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Causes and effects of spatial and temporal variations of cold period in Chinese oases between 1960 and 2014

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Abstract: Based on daily average temperatures and observation data from 74 meteorological stations in Chinese oases, we calculate five-day (pentad) average temperature ≤0℃ for the start and end pentad as well as pentads of cold period using linear regression analysis, nonparametric Mann-Kendall tests, the Morlet wavelet power spectrum, and correlation analysis. We also analyze spatial and temporal variations and their effects on the start and end pentad as well as pentads of cold period in Chinese oases. Results show that over the last 55 years, the start pentad of cold period has been postponed while the end pentad has been advanced. Overall, the pentads have gradually shortened over time at trend rates that are 0.3 p/10a, –0.27 p/10a, and –0.58 p/10a, respectively. Spatial differences are significant, especially for the Qaidam Basin oasis where the start pentad is the earliest, the end pentad is the latest, and the trend of change is most obvious. Mutation points for the start and end pentad as well as pentads of cold period were observed in 1990, 1998, and 1994, respectively. Of these, the start pentad and pentads of cold period show a periodic cycle, related to atmospheric circulation and El Nino events, while the end pentad exhibits a periodic cycle, related to solar activity. The Tibetan Plateau index (TPI), the Asian polar vortex area index (APVAI), and carbon dioxide emissions (CDE) are the main factors affecting cold period in the study area, whereas the South Asian summer monsoon (SASM) index exerts the greatest effect on the Qaidam Basin oasis. The start and end pentad as well as pentads of cold period increase in concert with latitude, longitude, and altitude; in response to these changes, the start pentad is advanced, the end pentad is postponed, and pentads of cold period are gradually extended. Results show that change in latitude is most significant. Overall, the start and end pentad as well as pentads of cold period show clear responses to regional warming, but there are different effects on each.

Keywords: Chinese oases; pentad average temperature; influencing factor; regional warming

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1 Introduction

The Fifth Assessment Report of the Intergovernmental Panel on Climate Change noted that global climate change will reach an unprecedented rate in the 21st century (IPCC, 2013). Extreme weather, including strong precipitation, heat waves, floods and droughts, will increase in frequency, and climate change will have a profound impact on natural ecosystems and socio-economic systems. Changes in climate will lead to sea level rise, ocean acidification, disappearance of the cryosphere, hydrologic cycle disorders, frequent extreme events, loss of biological diversity, and threats to food safety (Solomon *et al*., 2007; IPCC, 2013). In the context of global warming, unusual large-scale climate phenomena appear frequently, at an increasing rate worldwide, leading to serious impacts on society, economy, human health, and the natural environment (Feng *et al*., 1985; Ding and Geng, 1998; Changnon *et al*., 2000). Extreme temperature, for example, has been the focus of a great deal of research attention given the background of climate warming. Research has been focused on the USA and the USSR (Karl *et al*., 1991), the northeastern United States, Australia and New Zealand (Easterling and Horton, 1997; Plummer *et al*., 1999), Southeast Asia and the South Pacific (Manton *et al*., 2001), South Asia (Sheikh *et al*., 2015), and on the cities of Nis and Belgrade (Serbia) (Milanovic *et al*., 2015). Several studies have reported that warm extremes are increasing, cold extremes are decreasing, and significant increases in the annual numbers of hot days and warm nights are being seen, with significant decreases in the annual numbers of cool days and cold nights. For example, Alexander *et al*. (2006) reported that over 70% of sampled global land area has experienced a significant decrease in the annual occurrence of cold nights, coupled with a significant increase in the annual occurrence of warm nights. In China, Ren and Zhai (1998) and Zhai *et al*. (1999) noted that clear temporal (seasonal) and regional differences exist in extreme temperate trends, while Fu *et al*. (2011) showed that the frequency of extreme minimum temperatures has decreased throughout the country. In addition, Du *et al*. (2013) found that while the number of frost and ice days has decreased significantly, the length of the growing season, extra-maximum air temperature, and extra-minimum air temperature have all significantly increased. Wang *et al*. (2013) and Liu *et al*. (2013) analyzed extreme temperature events in the Yangtze and Pearl river basins and showed that they corroborate these trends.

Compared with other regions, Chinese oases are more sensitive to global warming. The effect of climate change on oases is complicated but serious and is expected to lead to huge losses. Previous studies have suggested that the changes in climate in northwest China are mainly the result of an increase in extreme low temperatures (Liu *et al*., 2005). Yang *et al*. (2006) demonstrated that the frequency and intensity of extreme low temperatures have decreased over a nearly 45-year period, whereas Chen *et al*. (2012) showed that areas of minimum temperature are located in northern Xinjiang and on the Qinghai Plateau. However, previous research on extreme low temperatures has been based on records of average temperatures, daily minimum temperatures, seasonal average extreme low temperatures, and indexes for extreme low temperatures. No research to date has been conducted on cold period by calculating pentad average temperature ≤0℃. Therefore, applying the 72 pentads division that is standard in climatology, pentad average temperature ≤0℃ are calculated here, data for the start and end pentad as well as pentads of cold period are presented, and spatial and temporal variations and causes are analyzed. The purpose of this paper is thus to provide a scientific basis for the determination of agricultural production and heating periods, and provide references for climate change research. It is hoped that the data presented here will enable the official agencies concerned to deal more effectively with climate change, will develop our scientific understanding of the regional responses to global warming, and will lay the foundations for the study of the evolution of extreme low temperature events across the whole of Central Asia.

