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The Siberian High and climate change over middle to high latitude Asia

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With 7 Figures

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Summary

The Siberian High is the most important atmospheric centre of action in Eurasia during the winter months. Here its variability and relationship with temperature and precipitation is investigated for the period 1922 to 2000. The pronounced weakening of the Siberian High during the last ~20 years is its most remarkable feature. Mean temperature, averaged over middle to high latitude Asia (30° E–140° E, 30° N–70° N), is correlated with the Siberian High central intensity (SHCI) with correlation coefficient of −0.58 (1922–1999), and for precipitation, the correlation coefficient is −0.44 (1922–1998). Taking the Arctic Oscillation (AO), the SHCI, the Eurasian teleconnection pattern (EU), and the Southern Oscillation (SO) index into account, 72 percent of the variance in temperature can be explained for the period 1949–1997 (for precipitation the variance is 26 percent), with the AO alone explaining 30 percent of the variance, and the Siberian High contributing 24 percent. The precipitation variance explained by the Siberian High is only 9.8 percent of the total.

1. Introduction

Global average temperature has risen over the past hundred years by about 0.5 °C (Jones et al., 1986; Jones, 1994). However, this increase has not been steady over time and has not been spatially uniform (IPCC, 1996). It is estimated that the global mean temperature rose by 0.25 °C to 0.4 °C during the past 20 years. The warming is most predominant in winter, and over the Northern Hemisphere, there are some regions showing dramatic changes. For example, Canada and Siberia have warmed much more rapidly (Hansen et al., 1999) than the average.

The association between the atmosphere and the surface temperature has attracted much attention. In particular, the role of large-scale atmospheric circulation has received much attention in the existing literature. For example, Hurrell (1995, 1996) indicated that the warming across Eurasia since the mid-1970s results mainly from the changes in the Northern Atlantic Oscillation (NAO). Some other atmospheric circulation systems such as SO and North Pacific Low also show their influence on the climate of the Eurasian continent (Hurrell and van Loon, 1997). The AO is also strongly coupled with surface air temperature fluctuations (Thompson and Wallace, 1998; Thompson et al., 2000). Some mid-high climate associations with the AO have been reported (Kerr, 1999). The AO accounts for more than half of the surface air temperature trends over Alaska, the eastern Arctic Ocean and Eurasia during the past two decades (Rigor et al., 2000).

Although the Siberian High is the dominant atmospheric circulation system in the lower

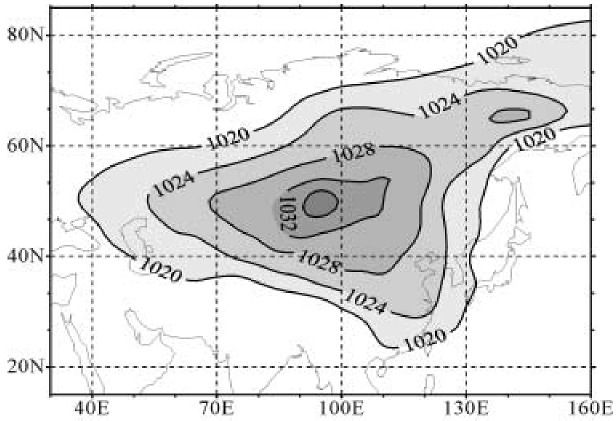

Fig. 1. Winter (January, February and March) sea level pressure climatology. Reference period is 1961–1990. Only pressures exceeding 1020 hPa are shown. Data are taken from National Center for Atmospheric Research (Trenberth and Paolino, 1980). It is evident that the strong Siberian High controls almost entire mid-high continental Asia

troposphere which controls almost the whole of continental Asia (Fig. 1), it has attracted much less attention. Whereas, there is evidence showing the Siberian High also exerts a powerful influence on climate over middle to high latitude Eurasia (Gong and Wang, 1999; Guo, 1996; Zhu et al., 1997; Miyazaki et al., 1999; Yin, 1999). To gain a better understanding of the recent dramatic climate changes over the largest continent, we will investigate the variability of the Siberian High and its relationship with the surface climate change in the winter season (January–March).

The data used in this study are described in Section 2. The variability of the Siberian High is analyzed in Section 3. The relationship of the Siberian High with temperature and precipitation is demonstrated in Section 4. Co-variability of the Siberian High with other atmospheric circulation systems is discussed in Section 5.

