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Why does the temperature rise faster in the arid region of northwest China?

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[1] During 1960–2010, the air temperature in the arid region of northwest China had a significant rising trend ($P < 0.001$), at a rate of 0.343°C/decade, higher than the average of China (0.25°C/decade) and that of the entire globe (0.13°C/decade) for the same period. Based on the analysis of the data from 74 meteorological stations in the region for 1960–2010, we found that among the four seasons the temperature change of winter has been playing the most important role in the yearly change in this region. We also found that the winter temperature in this region has a strong association with the Siberian High (correlation coefficient: $R = -0.715$) and the greenhouse gas emission ($R = 0.51$), and between the two the former is stronger. We thus suggest that the weakening of the Siberian High during the 1980s to 1990s on top of the steady increasing of the greenhouse emission is the main reason for the higher rate of the temperature rise in the arid region of the northwest China.

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1. Introduction

[2] A significant role of humans in altering the climate system has become a generally accepted fact and an arising environmental challenge in recent years, supported by both observations and global climate modeling studies [*Joos et al.*, 1999; *Meehl et al.*, 2005; *Tian et al.*, 2011; *National Research Council*, 2005]. However, applying global scale simulation results to interpreting and predicting regional situations is challenging and in fact, its applicability is questionable [*Pierce et al.*, 2009]. Recent research reveals that regional climate change may considerably deviate from the trends at the national and/or global scales [*Mariotti et al.*, 2011; *Tebaldi et al.*, 2005; *Wu et al.*, 2005]. As a particular case, the air temperature in the arid region of northwest China has been increasing by a rate of 0.33–0.39°C/decade in recent 50 years [*Shi and Zhang*, 1995; *Wang et al.*, 2008; *Q. Zhang et al.*, 2010; *X. Q. Zhang et al.*, 2010], considerably higher than the overall rate of China (0.25°C/decade) [*Ren et al.*, 2005] and that of the entire globe (0.13°C/decade) [*Intergovernmental Panel on Climate Change* (*IPCC*), 2007] for the same period. In the present study, we intended to identify the direct cause for this regional deviation.

[3] In this paper, the arid region of northwest China refers to the vast area generally defined by N30°–N50° and E70°–E110° (Figure 1). The total area of the region is about 2.5 million km^2, accounting for over 1/4 of China. It has a typical temperate continental climate, with long and cold winter, hot and dry summer, and short spring and autumn. The mean annual temperature is about 8°C, and the mean annual rainfall is less than 200 mm.

[4] *Wang et al.* [2008] and *Q. Zhang et al.* [2010] found that the temperature rise in the arid region of northwest China had a seasonal pattern: In spring and summer, the rising rate is relatively low, varying within 0.22–0.32°C/decade, whereas the winter temperature rises much faster, at a rate of 0.56–0.61°C/decade. We thus suspected that the contribution of the winter temperature change to the annual mean temperature change might have become the most important factor in the annual variation. We also suspected that the direct causes for the winter temperature dynamics might be related to those regional atmospheric circulations, particularly the Siberian High.

[5] The Siberian High is a cold or very cold dry air mass formed in the Mongolian-Siberian region. It has immense influence on the weather patterns in most parts of the Northern Hemisphere [*Gong and Ho*, 2002]. In winter, the Siberian High reaches its highest intensity and invades the East Asia, including China, often resulting in cold waves [*Ding*, 1990; *Park et al.*, 2010]. In spring, the Siberian High shifts from west to east, and gradually weakens until disappears in about April [*Panagiotopoulos et al.*, 2005]. *Gong and Wang* [1999b] found that weakening of Siberian High was a prime driver of warmer winter temperatures in almost all of inland extratropical Asia and even over most parts of Europe. For this reason, the Siberian High was the primary factor under examination in this study. We intended to find