2 Data and methods

2.1 Study area

Chinese oases are located in the Eurasian Hinterland, distributed alternately in high mountains and basins. The region of interest covers an area of nearly 1.9×10^5 km^2, and includes six oases in northern Xinjiang, southern Xinjiang, the Hexi Corridor, the Hetao Plain, the Qaidam Basin and Alxa. All of these oases are supplied mainly by mountain snowmelt, with the exception of the oasis on the Hetao Plain. The climate of these areas is dry with a mean annual rainfall less than 200 mm. It is cold in winters, hot in summer, temperature changes are obvious, and both annual and daily temperature ranges are large. Light and heat resources at these oases are also very abundant: solar global radiation is more than 5.04×10^5 MJ/m^2, annual sunshine duration is greater than 2800 h, accumulated temperature ≥10℃ is above 2600℃, and the frost-free period is about 140 days. Brown desert, gray-brown desert, and aeolian sandy soils dominate, and the zonal vegetation is mainly characterized by desert and desert steppe plants (Figure 1).

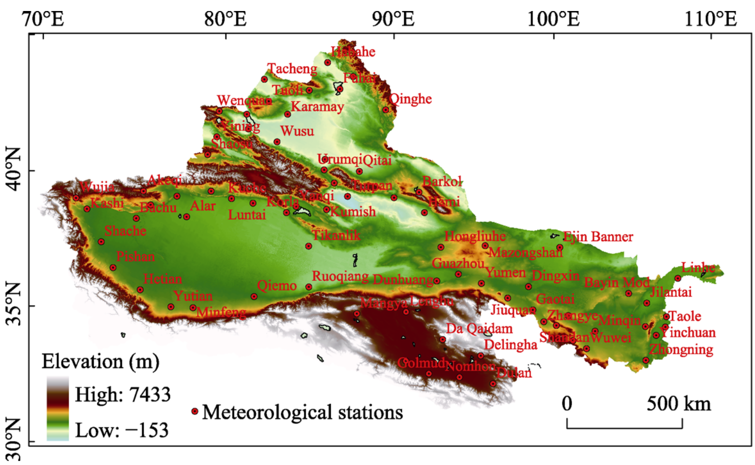

Figure 1 The distribution of meteorological stations in Chinese oases

2.2 Data

A dataset of daily average temperatures for the period between 1960 and 2014 from 74 meteorological observation stations is used in this research, with all data provided by the China Meteorological Science Data-sharing Service System (http://cdc.cma.gov.cn/home.do#). Monthly indices for the time series between 1960 and 2011 were extracted from 74 circulation indices issued by the Laboratory for Climate Studies, China Meteorological Administration National Climate Center and include the TPI, the APVAI, the Asian polar vortex intensity index (APVII), and the Westerly circulation index (WCI). Data for the monthly SASM index for the period 1960 to 2014 were downloaded from Professor Li Jianping's personal home page (http://ljp.lasg.ac.cn//), while the yearly Siberian high index (SHI) for the same period was provided by Yao Junqiang (Institute of Desert Meteorology, China Meteorological Administration, Urumqi). Annual mean CDE for the period 1960 to 2011 were extracted from the World Bank data center (http://data.worldbank.org.cn/). A linear equation was used to fit sequence variables when changes and trends in the start and end pentad as well as pentads of cold period were analyzed. In order to determine the significance of change trends, we tested the correlation coefficient between time and the original sequence variable (Wei *et al*., 1999). For mutation tests, we used the nonparametric Mann-Kendall test (Wei *et al*., 1999), sliding t tests, and the accumulative anomaly method. For Morlet wavelet power spectrum analysis, we used the wavelet analysis toolbox in the Matlab7.0 software.

The data processing method used here follows the standard division of 72 pentads commonly used in climatology to calculate pentad average temperature ≤0℃, and to determine the start and end pentad as well as pentads of cold period.

3 Results

3.1 Temporal variations in cold periods

(1) Inter-annual changes that characterize cold periods

Over the last 55 years, the variations in the start and end pentad as well as pentads of cold period in Chinese oases are extremely significant (Figure 2). Results show that the start pentad has consistently been postponed over this period, at a tendency rate of 0.3 p/10a (α≥0.001). In total, the start pentad has been postponed 1.7 pentads over the past 55 years, starting on average at the 63th pentad, around November 16–20. The earliest the start pentad was in 1981 while the latest was in 1994. In contrast, the end pentad has consistently been advanced, at a tendency rate of –0.27 p/10a (α≥0.001). The end pentad has been advanced 1.5 pentads over the last 55 years, ending on average in the 14th pentad, around March 6–10. The earliest end pentad was in 2013 while the latest was in 1976. It is also worth mentioning that trend towards postponement of the start pentad of cold period is more significant than trend towards advancement of the end pentad; pentads of cold period show a trend towards shortening at a tendency rate of –0.58 p/10a (α≥0.001) and have been decreased by an