2. Data

Two gridded pressure data sets are used in this study. The primary sea level pressure (SLP) data are obtained from the Data Support Section at National Center for Atmospheric Research (NCAR) (Trenberth and Paolino, 1980). These data are gridded at 5°latitude by 5°longitude meshes, and cover 102 years (1899–2000). Another SLP data sets, obtained from the Climatic Research Unit (CRU) of the University of East Anglia, is also used for comparison (Jones, 1987; Basnett and Parker, 1997). This CRU pressure data are on 5°latitude by 10°longitude meshes and available for the period 1873–1995. Surface temperature and precipitation data sets used are also from the CRU. Both the monthly temperature and land precipitation data are archived in 5°latitude by 5°longitude grids. Surface temperature covers the period 1856–2000 (Jones, 1994; Parker et al., 1995). The precipitation period of record is from 1900 to 1998 (Hulme, 1992). Because the data coverage and availability during the early periods is relatively poor, only post-1922 periods are analyzed in this study to give reliable results. Only regions with more than 95% temperature and precipitation data coverage are used for the analysis.

3. Variability of the Siberian High

3.1 Siberian High central intensity

Figure 1 shows the climatological means of SLP during the winter (JFM) over Asia. The most pronounced feature is that the surface circulation is dominated by the huge atmospheric center of action, the Siberian High. This strong anticyclone circulation system, centered over the interior of the continent, controls almost the entire region of continental Asia. A quantitative index of the Siberian High central intensity is defined as the regional mean SLP averaged over the 70° E–120° E and 40° N–60° N to measure the strength of Siberian High. This rectangular area generally covers the central regions of the anticyclone, where the pressure is generally greater than 1028 hPa.

Based on the NCAR SLP data sets, the Siberian High central intensity is established for the period 1922–2000. However, there are some data that are not available for several years. The total numbers of data are 165 for each JFM (3 months $\times$ 5 grids in latitude $\times$ 11 grids in longitude $= 165$). Before 1922 data availability is low in some years. Although the observations have increased significantly since 1922, there are still missing data in 5 years. Only one point has been missed in 1931 and 1957. There are 9 and 2 grids without data in 1945 and 1967, respectively. Due to World War Two, there are 73 data points missing in 1939. In general, the grid numbers without

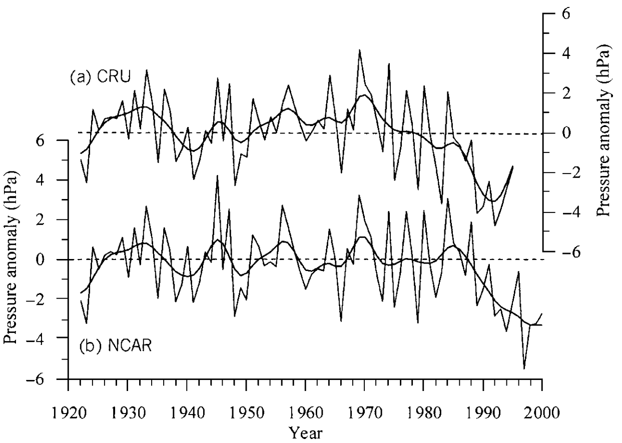

Fig. 2. Time series of Siberian High central intensity, defined as the regional mean SLP averaged over 70° E to 120° E, 40° N to 60° N for the months January–March beginning in 1922. Shown are anomalies with respect to 1961–90. The upper curve is computed using the data sets obtained from Climatic Research Unit (CRU) of University of East Anglia, U.K., and the data for the lower curve are obtained from National Center for Atmospheric Research (NCAR). Two curves correlated at 0.88 during the 74 winters from 1922 to 1995. Smooth lines represent results from a 9-point low-pass filter

data are few and the missing data are assumed to have small effects on the regional SLP means over such a large area as defined in this study. Thus no interpolation was carried out to fill the gaps.