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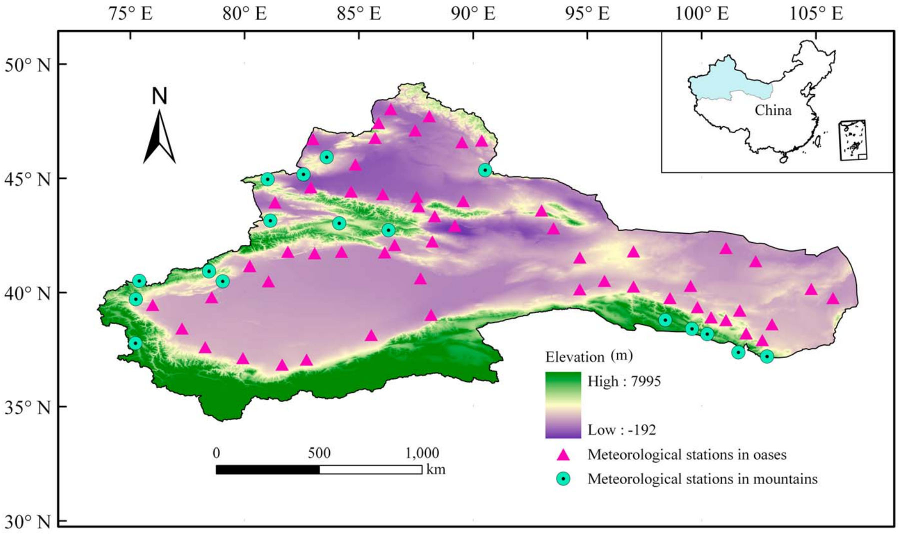

Figure 1. Study area and the meteorological stations.

out if the Siberian High had a similar effect on a higher-latitude region.

[6] Besides the Siberian High, in this study we also detected if there exist associations between the winter temperature variation and other major atmospheric circulations that may affect the region, as well as the regional carbon dioxide emissions (CDE). The atmospheric circulations we tested include the Arctic Oscillation (AO), North Atlantic Oscillation (NAO), Pacific-North American pattern (PNA), Antarctic Oscillation (AAO), Southern Oscillation (SO) and Westerly Circulation Index (WCI). The Arctic Oscillation (AO) is an indicator of primarily winter sea level pressure. It explains 16% of the total variance of the warm season atmospheric circulation in the midlatitude and high-latitude regions [*Thompson and Wallace*, 2000]. The North Atlantic Oscillation (NAO) is a dominant pattern of weather and climate variability over the Northern Hemisphere. It swings from one phase to another, resulting in great changes in surface air temperature over the Atlantic, as well as the adjacent continents, including Asia [*Hurrell and Deser*, 2009]. The Pacific-North American (PNA) pattern is a leading mode of atmospheric circulation over North America, which strongly influences interannual climatic variability [*Barnston and Livezey*, 1987]. The PNA is most strongly expressed in the winter season as a distinct configuration in the mid-tropospheric geopotential height field over North America and the North Pacific [*Trouet and Taylor*, 2010]. The Antarctic Oscillation (AAO) refers to a large-scale alternation of atmospheric mass between the midlatitudes and high latitudes surface pressure [*Gong and Wang*, 1999a]. The AAO has impacts on climate variations in the East Asian-western Pacific sector, including weather extremes in northern China and tropical cyclones in the East China Sea [*Fan and Wang*, 2004; *Ho et al.*, 2005]. The Southern Oscillation (SO) is the dominant interannual climate phenomenon in the tropical ocean-atmosphere system. The Westerly Circulation Index (WCI) is used to measure the winter monsoon intensity in the East Asia; it can be used to characterize winter temperature anomalies in China [*Chen and Sun*, 2001].