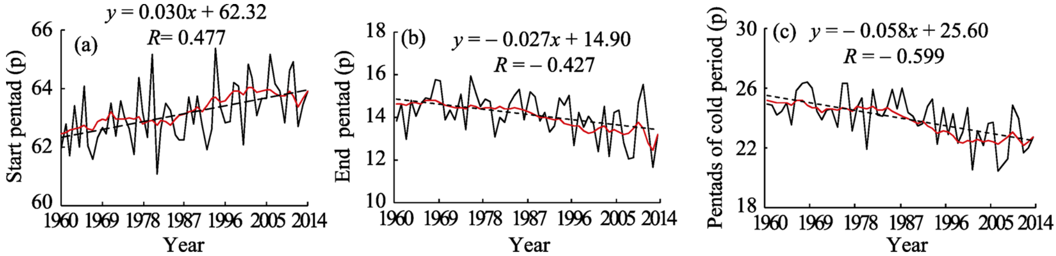

Figure 2 Trends in inter-annual variation in the start (a) and end pentad (b) as well as pentads of cold period (c) in Chinese oases

average of 3.2 pentads over the last 55 years. On average, these periods are 24 pentads in length, with the shortest on record in 2006 and the longest in 1968 (Figure 2). The red line in Figure 2 is the ten-year sliding curve; variation in the start pentad has fluctuated upwards, with an obvious rise after 1994 (Figure 2). In contrast, variations in the end pentad and pentads of cold period are consistent, although both show a downward trend; after 1994, this decline is very obvious.

(2) Inter-decadal changes that characterize cold periods

In terms of inter-decadal variations in the start and end pentad as well as pentads of cold period in Chinese oases (Table 1), results show that the start pentad exhibits a remarkable trend in postponement with anomaly values that vary from –0.71 (1960s) to –0.26 (1980s) and a postponing of 0.45. Since the 1990s this anomaly value has changed from negative to positive, reaching a maximum value of 0.76 in the period 2010 to 2014. The end pentad also shows a significant trend towards advancement, although this change is not obvious between the 1960s and 1980s. In the 1990s, the anomaly value changed from positive to negative, reverting from –0.14 (1990s) to –0.39 (2010 to 2014), advancing most obviously and reaching a maximum value of –0.9 in the period between 2000 and 2009. Pentads of cold period show significant shortening trends, and the anomaly value varies between 1.17 (1960s) and 0.49 (1980s), a shortening of 0.68. Since the 1990s, this anomaly has changed to negative from a positive value, from –0.34 (1990s) to –1.39 (2010–2014), shortening most obviously between 2000 and 2009. In summary, the start and end pentad as well as pentads of cold period changed most statistically subsequent to the 1990s.

Table 1 Decadal mean anomalies of the start and end pentad as well as pentads of cold period in Chinese oases

Decade	Start pentad (p)	End pentad (p)	Pentads (p)
1960–1969	–0.71	0.34	1.17
1970–1979	–0.25	0.54	0.67
1980–1989	–0.26	0.34	0.49
1990–1999	0.21	–0.14	–0.34
2000–2009	0.61	–0.9	–1.47
2010–2014	0.76	–0.39	–1.39

3.2 Spatial variations in cold periods

In order to better understand the characteristics of spatial variations in the start and end pentad as well as pentads of cold period for Chinese oases, we developed a spatial distribution map for the start and end pentad as well as pentads of cold period using the Kriging method in geographic information system software (Figure 3). This map incorporates time series and tendency rates for the start and end pentad as well as pentads of cold period based on data from the 74 meteorological stations in Chinese oases.

Results demonstrate that there are remarkable spatial differences across the study area (Figure 3). Considering spatial variations in the start and end pentad as well as pentads of cold period (Figure 3), the start pentad varies from 59 to 67 pentads with a difference of 8 pentads between the highest and the lowest. The cold period in the Qaidam Basin oasis started earliest, in the 60th pentad, whereas this period in the northern Xinjiang oasis started second, in the 62th pentad. The cold period in the southern Xinjiang oasis started last, in the