Figure 2 shows the time series of the Siberian High central intensity. This NCAR series is compared to the index inferred from the CRU SLP data sets. The CRU series is established using the same method. From 1922 to 1995, there is only one year with missing data, in 1939 (28 out of 90 points are not available). The means and standard deviations for these two indices are slightly different due to the different data sources and the different spatial resolutions. Means for CRU and NCAR data sets are 1027.98 hPa and 1025.59 hPa, respectively. The standard deviation for NCAR data sets is 1.77 hPa, which is lower than for the CRU records (2.1 hPa). However, as shown in Fig. 2, the two Siberian High central intensity indices agree very well. The correlation coefficient between the two SHCIs is +0.88 (for the period 1922–1995). Thus, these Siberian High central intensity indices are both reliable and representative for describing the interannual variations of the Siberian High.

3.2 Trend analysis

In addition to a large amount of interannual variability there have been several periods when the Siberian High persisted in strong or weak states over many years. Some previous studies that measured the Siberian High in slightly different forms have shown that interdecadal scale periods in the order of 30–40 years have been predominant as was demonstrated by power spectrum analysis the hundred-year record (e.g. Gong and Wang, 1999). During the past one hundred years, the Siberian High was strong during the 1960s, and very weak in the late 1980s and the early 1990s (e.g. Wang, 1963; Gong and Wang, 1999). However, no similar low frequencies are found to exceed the 95% confidence limit for both the NCAR and CRU series. This may be due to the short length of records used in this study.

Let us now examine the time series of the SHCI in more detail. Striking features are the low values during the period from the early 1980s and the entire 1990s, and the relatively high values in the 1960s. The low-frequent variations are more evident in the CRU series (Fig. 2). Looking at Fig. 2, there are differences between the NCAR and CRU data during the 1970s. The pronounced weakening trend begins in early 1970s in the CRU series, but there is no clear trend in NCAR series during the same period. This may result from possible inhomogenities in the historical SLP records. However, the continual decreases are dominant since the early 1980s in both series.

Comparison of CRU and NCAR data sets would be helpful to reduce the uncertainty. Table 1 presents linear trends during different periods. From 1922 to the mid-1970s, there are slight positive trends, but these are not

Table 1. Trends in Siberian High for the different periods (in hPa per decade). Values with ** are significant at the 99% confidence level, those with * at 95%

	NCAR	CRU
1976–1995	−1.57*	−2.15**
1976–2000	−1.78**	
1922–1995	−0.09	−0.28**
1922–2000	−0.21*	
1922–1975	+0.07	+0.16

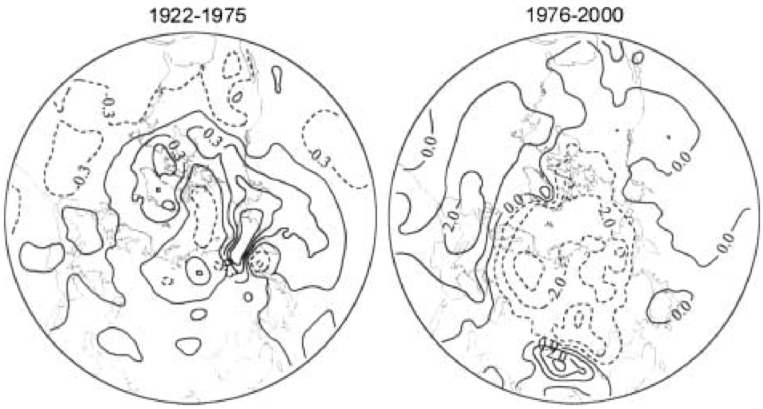

Fig. 3. Trends in SLP for winter (JFM) during two periods of 1922–1975 and 1976–2000. In hPa per decade. NCAR SLP data sets

significant. In contrast, striking downward trends are most remarkable during the past ~ 20 years. Linear trend for the NCAR series is -1.78 hPa/decade from 1976 to 2000, for the CRU series the trend is -2.15 hPa/decade from 1976 to 1995, both statistically significant at 95% confidence level. The somewhat stronger trends in the CRU series may be due to the greater standard deviation. It is apparent that the trends would change substantially if periods prior to mid-1970s are included. However, it is clear that the Siberian High central intensities are markedly weakening from the late 1970s to the 1990s, as displayed by both data sets.