[7] Besides the overall temperature change, we further looked into its variations in different landscapes for the study area. This area is composed of three types of distinctive geographical units, including mountain, oasis, and desert. On the one hand, the oases occupies less than 5% of the total area, but carries 95% of the population and more than 90% of GDP [*Wang*, 1995]. With the socioeconomic development in recent years, the urbanization in the oases is increasing. Studies find that the urbanization in the northwestern China affects the local temperature through the effects of *urban heat island* and *urban wet island*, and the greater the urbanization is, the stronger its effect on the temperature [*Ren et al.*, 2006; *Fang et al.*, 2007]. Therefore, in urban areas human activities may considerably modify the temperature pattern driven by broader natural factors [*Fall et al.*, 2011; *Watts*, 2009]. On the other hand, in those areas that are less impacted by human activities, such as mountains and deserts, this modification can be less as well. In this study, we compared the temperature trends in the oases and mountains. We were not able to include the desert areas in the comparison due to lack of data.

2. Data and Methods

2.1. Data

[8] In this study, we used the monthly and annual temperature for the period of 1960–2010 from these 74 stations to characterize the temperature variation during this period in the study area. The data from a total of 17 meteorological stations in the mountainous areas were available to this study. The average elevation of the 17 stations is 2363 m. In the oasis area, the data from 57 stations were available and the average elevation of these stations is 1080 m (Figure 1). All the 74 meteorological stations selected for this study had been maintained following the standard of the National Meteorological Administration of China (NMAC). The standard requires strict quality control processes including extreme inspection, consistency check, and others before releasing these data. However, the quality of the siting of these stations still needs to be assessed in order to determine

if any of the trend is due to very local effects, such as found for the USA in *Fall et al.* [2011] and *Jamiyansharav et al.* [2006] for Mongolia. This issue exists even for non-urban areas, as it is not a result of regional or mesocale landscape change, but due to non-spatially representative siting of surface observing stations.

[9] To detect the association between the winter temperature trend and the Siberian High dynamics, we needed a quantitative measurement of the intensity of the Siberian High. *Gong and Wang* [1999b] defined a Siberian High intensity index (SHI), which was adopted in this study:

$$SHI = \frac{\sum_{i=1}^{n} P_i \lambda \cos\varphi_i}{\sum_{i=1}^{n} \lambda \cos\varphi_i} \tag{1}$$

where *SHI* is the Siberian High intensity value for the entire region, P_i is the value of sea level pressure at i, which is a location that falls into the region; n is the total number of locations for which the sea level pressure values are available, and in this study n = 144; φ_i is the latitude of the location; and λ is a factor restricting the SHI calculation only to those locations where the sea level pressure value is greater than a threshold. Following *Gong and Wang* [1999b], in this study the value of λ was set as follows:

$$\lambda = \begin{cases} 1 & \text{if } P_i \geq 1028 \text{ hPa} \\ 0 & \text{if } P_i < 1028 \text{ hPa} \end{cases}. \tag{2}$$

[10] In this study, for calculating *SHI* we used the monthly mean sea level pressure data of the northern hemisphere provided by Hadley Center (HadSLP) [*Allan and Ansell*, 2006]. The data are for the period of 1850–2010, and in the format of 5° latitude by 5° longitude grid points. Using this data, we calculated the winter *SHI* (December to February) for the period of 1960–2010.

[11] The data of Arctic Oscillation Index (AOI), North Atlantic Oscillation Index (NAOI), Pacific-North American Pattern Index (PNAI), Antarctic Oscillation Index (AAOI) during 1960–2010, and Southern Oscillation Index (SOI, 1960–1999) are from the Climate Prediction Center (CPC) of the National Weather Service, U.S. (http://www.cpc.ncep.noaa.gov).

[12] The data of the Westerly Circulation Index (WCI) for 1960–1997 are from *Chen and Sun* [2001].

[13] The data of the carbon dioxide emissions (CDE) in China for 1960–2005 are from the World Development Indicators (WDI) (http://data.worldbank.org).

2.2. Methods

[14] We used the average of the values from the 74 meteorological stations as the representative value of the entire region. In this way, we calculated the annual and monthly average temperatures of the study area for the period of 1960–2010. The monthly values were used to further calculate the seasonal average temperature values. In this study, we defined spring as March–May, summer as June–August, autumn as from September–November, and winter as December–February. In the same way, we calculated the annual and seasonal average temperatures for the oasis areas and mountainous areas for the same period, using the data from the meteorological stations located in these two types of areas, respectively.