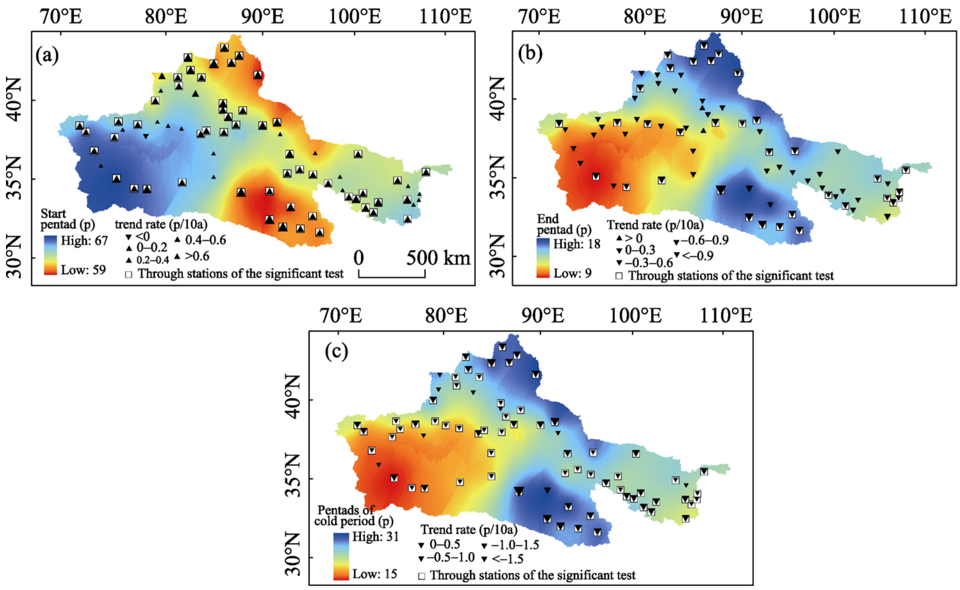

Figure 3 Trends in the spatial distribution of the start (a) and end pentad (b) as well as pentads of cold period (c) in Chinese oases

65th pentad, a difference of 5 pentads between the first and the last. In contrast, the end pentad varies between 9 and 18, and there is a difference of 9 pentads between the highest and the lowest. The cold period in the Qaidam Basin oasis ended latest, in the 17th pentad, whereas in the northern Xinjiang oasis it ended second, in the 16th pentad. The southern Xinjiang oasis has the earliest cold period start, in the 11th pentad, a difference of 6 pentads between the first and the last. Thus, the pentads of cold period vary between 15 and 31, a difference of 16 between the highest and the lowest. The cold period in the Qaidam Basin oasis is the longest, lasting 30 pentads, while that in the northern Xinjiang oasis is second-longest, lasting 28 pentads. In contrast, the southern Xinjiang oasis has the shortest cold period, lasting 19 pentads, an overall difference of 11 pentads.

In terms of spatial variations of the start and end pentad as well as pentads of cold period, the start pentad of 99% of stations are postponed and the rates of changing trend of most stations vary from 0 to 0.4 p/10a. Only the start pentad of the Alar station is advancing, and it does not pass the significance test. Across the whole region, 76% of the stations pass the significance test at the 0.05 level, while the Qaidam Basin oasis shows a more obvious trend towards postponement, averaging 0.48 p/10a. Data show the end pentad of 97% of the stations advanced, at a rate of –0.6 to 0 p/10a for most stations. Urumqi and Kumux stations, however, show postponement and do not pass the significance test. Across the whole region, 47% of stations pass the significant test at the 0.05 level, while the Qaidam Basin oasis is advancing more obviously at a rate of –0.52 p/10a and 75% of stations pass the significance test. The pentads of all stations show a shortening trend, with 89% passing the significance test at the 0.05 level, while rates for most stations vary from –1 to 0 p/10a. The Qaidam Basin oasis is decreasing most obviously at a rate of –0.9 p/10a, while 88% of the stations pass the significance test.

The cold period in the Qaidam Basin oasis starts earliest, ends latest, and is the longest. In addition, the start and end pentad as well as pentads of cold period in this oasis are the most obviously postponed, advanced, and shortened, which suggests that it exhibits most sensitive responses to global climate change. This result is consistent with the conclusion that the climate of this oasis is most sensitive and significant because it is on the Tibetan Plateau (Li *et al*., 2010); this relates to the observation that it is 'the driver and amplifier' of global climate change (Pan and Li, 1996), and the conclusion that the responses to global climate change of high-altitude areas are more sensitive than those of low-altitude areas (Yao *et al*., 2000).

3.3 Mutation analysis

Climate mutation is not only an important phenomenon in climate change but also an important factor in climate prediction and simulation. Here we used the nonparametric Mann-Kendall test, sliding t tests, and the cumulative anomaly method to analyze abrupt changes in the start and end pentad as well as pentads of cold period in Chinese oases and their subregions over the last 55 years (Table 2). Of these tests, the sequence length of the Mann-Kendall and sliding t test is three years, while the significance level is 0.01 and the critical line is U = ±2.58. Results indicate that over the last 55 years, mutation of the start pentad in the study area occurred in 1990, for the end pentad in 1998, and for pentads of cold period in 1994. Mutation of the start pentad in the subregion occurred in the early

Table 2 Mutation analysis of the start and end pentad as well as pentads of cold period in Chinese oases