As shown in Fig. 3, there are evident shifts in the large scale SLP. Recently, about two decades of pressure decreases occurred over the middle to high latitude Asia and the Arctic Ocean. Trends over most of these regions are about -2.0 hPa/decade or even stronger. However, strong upward trends appear over western and southern Europe, and areas with $+1$ hPa/decade or higher values extend across the Atlantic to eastern America. There is another center with trends exceeding $+2.0$ hPa/decade over Tibet (covering a relatively small area), but, this may be an artifact due to the high altitude of the Tibetan Plateau. These results are generally in agreement with the previous results. Composite analysis from other data sources, and over slightly different periods, showed the large pressure reduction over the central Arctic Ocean during the early 1980s to early 1990s, compared to the previous decade (Walsh et al., 1996; Serreze et al., 1997). The main difference here is that our results show that even broader regions display the tendency for the decrease in SLP. The changes over the Arctic Ocean are only a relatively small part of the large-scale SLP decrease. Associated climate and environmental changes in northern high-latitudes are profound (Serreze et al., 2000).

Some other atmospheric system indices of northern mid-high latitudes, such as the NAO and/or AO (Hurrell and van Loon, 1997; Thompson and Wallace, 2000), also manifest this systematic shift in SLP. The variations in the NAO/AO index and the SHCI index show some similar features, for example, since the middle of the 1970s the generally positive phase for NAO/AO and the negative state of the Siberian High produce significant correlation coefficients, however, there are also differences, as seen in Fig. 3. The trend in SLP over Iceland is slight, the strengthening of the NAO is mainly attributed to the increase in SLP over the middle Atlantic region. Whereas the recent decrease in the SHCI indices are primarily related to the reduction of pressure over the middle to high latitude Asia and the Arctic Ocean.

Of course, there are possibilities that the Siberian High can be impacted by the planetary AO via a non-direct, dynamic process. Gong et al. (2001) reported that there is a significant out-of-phase relationship between the AO and Siberian High intensity. The correlation coefficient between these two indices is -0.48 for the period 1958–98 (December, January and February). It was found that the negative phase of the AO is concurrent with a stronger East Asian Trough and an anomalous anticyclonic flow over the Urals in the middle troposphere (500 hPa). This anomalous circulation pattern could bring stronger northwesterlies and may enhance the upper-level air flow convergence in the rear of the trough. This would imply that a weaker AO might dynamically strengthen the Siberian High, and vice versa.

4. Relationship between the Siberian High and climate variability

4.1 Relationships with temperature

Some previous studies have found that almost half of the wintertime (December–March) temperature variance over the mid-high northern hemisphere could be explained by the NAO and SO (Hurrell, 1996). In addition to these atmospheric systems, which are somewhat distant from the Eurasian continent, we demonstrate that there is also very strong coupling between the local Siberian High and the surface temperature and precipitation across the Asian continent.

Surface temperature anomalies over Eurasia were regressed with the SHCI for DJM from 1922 to 1999. As displayed in Fig. 4, there are strong tendencies for cold conditions over most of the Eurasian continent associated with the strengthened Siberian High. Corresponding to one standard deviation stronger SHCI, temperature would decrease by 0.3 °C or even more, from western Siberia to far eastern Asia. The centre of cooling with values lower than −1.5 °C appears in the interior of the continent, and is virtually identical to the location of the centre of the Siberian High (see Fig. 1). Except for some small regions such as India and Middle Asia, almost

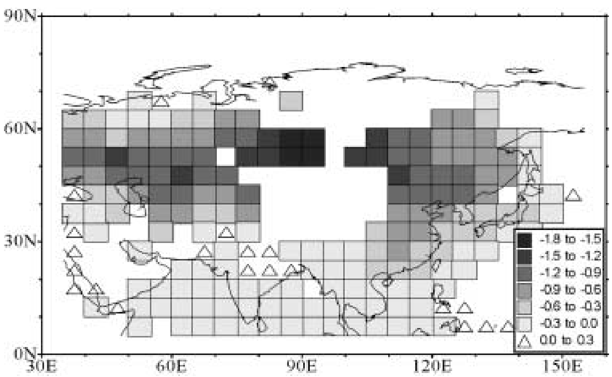

Fig. 4. Changes in temperatures (°C) corresponding to one standard deviation of the Siberian High central intensity index (NCAR series), computed over the JFM from 1922 through 1999. Regions of insufficient data are blank