[15] We used the Mann-Kendall (MK) statistical test [*Mann*, 1945; *Kendall*, 1975] to test the significances of trends in the annual mean temperatures of the entire area, the oases, and the mountains. The nonparametric Mann-Kendall statistical test has been commonly used to assess the significance of monotonic trends in meteorological and hydrologic series [*Yue et al.*, 2002; *Chen and Xu*, 2005; *Zhang et al.*, 2011]. For a time series $X = \{x_1, x_2, \ldots, x_n\}$, when $n > 10$, the standard normal statistic Z is estimated as follows:

$$Z = \begin{cases} (S-1)/\sqrt{\mathrm{var}(S)} & S > 0 \\ 0 & 0 \\ (S+1)/\sqrt{\mathrm{var}(S)} & S < 0 \end{cases} \tag{3}$$

where

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \mathrm{sgn}\,(x_j - x_i) \tag{4}$$

$$\mathrm{sgn}\,(\theta) = \begin{cases} +1, & \theta > 0 \\ 0, & \theta = 0 \\ -1, & \theta < 0 \end{cases} \tag{5}$$

$$\mathrm{var}(S) = \left[n(n-1)(2n+5) - \sum_t t(t-1)(2t+5) \right] / 18 \tag{6}$$

where t is the extent of any given tie, and $\sum_t$ denotes the summation of all ties.

[16] Between the winter temperature and each of the atmospheric circulation indices considered in this study, we calculate Pearson's correlation coefficient to detect the association between them. This statistic was also calculated between the winter temperature and CDE.

[17] For the entire area, the oases, and the mountains, we calculated change rates for the annual and seasonal average temperatures during 1960–2010.

[18] We also calculated the importance of the temperature change for each individual season in the yearly change, in order to find out if certain season has been playing a greater role than others in the yearly change. In this study, we used the mean air temperature of 1960–1980 as the benchmark to measure the change. We chose this particular period to set the benchmark, because previous studies showed that early 1980s is a turning point, after which the air temperature in the arid region of northwest China has increased markedly [*Chen and Xu*, 2005; *X. Q. Zhang et al.*, 2010]. The importance of the change of one season in the yearly change is quantified as its proportion in the total change of the four seasons, and this proportion was calculated for the four seasons of each year since 1981, until 2010. The process can be represented as follows:

$$I_{s,i} = \frac{\left| T_{s,i} - \overline{T}_{winter,1960\text{–}1980} \right|}{\sum_{s \in \{spring,summer,autumn,winter\}} \left| T_{s,i} - \overline{T}_{s,1960\text{–}1980} \right|} \times 100 \tag{7}$$

where $I_{\mathrm{winter},i}$ is the importance of the winter temperature variation of year i in the overall temperature variation of the