		M-K	Sliding t test	Cumulative anomaly method
The start pentad	Entire region	1990/1991	–	1990
	Beijiang	1990/1991	–	1991
	Nanjiang	1988	1987/1993	1993
	Hexi	1976/1981/1992	–	1992
	Hetao	1970/1987/1993	1967/1969/1971	1993
	Qaidam	–	1993/1994	1993
	Alxa	1983/1984/1987	1971/1992	1992
The end pentad	Entire region	1998	–	1998
	Beijiang	2007/2009/2012	1964/1971/1982	2007
	Nanjiang	1997	1984/1997/2010	1995
	Hexi	1992/1994/1995	1995	1985
	Hetao	1992/1995	1981/1984/1990/1997	1995
	Qaidam	1994	1979/1994	1994
	Alxa	2007/2010/2012	1969/1989/2007	1990
Pentads	Entire region	1994	1971	1994
	Beijiang	1999	1970/2006/2007	1999
	Nanjiang	1997	1967/1971/1991	1997
	Hexi	1995	1971/1972/1995/2007	1995
	Hetao	1995/2005/2007/2010	2007	1993
	Qaidam	–	1993/1996	1993
	Alxa	1999	1969/1987/1989/1999	1986

Abbreviations: Beijiang, northern Xinjiang oasis; Nanjiang, southern Xinjiang oasis; Hexi, Hexi Corridor oasis; Hetao, Hetao Plain oasis; Qaidam, Qaidam Basin oasis; Alxa, Alxa oasis.

1990s, although this took place slightly earlier in 1991 in the northern Xinjiang oasis. Mutation of the end pentad in the subregion is postponed compared to the start pentad, whereas the Qaidam Basin oasis showed an abrupt change in 1994, the earliest recorded. Mutation of pentads of cold period in the subregion occurred after the 1990s, although the Qaidam Basin oasis again showed the earliest recorded abrupt change in 1993. Mutation of the end pentad and pentads of cold period in the Qaidam Basin oasis were earlier than in other regions, further confirming that this oasis acts as a 'driver and amplifier' of global climate change. Mutation of the start and end pentad as well as pentads of cold period in Chinese oases and their subregions all occurred after the 1990s, consistent with the occurrence of subsequent marked warming in China at this time (Lin and Qian, 2003).

3.4 Period analysis

We used Morlet wavelet power spectra to analyze changes in terms of the sequence of the start and end pentad as well as pentads of cold period in Chinese oases (Figure 4). Results show that the start pentad has a period of 3.39 years and 4.98 years (α⩾0.1), while the end pentad has a period of 8 years and 10.53 years (α⩾0.1). Pentads occur with a period of 3.17 years, while the start pentad and pentads of cold period have in common a short period (3–5 years), more in line with the atmospheric circulation period of 2–4 years and the El Nino period of 2–7 years. However, the end pentad has a period of 10.53 years (α⩾0.1), which is consistent with the solar activity cycle period of 10.3–11.2 years. Thus, the start pentad and pentads of cold period appear to be mainly impacted by atmospheric circulation and El Nino events, while the end pentad is mainly influenced by solar activity.

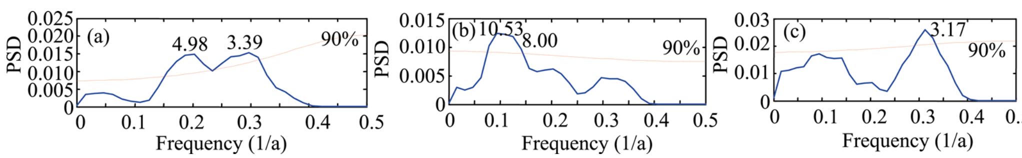

Figure 4 Morlet wavelet power spectra showing the periods of the start (a) and end pentad (b) as well as pentads of cold period (c) in Chinese oases

3.5 Correlation analysis to determine influencing factors

In order to further analyze the factors influencing the start and end pentad as well as pentads of cold period in Chinese oases, correlation coefficients with TPI, APVAI, APVII, WCI, SASM, SHI, and CDE data were calculated (Table 3). Results show that the start and end pentad as well as pentads of cold period are mainly influenced by TPI, APVAI, and CDE. The TPI is positively correlated with the start pentad, with correlation coefficients between 0.26 and 0.392 (α⩾0.05), and is negatively correlated with the end pentad and pentads of cold period, with correlation coefficients between –0.525 and –0.219. While APVAI is negatively correlated with the start pentad, with correlation coefficients between –0.578 and –0.218, it is positively correlated with the end and cold period pentads, with correlation coefficients between 0.219 and 0.617. CDE are positively correlated with the start pentad, with correlation coefficients between 0.23 and 0.627, and negatively correlated with the end pentad and pentads of cold period, with correlation coefficients between –0.567 and –0.235.

Table 3 Correlation coefficients for the start and end pentad as well as pentads of cold period in Chinese oases and possible impact factors