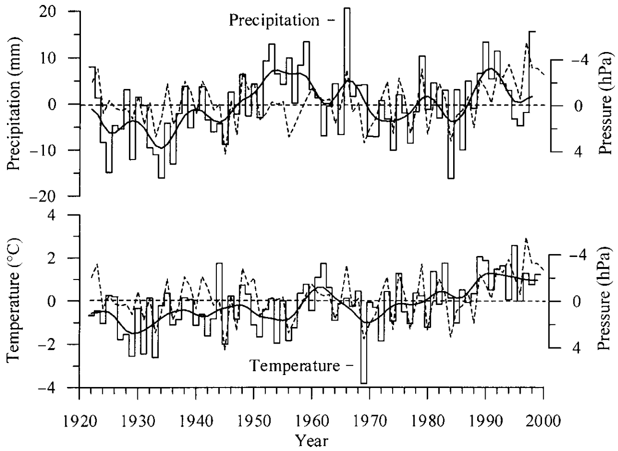

Fig. 5. JFM time series of averaged precipitation (upper panel, in solid line) and temperature (lower panel, in solid line) anomalies over middle to high latitude Asia, compared to SHCI anomalies (shown as dashed lines, the axes for pressure curves are inverted)

the entire middle to high latitude Asia shows a remarkable cooling (warming) tendency relating to the strengthening (weakening) of the Siberian High. The lower panel of Fig. 5 also presents the variations in mean temperatures averaged over middle to high latitude Asia (30° E–140° E, 30° N–70° N). Obviously, the Siberian High and average temperature anomalies demonstrate very similar variations. The time series of temperature closely resembles the pressure series, the similarity is evident not only in the year-to-year variations but also in the secular trends. The two curves correlate at −0.58. This suggests that 33.6% of the variance in temperature anomalies is related to the Siberian High. Certainly, the Siberian High has a connection with other atmospheric circulation systems, so that this is not the true fraction of variance accounted for solely by the Siberian High. The fractions related to other systems are discussed in detail in Section 5.

The out-of-phase relationship between SLP and temperature may be due to the associated changes in radiation condition and heat budget. The genesis and development of the Siberian High results from the combined effects of the mass convergence at the middle and upper-level and radiative cooling (Ding and Krishnamurti, 1987; Ding, 1990). Some other mechanisms have also been reported. Thompson and Wallace (2000) examined the role of advection in maintaining surface air temperature anomalies associated with the AO. Warm advection is found over Siberia, and cold advection over the eastern Siberia and China. Over the mid-lower eastern Asia, dramatic changes in temperature are mainly induced by cold waves or surges related to the Siberian High (Zhang et al., 1997). The anticyclonic circulation system usually brings strong northerly and northeasterly winds over East Asia (most strongly manifest over northern and central China and the South China Sea), and also brings intense cold air masses from the interior to lower latitude coastal regions. However, the underlying mechanism responsible for establishing and maintaining the anomalous surface temperature over Eurasia needs further investigation.

4.2 Relationships with precipitation

Changes in precipitation often show large variability over small spatial scales. It is of interest to note that the variations in precipitation relating to the Siberian High over Eurasia show large scale coherence. As demonstrated in Fig. 6, precipitation decreases over most of the continent when the Siberian High gets stronger. Precipitation over much of middle to high latitude Asia is 5% less than normal associated with one standard deviation of SHCI. The largest changes are found in the Ural regions, where the reduction in precipitation exceeds 10–15%, when the Siberian High becomes one standard deviation stronger. The associated decreases over East Asia are also notable. It is interesting to note that the associated precipitation pattern differs from the temperature pattern. As shown in Fig. 4 changes in temperature resemble the spatial pattern of surface pressure. The strongest association is found in the central region of the Siberian High and the relationship weakens steadily with distance to the central region. While the related changes in precipitation are in many ways different compared to temperature. The central regions show only small changes. The remarkable precipitation changes related to the Siberian High also appears in regions far away from the center of the Siberian High. Some scattered sites also show strong precipitation changes, where the regional or local impacts may play a more important role.