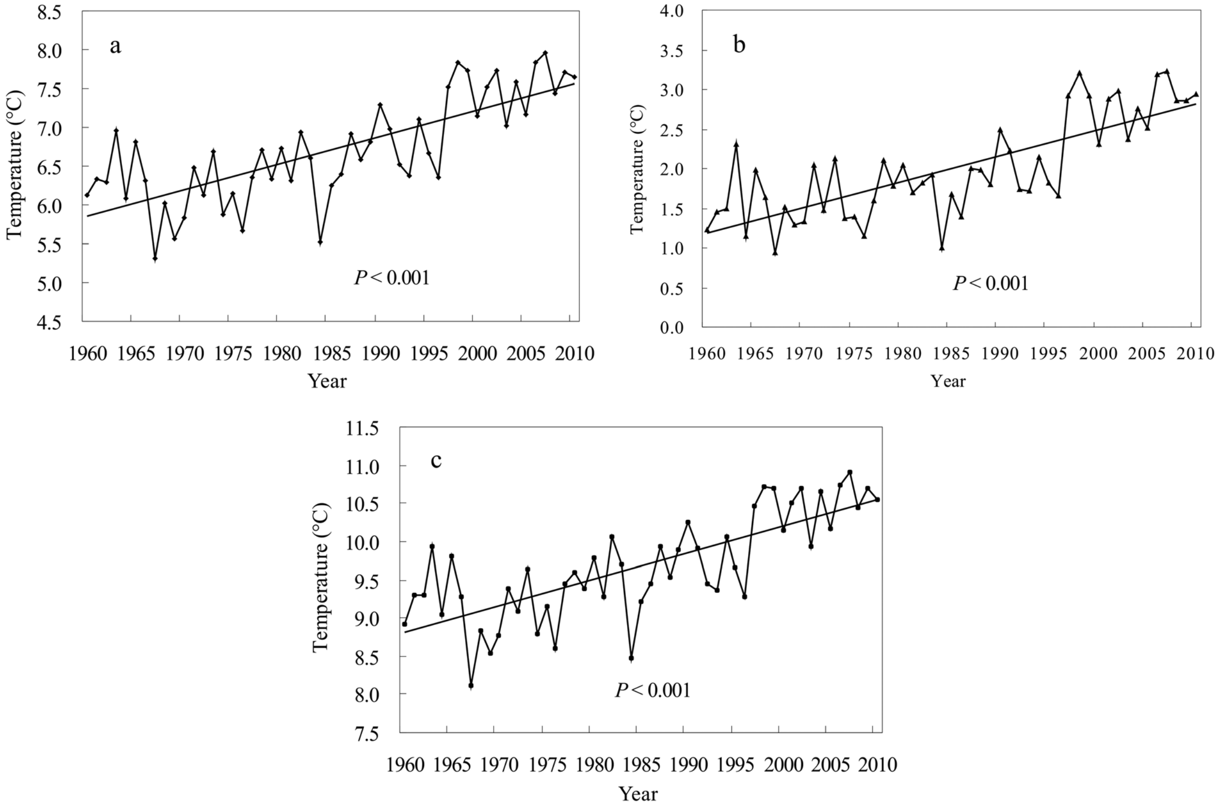

Figure 2. The trends of the average annual air temperature in (a) the arid region of northwest China, (b) the mountainous areas in this region, and (c) the oasis areas in this region, for the period of 1960–2010, based on 74 meteorological stations.

same year, and in this study $i = 1981, 1982, \ldots 2010$; $T_{\text{winter},i}$ is the winter temperature of year i; $\bar{T}_{\text{winter},1960\text{–}1980}$ is average of the winter temperatures during 1960–1980; and $T_{s,i}$ is the seasonal temperature of year i.

3. Results and Discussion

3.1. Temperature Trend

[19] The Mann-Kendall (MK) statistical test revealed a significant rising trend in the air temperature in the arid region of northwest China during 1960–2010 ($P < 0.001$), with a rate of 0.343°C/decade (Figure 2a). These values are consistent with the results from previous research [*Shi and Zhang*, 1995; *Wang et al.*, 2008; *Q. Zhang et al.*, 2010; *X. Q. Zhang et al.*, 2010]. A rising trend was found in both oasis areas and mountainous areas (Figures 2b and 2c), with not surprisingly, a lower changing rate in the mountainous areas (0.325°C/decade), and a higher rate in the oasis areas (0.35°C/decade). Even the lower rate in the mountainous areas, however, is much higher than the average of China (0.25°C/decade) [*Ren et al.*, 2005] and the average of the entire globe (0.13°C/decade) [*Brohan et al.*, 2006; *IPCC*, 2007]. Due to the relatively low population density in the arid region of northwest China, we do not consider human activities as a major factor in this region that drives the overall regional temperature change to deviate considerably from the national and global trends. The finding that the temperature of the arid region of northwest China has a faster rise is consistent with the results from previous research [*Wang et al.*, 2008; *Q. Zhang et al.*, 2010; *X. Q. Zhang et al.*, 2010; *Sun et al.*, 2010] and the statement in the Fourth Assessment Report of Intergovernmental Panel on Climate Change (IPCC) that the mid-high latitude regions of north hemisphere has a higher temperature rising rate.