		TPI	APVAI	APVII	WCI	SHI	SASM	CDE
The start pentad	Beijiang	0.26*	–0.454**	–0.307*	0.213	–0.361**	–0.001	0.467**
	Nanjiang	0.287*	–0.454**	–0.41**	0.175	–0.249	–0.123	0.389**
	Hexi	0.387**	–0.371**	–0.21	0.207	–0.327*	–0.118	0.422**
	Hetao	0.355**	–0.288*	–0.13	0.178	–0.077	–0.063	0.23
	Qaidam	0.339**	–0.218	–0.055	0.122	–0.439**	–0.345**	0.627**
	Alxa	0.392**	–0.578**	–0.431**	0.186	–0.239	–0.01	0.374**
The end pentad	Beijiang	–0.23	0.322*	0.247	–0.414**	–0.045	–0.145	–0.313*
	Nanjiang	–0.525**	0.219	0.26*	–0.385**	–0.1	0.083	–0.389**
	Hexi	–0.248	0.382**	0.134	–0.235	–0.173	–0.138	–0.259*
	Hetao	–0.298*	0.302*	0.114	–0.239	–0.105	0.095	–0.235
	Qaidam	–0.324*	0.308*	0.118	0.05	–0.164	0.297*	–0.451**
	Alxa	–0.241	0.336**	0.436**	–0.306*	–0.277*	–0.138	–0.27*
Pentads	Beijiang	–0.219	0.617**	0.448**	–0.021	0.141	0.001	–0.451**
	Nanjiang	–0.406**	0.431**	0.342**	–0.229	0.145	0.045	–0.522**
	Hexi	–0.358**	0.609**	0.424**	–0.153	0.21	0.179	–0.402**
	Hetao	–0.305*	0.533**	0.37**	–0.175	0.118	0.055	–0.239
	Qaidam	–0.376**	0.428**	0.212	–0.239	0.1	0.26*	–0.567**
	Alxa	–0.371**	0.523**	0.335*	–0.088	0.045	0.045	–0.351**

Note that the abbreviations used in this table are the same as Table 2. * and ** denote α = 0.05 and α = 0.01 respectively pass the significance test.

This result is consistent with the view that excessive emissions of carbon dioxide are the main cause of global warming (IPCC, 2007). The Qaidam Basin oasis and the SASM are well correlated, with coefficients of –0.345, 0.297, and 0.26 ($\alpha \geqslant 0.05$), reflecting the low-lying southeastern part of the region containing many valleys and the presence of warm and humid air from the Indian Ocean. This result is also consistent with period analysis of atmospheric circulation. Li *et al*. (2012) found that temperature changes in northwest China are mainly affected by Siberian high pressure, and that CDE have accelerated this process. Because the thermal and dynamic effects of the Tibetan Plateau megarelief also have impacts on atmospheric circulation and climate, this region has attracted a good deal of attention from meteorologists (Duan and Wu, 2005; Li *et al*., 2012). Variation in thermodynamic properties on the Tibetan Plateau have a significant impact on the temperature of the surrounding areas, mainly reflected through changes in the surface area of snow cover and vegetation status (Liu *et al*., 2002).

3.6 Relationship with geographical parameters

In order to understand the relationships between the start and end pentad as well as pentads of cold period in Chinese oases and geographical parameters, we calculated mean values for cold period after each of the start and end pentad as well as pentads of cold period, using one degree of latitude and longitude as equal distances. However, because the altitudes of the oases in the study area are all less than 4,000 m above sea level (asl), we selected areas where altitude is less than 4000 m asl and reclassified every 100 m space as an equal distance within the area. We then calculated the mean values for the start and end pentad as well as pentads of cold period above this height on this basis.

Trends in variation of the start and end pentad as well as pentads of cold period with respect to longitude, latitude, and altitude are shown in Figure 5. Results show that as longitude increases, the start pentad is advanced, whereas the end pentad is postponed, and the pentads of cold period are extended. Change tendency rates for these effects are –0.08 p/1°E, 0.113 p/1°E, and 0.195 p/1°E (α⩾0.001), respectively. Whereas the start pentad reaches a minimum in the longitudes between 86°E and 99°E, the end pentad and pentads of cold period reach maxima. The eastern edge of the northern and southern Xinjiang oases, the western margin of the Hexi Corridor oasis, and the entire area of the Qaidam Basin oasis in the study area are distributed within longitudes between 86°E and 99°E. As longitude increases, the start pentad of cold period in the central-western part of the study area is the earliest, the end pentad is the latest, and the pentads of cold period are the longest.

As latitude increases, the start pentad is advanced, the end pentad is postponed, and the pentads of cold period are extended, with change tendency rates of –0.289 p/1°N, 0.769 p/1°N and 0.471 p/1°N (α⩾0.001), respectively. In latitudes between 47°N and 50°N, the start pentad reaches a minimum, while the end pentad and pentads of cold period reach maximum values, followed by 36°–39°N. Because the entire area of the northern Xinjiang oasis in the study area is distributed in northern latitudes between 47°N and 50°N, and the

