Rainfall spectrum change in North China and its possible mechanism*

DAI Xingang[1,2]**, WANG Ping[3], ZHANG Peiqun[4] and CHOU Jifan[1]

(1. College of Resources and Environmental Sciences, Lanzhou University, Lanzhou 730000, China; 2. State Key Laboratory LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029, China; 3. College of Physics, Peking University, Beijing 100871, China; 4. National Climate Center, Beijing 100081, China)

Received October 13, 2003; revised November 20, 2003

Abstract The seasonal distribution of the rainfall in North China has changed greatly since 1977, with more rainfall in spring and less in July, August, and September (JAS). Wavelet analysis showed that the JAS rainfall underwent an abrupt spectrum change in the mid-1960s. Its interannual variability has declined while the interdecadal component has become the dominant mode, associated with the dry climate. Correlation analysis found that the JAS rainfall is negatively correlated with the departures of the 500 hPa geopotential height significantly over the northwest and southwest of China, and positively correlated with the summer monsoon over eastern China. Therefore, the interdecadal ascending of the air pressure in northwestern China and the monsoon decaying over East Asia in the past 20 years may be the two major causes of North China drought.

Keywords: North China drought, wavelet spectrum abruption, monsoon, geopotential height, interdecadal change.

North China began to experience a dry climate from the mid-1960s and a severe drought after the 1980s[1~3]. The Yellow River, the greatest river in northern China, has also dried up frequently in recent 20 years[4]. The water shortage has brought forth many problems on agriculture and daily life[5]. In order to alleviate the predicament the Chinese government has launched the great project for introducing the water of Yangtze River to Yellow River. Under such circumstances, to explore the cause of the North China drought and its future trend becomes an urgent task for Chinese scientists.

The rainfall in July, August and September (JAS) may be influenced by the monsoon and the cold air activities on boreal westerlies, for it assembles in North China during the rainy season (July ~ September). Generally the monsoon variability highly involves the sea surface temperature anomalies, for example, during El Nino years, the East Asian monsoon[6] and South Asian monsoon are usually weak[7, 8], accompanied by a dry summer climate in North China[9]; whereas, in La Nina years, an opposite effect dominates the atmospheric circulation over East Asia. Nevertheless, the La Nina events are generally less than the El Nino ones, and have less influence on East Asian circulation. Another study found that the interdecadal abrupt change of Asian and African monsoon was associated with the monsoon decaying[10], and the rainfall decreased simultaneously on the belt of Sahara-Sahel-Middle East-northern India-North China. Hence, the drought in North China is under a planetary circulation background with the weakening of the whole Asia-African monsoon system.

The cold current intensity over North China is related to the quasi-stationary waves on the westerlies. The anomaly of the westerlies might be due to many factors, for instance, the sea ice and the great ice sheets covering the Arctic region[11]. The retreat of the ice sheets has come to scientist's attention because it can influence the Artic Oscillation (AO) and, therefore, the atmospheric general circulation in middle latitude in connection with North China climate[12].

Besides, human activities can also significantly influence the distribution of wet and dry climate in China. For instance, the thermal effect of the black carbon aerosols might decrease atmospheric hydrostatic stability over southern China and bring more rainfall there[13], which prevents the summer monsoon from further advancement northward in eastern China and, thereby, forms a rainy climate in the south of China and a drought in the north in recent 20 years.

* Supported by the National Natural Science Foundation of China (Grant No. 49875024), the Major State Basic Research Development Program of China (Grant No. G1999043400) and State Key Laboratory LASG, Chinese Academy of Sciences
** To whom correspondence should be addressed. E-mail: daixg@lzu.edu.cn

A numerical investigation[14, 15] proposes that the major rainfall belt over China would shift northward in rainy season and significantly increase the precipitation in North China if atmospheric CO_2 continuously increases in the future.

The meteorological observation shows that two interdecadal abrupt changes of atmospheric general circulation took place in the mid-1960s and the end of 1970s[16~18], respectively. In recent 20 years the summer thermal lows in India and Central China became weaker than those before 1977, and the 500 hPa geopotential height had significantly ascended over northwestern China. Moreover the subtropical high over the northwestern Pacific appeared more frequently in a position further south and further west than its climate in recent 20 years[17, 18]. These changes brought forth a decadal weak summer monsoon and a dry climate in North China, and, conversely, a rainy climate in the south of China. Thus, the persistent drought in North China is a climate event on interdecadal time scale.

In the following, we will first investigate the characteristics of the North China rainfall in rainy season by using wavelet transform, and then study its connection with the interdecadal changes of the summer monsoon and the atmospheric circulation over East Asia.

The North China rainfall data we used are recorded by 17 standard observatories that belong to Hebei and Shanxi provinces, Inner Mongolia autonomous region, and two cities: Beijing and Tianjin. The monthly rainfall records cover the period 1951 ~ 2000. The 850 hPa wind and 500 hPa height fields are NCEP reanalysis data sets with a resolution $2.5^{\circ}\times 2.5^{\circ}$ for both latitude and longitude. The Fortran code of wavelet transform is supplied by C. Torrence of National Center for Atmospheric Research (NCAR)[19].

1 Rainfall in North China

North China is situated in the arid and half-arid climate zones. Its annual precipitation is about 424 mm on average, 70 percent of which falls within June through September. The climate rainfall peak is in July and August. The trend of its annual rainfall is about -1.8655, less than the one -4.5791 for June-September (JJAS). In other words, the annual precipitation decreased by about 1.9 mm/yr versus 4.6 mm/yr for the JJAS rainfall. It seems that the North China drought is greatly associated with the JJAS rainfall decreasing. Besides, the more positive departures of the rainfall appeared in the 1950s and the beginning of the 1960s, while the more negative ones can be found in recent 20 years. The maximum and minimum departures are 815 mm and -500 mm, appearing in 1959 and 1965, respectively.