[20] Using equation (7), we calculated the seasonal importance in the yearly change for each year between 1981 and 2010. Over this period, the mean importance values for spring, summer, autumn, and winter are 19.3%, 13.7%, 23.6%, and 43.4%, respectively (Figure 3). For the particular period of 1984–1995, during which SHI was the weakest in

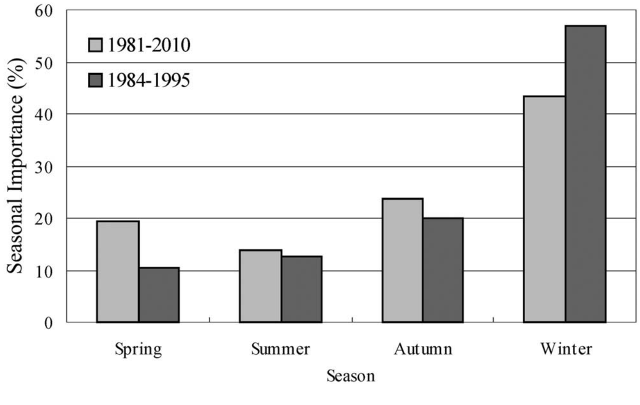

Figure 3. The seasonal importance of temperature changes in different periods (1981–2010, 1984–1995).

Table 1. The Correlation Coefficients Between the Winter Temperature in the Entire Region (the Arid Region of Northwest China), Mountains, Oases and Certain Factors That May Affect the Temperature

Factor	SOI	AAOI	NAOI	AOI	PNAI	WCI	SHI	CDE
Entire region	−0.256	0.128	0.329[a]	0.371[a]	0.023	0.377[a]	−0.715[b]	0.510[b]
Mountains	−0.238	0.078	0.220	0.276	0.021	0.236	−0.629[b]	0.498[b]
Oases	−0.255	0.177	0.350[a]	0.388[a]	0.033	0.402[a]	−0.723[b]	0.504[b]

[a] Significant at $P < 0.05$.
[b] Significant at $P < 0.001$.

the past 50 years, the importance of winter change is 57.01%. These results suggest that the winter temperature change is the most important factor for the annual air temperature in the arid region of northwest China to have been rising faster than other areas.

3.2. Potential Causes of Winter Temperature Change

[21] The Pearson's correlation coefficient values (Table 1) show that the winter temperature of the arid region of northwest China has a strong and significant correlation with the Siberian High Index (SHI, $R = -0.715$, $P < 0.001$) and China's carbon dioxide emissions (CDE, $R = 0.51$, $P < 0.001$). For all the other tested atmospheric circulations, the correlations are much weaker and less significant. Another feature is worth mentioning that the correlations in oases are higher than those of mountains, which means the impacts of atmospheric circulations on temperature in oases are stronger than in mountains. Figure 4 shows that in general, the Siberian High and the winter temperature in the region have an almost perfect "mirroring" relationship during 1960–2010, suggesting a direct impact of the former on the latter. Particularly, the Siberian High intensity in the region had a deep "valley" between late-1980s and mid-1990s, and this confirms the finding of *D'Arrigo et al.* [2005], *Panagiotopoulos et al.* [2005], and *Gong and Ho* [2002] that 1980s–1990s was the weakest period of the Siberian High in the past one hundred years. This valley of the Siberian High intensity well coincides with the most obvious peak of the winter temperature in the region; recently (2005–2010), along with the Siberian High intensity's recovery, the winter air temperature was falling as well.