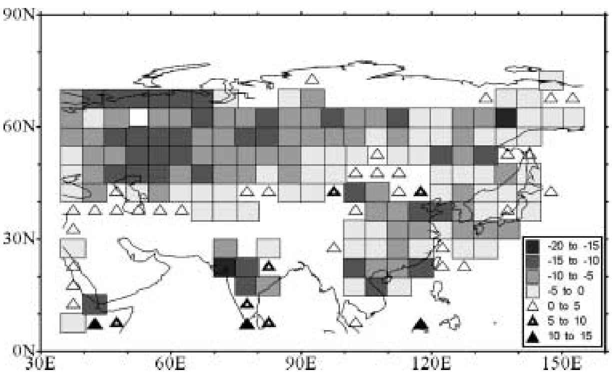

Fig. 6. Changes in precipitation (%) corresponding to one standard deviation of the Siberian High central intensity index (NCAR series), computed over the JFM from 1922 through 1998. Regions of insufficient data are blank

Absolute measurements of precipitation (usually in the form of snow) in the middle to high latitudes in winter are often influenced by local winds, slope, altitude, and other factors. This brings uncertainty into the precipitation records, however, the large-scale regional averaged values and trend analysis reduce these uncertainties and indicate variability and change with more confidence. Thus, the mean precipitation averaged over 30° E to 140° E and 30° N–70° N is shown in Fig. 5 and compared to the Siberian High. Clearly, there is a strong relationship between the Siberian High and mean precipitation. For winter (JFM) averages over 1922–1998, the two indices correlate at -0.44, also significant at 99% confidence level.

However, the precipitation anomalies associated with the Siberian High are somewhat low during the 1950s which is the wettest decade since the 1920s. Although the year-to-year variability agrees well between the two curves, the decadal means of observations in the 1950s are too high to be mainly due to the SHCI. Some contribution from other factors may be responsible and this is discussed in the next section.

5. Discussion

Our research reveals that the continental scale Siberian High exerts an influence on surface temperature and precipitation. Of course, it is not necessary to exclude the NAO/AO's contribution to surface climate anomalies. Some other teleconnection patterns, such as the SO and EU, are also found to be responsible for climatic changes over mid-high latitude continents to some extent (Hurrell, 1996; Zhu et al., 1997). Furthermore, there is clear co-variability among

Table 2. Summary of correlation statistics for winter (JFM). * Significant at 95% confidence level. Shown in parentheses are sample numbers used to compute the correlation

	SHCI	AO	EU	SO	Precipitation	Temperature
SHCI	1	− 0.52*(76)	0.30*(52)	0.14(79)	− 0.44*(77)	− 0.58*(78)
AO		1	− 0.37*(49)	0.12(76)	0.14(76)	0.53*(76)
EU			1	− 0.07(52)	− 0.28*(50)	0.21(51)
SO				1	− 0.38*(77)	− 0.28*(78)

Table 3. Multiple regression on temperature and the fractions of the variance in temperature associated with the AO, SHCI, EU, and SO (1949–1997)

Parameter	Value	Error	t-Value	Prob > |t|	Explained variance	
Y-Intercept	− 0.068	0.098	− 0.685	0.49685		
Arctic Oscillation	0.550	0.099	5.568	< 0.0001	0.30	41.7%
Siberian High	− 0.272	0.062	− 4.377	< 0.0001	0.24	33.3%
Eurasian pattern	0.829	0.136	6.057	< 0.0001	0.11	15.3%
Southern Oscillation	− 0.249	0.091	− 2.750	0.00861	0.07	10.0%
Total					$R^2 = 0.72$	100%

some components. For example, some recent research reported there are strong connections between the Siberian High and the NAO/AO (Gong et al., 2001; Gong and Wang, 2001). The spatial features of temperature anomalies related to the Siberian High, as shown in Figs. 4 and 5, are reminiscent of the results of Hurrell (1996) and Thompson and Wallace (2000). The associated changes in temperature over Eurasia, deduced from these atmospheric circulation systems, are virtually similar. Table 2 presents the correlations between the Siberian High, AO, EU, SO, precipitation and temperature. Here, the EU indices follow the definition of Wallace and Gutzler (1981) but are based on the National Centers for Environmental Prediction/National Center for Atmospheric Research Reanalysis 500 hPa height data sets. Due to the data availability, the record lengths for computing correlation coefficients are variable, as shown in the parentheses. The relationship of temperature to SHCI, AO, EU, and SO is most evident. Precipitation displays significant associations with the SHCI, EU and SO. Obviously, the correlation between precipitation, temperature and the Siberian High shows the highest values in absolute terms. But it may not be true that the Siberian High contributes the most variance in temperature and precipitation since they may share the variance.