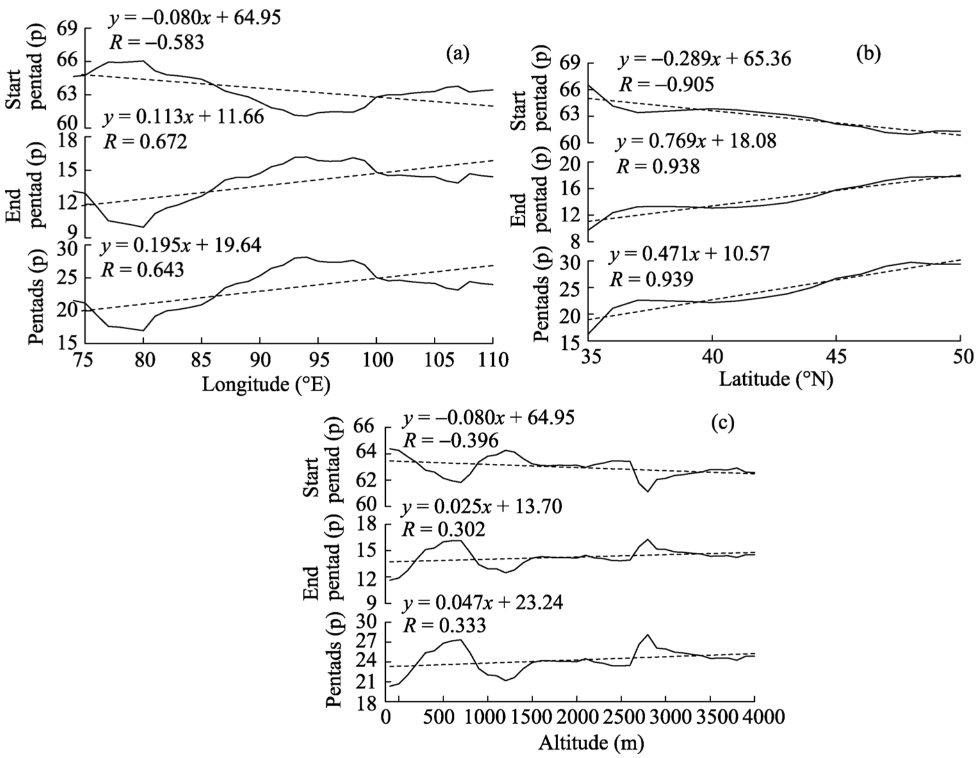

Figure 5 Mean change trends in the start (a) and end pentad (b) as well as pentads of cold period (c) at different longitudes, latitudes, and altitude ranks over Chinese oases

Qaidam Basin and southern Xinjiang oases are distributed in northern latitudes between 36°N and 39°N, the results latitude increases, the start pentad of the northern Xinjiang oasis is the earliest, the end pentad is the latest, and the pentads of cold period is the longest. The Qaidam Basin and southern Xinjiang oases are ranked in second place, confirming that latitude is also an important factor affecting cold period of the northern Xinjiang oasis.

As altitude increases, the start pentad is advanced, the end pentad is postponed, and the pentads of cold period is extended, with change tendency rates of –0.08 p/100m, 0.025 p/100m, and 0.047 p/100m ($\alpha \geqslant 0.001$), respectively. In high-altitude areas (2600–3200 m asl), the start pentad reaches a minimum, and the end pentad and pentads of cold period reach maximum values, while lower-altitude areas (below 1000 m asl) are ranked second. As altitudes 2600–3200 m asl encompass the Qaidam Basin oasis and an altitude of 1000 m asl encompasses the northern Xinjiang oasis, it is clear that as this factor increases, the start pentad for the Qaidam Basin oasis is the earliest, the end pentad is the latest, and the pentads of cold period are the longest. The northern Xinjiang oasis ranks second, this illustrates that altitude is an important factor affecting the cold period in the Qaidam Basin oasis.

3.7 Responses to regional climate warming

In order to investigate the relationship between average monthly temperature and the start and end pentad as well as pentads of cold period in Chinese oases, the average temperatures for March and for November and for the period between November and March in the subsequent year, and the annual mean temperature recorded at each station in the study area, were all collected for analysis (Figure 6). Previously, trends in average temperature changes for March and for November, and for the period between November and March of the subsequent year, showed that average temperatures in these time slices conform to a warming trend,

