10.7% per decade. The mean and variance of AO both exert a significant influence on σ_T^2. The background of hemispheric atmospheric circulation indicated by $\overline{AO}$ modulates the high-frequency components of the Siberian high (with a correlation of -0.45 between them). Therefore, the increasing trend in AO in the last few decades could explain a considerable part of the decrease in σ_{SH}^2 and σ_T^2.

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