[22] Excessive greenhouse gas emissions are generally regarded as the main cause of global warming [*Crowley*, 2000; *Mahlstein and Knutti*, 2010; *IPCC*, 2007]. However, as shown by Figure 5, while the carbon dioxide emissions in the past 20 years maintained a strongly increasing trend, the winter temperature was not following. It can be inferred that the rising winter temperature during the period 1960–2005 seems to be more associated with the Siberian High than with China's carbon dioxide emissions.

[23] The R value calculated by *Gong and Ho* [2002] for the Siberian High intensity and air temperature in mid-to-high latitude Asia (30°N∼70°N, 30°E∼140°E) is −0.58, lower than that of the arid region of northwest China (−0.715), suggesting that the Siberian High had a stronger influence on the air temperature in the arid region of northwest China than in other regions.

4. Conclusion

[24] In the past 50 years, the air temperature in the arid region of northwest China has been rising faster than the average rates of China and the entire globe. The analysis in this study shows that in the past 50 years, among the four seasons the temperature change of winter has the greatest importance in the yearly change. We also found that the winter temperature of this region has a strong and significant associations with the Siberian High and greenhouse gas emission, and between the two, the former seems stronger ($R = -0.715$, $P < 0.001$ versus $R = 0.51$, $p < 0.001$). A weak Siberian High results in a relatively high winter temperature in the region. Therefore, the weakening of Siberian High from 1980s to 1990s on top of the increasing of greenhouse gas emission might be the main reason for the faster temperature rise in this region.

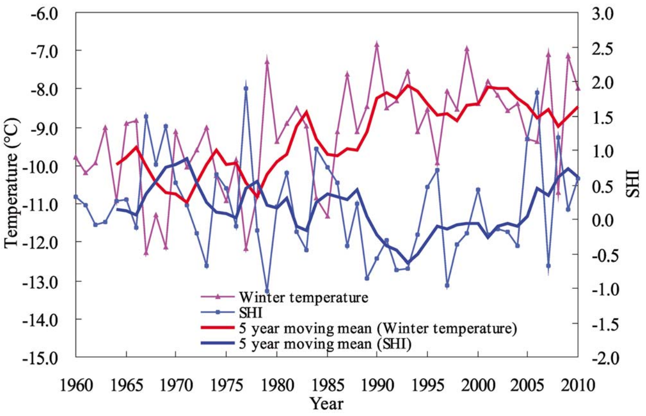

Figure 4. The Siberian High Intensity and the winter temperature in the arid region of northwest China.

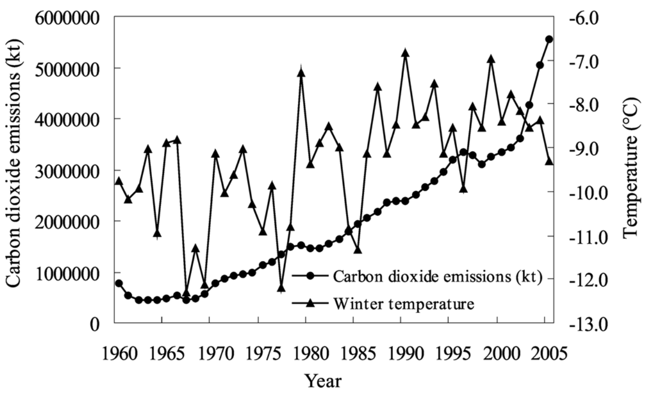

Figure 5. The winter temperature in the arid region of northwest China and the yearly carbon dioxide emission in China.

[25] Accordingly, a model aiming to predict the climate of the arid region of northwest China or the East Asia region should take into account the Siberian High, which should be a major item on the future research agenda. Particularly, a recent research shows that the increase of snow cover in Eurasian contributes to the Siberian High recovery [*Jeong et al.*, 2011], which, if continues, may result in a decrease of the rising rate of the air temperature in this area.

[26] We understand that the climate change is the result of many different factors and their complicated interactions. In this study, we have focused on atmospheric circulations and greenhouse gas emission, which we consider to be major factors in climate change and have controls or influences over a vast area like our study region. More comprehensive, localized, and in-depth analysis is following.

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