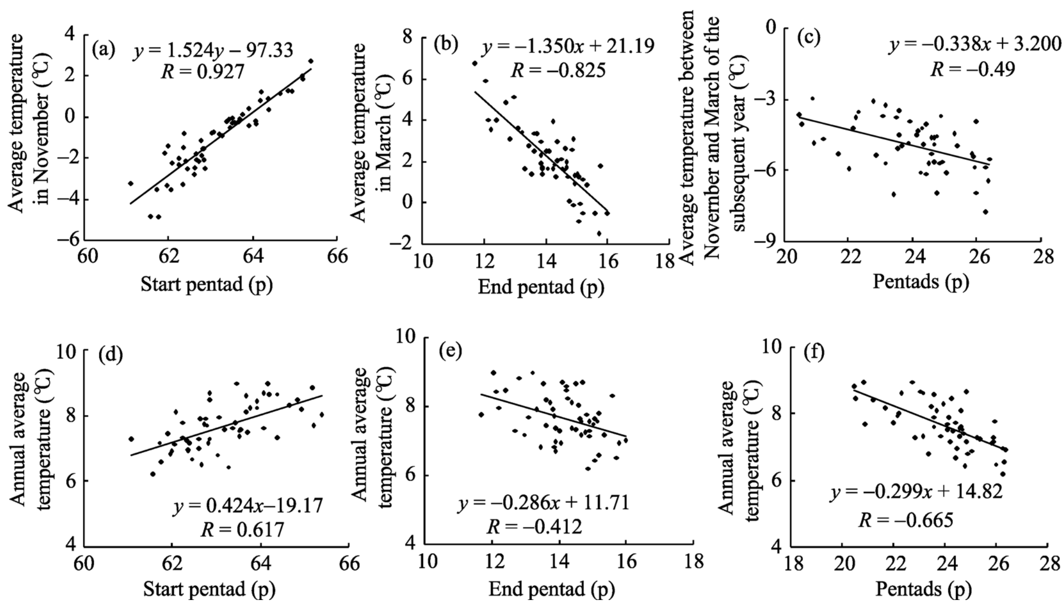

Figure 6 Relationship between trend magnitudes of the start (a), (d), end (b), (e), and pentads of cold period(c), (f) and average temperature in Chinese oases

with correlation coefficients of 0.442, 0.451, and 0.617 ($\alpha \geqslant 0.001$), respectively. These results show that the start pentad is mostly affected by November average temperature; thus, if the average temperature in November is higher, the beginning of cold period will be later. This result is supported by a correlation coefficient as high as 0.927 ($\alpha \geqslant 0.001$). Results also show that the end pentad is mainly affected by March average temperature; thus, if the average temperature in March is higher, the end of cold period will be earlier. This result is supported by a correlation coefficient as high as –0.825 ($\alpha \geqslant 0.001$). Finally, results show that the pentads of the cold period are mainly affected by average temperature during the period November to March of the subsequent year; thus, if the average temperature during this period is higher, then the cold period will be shorter. This result is supported by a correlation coefficient as high as –0.49 ($\alpha \geqslant 0.001$).

In terms of the correlation coefficient of annual average temperature and the start and end pentad as well as pentads of cold period, when annual average temperature is higher, correlation coefficients are 0.617, –0.412, and –0.665 ($\alpha \geqslant 0.001$), respectively. These results indicate that the start and end pentad as well as pentads of cold period respond very clearly to regional warming, while at the same time the correlation coefficient of the start pentad is higher than that of the end pentad. This indicates that the postponement response of the start pentad of the cold period to regional warming is more significant than advancement of the end pentad.

In order to further analyze the effects of regional warming on the start and end pentad as well as pentads of cold period, we conducted mutation tests for annual average temperature in northwest China using the Mann-Kendall test to show that there was an obvious mutation in 1987. Thus, we calculated average values for the start and end pentad as well as pentads of cold period before, and after 1987 (Table 4). Results show that, subsequent to 1987, the start pentad mutation has been postponed by 0.9 pentad, while the end pentad has advanced by 0.8 pentad, and the cold period has been shortened by 1.8 pentads. This indicates that regional warming has had different effects on the start and end pentad as well as pentads of cold period, and that its influence of the start pentad has been greater than on the end pentad.

Table 4 Mean values of the start and end pentad as well as pentads of cold period between 1960 and 1986, and between 1988 and 2014 in Chinese oases

	Start pentad (p)	End pentad (p)	Pentads (p)
Before abrupt change	62.7	14.6	24.8
After abrupt change	63.6	13.8	23
Influence	Postponed	Advanced	Shortened

4 Conclusions

(1) Over the last 55 years, the start pentad of cold period has been postponed, the end pentad has been advanced, and the pentads of cold period have been gradually shortened. Trend rates for these phenomena are 0.3 p/10a, –0.27 p/10a, and –0.58 p/10a, respectively. Mutation points for the start and end pentad as well as pentads of cold period were seen in 1990, 1998, and 1994, respectively, consistent with strong warming in China after 1990.

(2) Spatial differences in the start and end pentad as well as pentads of cold period are

significant. The cold period in the Qaidam Basin oasis starts earliest, ends latest, and has the longest cold period, while the northern Xinjiang oasis is placed second. The cold period in the southern Xinjiang oasis starts latest, ends earliest, and has the shortest cold period. The rate of change in the cold period in the Qaidam Basin oasis is most obvious, however, suggesting that this has the most sensitive responses to global climate change.

(3) The TPI, APVAI, and CDE are the main factors affecting the cold period in the study area, while the SASM exerts the greatest influence on the Qaidam Basin oasis. Wavelet analysis shows that the start pentad and pentads of cold period are closely related to atmospheric circulation and El Nino events, whereas the end pentad of cold period is closely related to solar activity.

(4) As longitude increases, the start and end pentad as well as pentads of cold period exhibit change rates of –0.08 p/1°E, 0.113 p/1°E, and 0.195 p/1°E, respectively, while as latitude increases, these rates are –0.289 p/1°N, 0.769 p/1°N, and 0.471 p/1°N, respectively. As altitude increases, the change rates are –0.08 p/100m, 0.025 p/100m, and 0.047 p/100m, respectively.

(5) Average temperature in March, November, and the period between November and March of the subsequent year exert the greatest effects on the start and end pentad as well as pentads of cold period, respectively. The start and end pentad as well as pentads of cold period have shown good responses to regional warming, but there have been different effects on all three. Postponement of the start pentad as a regional warming response is more significant than advancement of the end pentad.

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