To check the contribution by these elements a multiple regression analysis was carried out. Table 3 shows the results for temperature. For the sake of establishing equal record length for the indices, all the data were adjusted to the period from 1949 to 1997. The Siberian High, AO, EU and SO all together can explain 72 percent of the variance in temperature. The isolated variance reveal that the AO-related changes are most important, reaching 30%. This value is nearly identical to the results of Hurrell (1996), who found that the NAO accounts for about 31% of the interannual variance in hemispheric temperature over the 60 winters from 1935–94. The Siberian High also explains 24 percent of the variance in temperature. The fractions related to the EU and SO are 11% and 7%, respectively.

Figure 7 shows the temperature anomalies contributed by the above factors, the residuals are also plotted in the lower panel. Linear least-squares regression lines are fitted to each time series and shown as dashed lines. The trends are calculated from the end points of the regression lines. Clearly, the AO, Siberian High, EU and SO related temperature shows a secular warming trend at a rate of 0.27 °C/decade from 1949 to 1997. The observed extreme winters, such as the cold winter of 1969 and the warm winter of 1995, are also notable in the computed

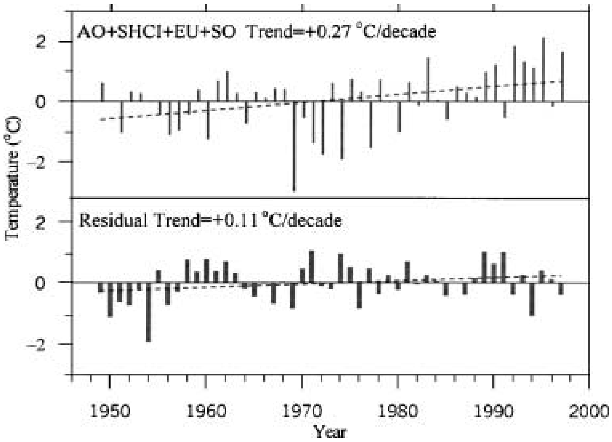

Fig. 7. Temperature anomalies related to SHCI, AO, EU and SO, in the lower panel shows the residues after removal of their contribution from the observations. (1949–1997)

series. The residual temperature departures show a slight upward trend of 0.11 °C/decade. It is of great interest to note that the linear trend in global mean temperature for January to March in the same period is $+0.10\,°C/decade$. The two trends are nearly the same. This implies that the trend in the residual series may be the global warming signal. In addition to the weak trend, the residuals also show evident periodic changes on interdecadal time scales. This suggests there may be other important factors involved (e.g. Polyakov and Johnson 2000).

In contrast to temperature, the precipitation variance explained by the AO, SHCI, EU and SO is much lower, only 26%. The fraction relating only to the Siberian High is relatively high, 9.8%. One possible reason for this is the small spatial scale of precipitation. Precipitation is vastly variable, and it is usually hard to explain its changes, especially in the mid-high latitudes. After all, the strong relation between the Siberian High central intensity and large-scale precipitation over mid-high continental Asia suggests the powerful influence of the regional atmospheric center of action. This may be very helpful to understand and predict the continental changes in climate and hydrological conditions.

6. Conclusion

Variability in the Siberian High central intensity over the 79-year period from 1922 to 2000 was investigated. Pronounced weakening has occurred in recent decades. Decreases in sea level pressure appeared not only in the central Arctic Ocean, as some existing literature indicates, but also over most of middle to high latitude Eurasia.

There are very strong couplings between the Siberian High and surface temperature (and precipitation) across continental Asia. Mean temperature averaged over 30° E to 140° E and 30° N to 70° N correlates with the SHCI at -0.58 for 78 winters from 1922 to 1999. Mean precipitation averaged over the same domain correlates with the SHCI at -0.44 during 1922 to 1998, both correlations are statistically significant at the 99% confidence level.

The surface climate over Eurasia is also influenced by other atmospheric circulation systems. The Siberian High, AO, EU, and SO all together can explain 72 and 26 percent of the variance in temperature and precipitation, respectively. The fraction solely related to the Siberian High is 24 and 9.8 percent in temperature and precipitation. Linear regression analysis showed that the planetary scale AO is most important for temperatures over Eurasia, which can explain 30 percent of the variance in surface temperature, whilst the Siberian High produces the second most important influence.

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