Besides, the seasonal rainfall distribution has changed in recent 20 years. The rainfall difference of 1978 ~ 1998 and 1956 ~ 1976 shows that the monthly rainfall increased in March, May and June, but decreased in January, April and July through November (Fig. 1). This shows that the North China drought can be well characterized by the decreasing of the rainfall in rainy season (JAS).

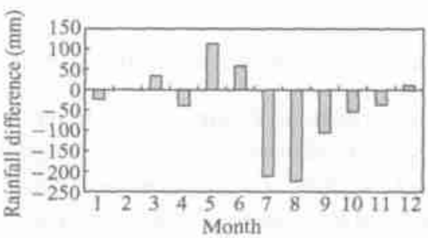

Fig. 1. Interdecadal change of monthly rainfall in North China, represented by the mean difference between 1978 ~ 1998 and 1956 ~ 1976.

1.1 Wavelet analysis

Wavelet analysis provides a powerful tool for studying local spectra at different scales or periods[20]. In this section we use Morlet wavelet to study the multi-scale characteristics of JAS rainfall. Wavelet transform of the rainfall sequence shows that there exist periods of 2, 5, 10 and about 18 years. The positive (negative) departures of the JAS rainfall are more closely related with the positive (negative) phase of 18-year period component. Thus, the interdecadal component behaves somehow like a modulation of the rainfall variability. In addition, the big departures, positive or negative, are mostly constituted by more than two components with different scales at the same phase. For example, the positive departure in 1959 is made up of 2-year, 10-year and 18-year components at their positive phase, while the negative one in 1999 consists of 10-year and 20-year periods at their negative phase. These phenomena reveal important impacts of the frequencies and phases on the rainfall evolution and provide a new multi-scale method for inter-seasonal climate prediction, which indicates that the phase evolution for different scale components should be well considered in the forecasting operation.

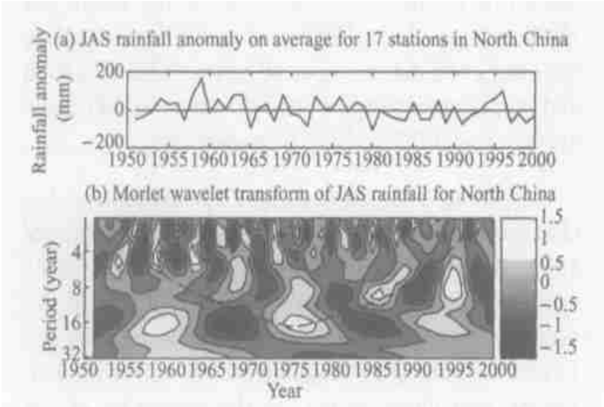

Fig. 2. JAS rainfall anomaly in North China during 1951 ~ 2000 and its wavelet transform. (a) Rainfall anomaly, unit: mm; (b) Morlet wavelet transform.

1.2 Interdecadal change of rainfall spectrum

The interdecadal change refers to variation on a scale of several decades. The JAS rainfall spectra (Fig. 2(b)) exhibit an abruptly interdecadal change in the mid-1960s, namely, the spectrum of 5-year period disappeared and 10-year spectrum appeared. In addition, the biennial oscillation has gradually declined since the mid-1960s, especially, after 1980, when North China began to experience a severe dry climate. Therefore, the persistent drought in North China is characterized by the weakening of the rainfall interannual variability. A sudden strengthening of the interannual variance in 1996 was brought about by a typhoon invading, a climate noise.

As we have mentioned, two interdecadal abrupt changes of atmospheric general circulation took place in the mid-1960s and the end of 1970s[16~18], respectively. Accordingly the abrupt rainfall change appeared nearly at the same time as the circulation. The first abrupt change of the rainfall in the mid-1960s is a sharp spectrum change, while the second one exhibits an overlapping of different components at their negative phase and a considerable decaying of the biennial oscillation. The former can be regarded as a qualitative change against the latter, a quantitative one.

Beijing Observatory has the longest precipitation records in North China, which can be regarded as a reference for study of the interdecadal change of North China rainfall. Its continuous monthly precipitation records from 1914 ~ 2000 are taken for analysis. It shows that Beijing's rainy climate appeared in the 1920s and 1950s, respectively, accompanying intensive interannual variability, while the dry climate covers the 1930s, 1940s and the period after the mid-1960s, corresponding to a weak interannual variability. In short, the drought in Beijing is well correlated to the weakening of the interannual variability, similar to North China drought, especially, in recent 20 years. This result is also supported by a recent numerical simulation[15]. The wavelet analysis for Beijing rainfall in rainy season shows a spectrum abrupt change in the mid-1960s, which is similar to North China during recent 50 years.

2 Correlation of rainfall and height

Since North China lies in the middle and high latitude zones, its rainfall variability can be partly interpreted by the geopotential height anomaly over Euro-Asian continent for different rainfall patterns may be correlated with different height anomalies. We calculate the correlation between the monthly rainfall and the height field so as to find out the possible circulation patterns associated with North China drought. To attenuate the noise of the rainfall and the height sequences, a 3-year running-mean operation is performed before calculation. The two sequences are both from 1951 to 2000.

In Fig. 3, a significantly negative correlation pattern exists in western China, which indicates that the interplay between cold air from the west and warm-wet air from the southwest is important to North China rainfall in the season. In July, a significant negative correlation center is located at Balkhash Lake, and a positive center is over the Korean peninsula. Hence, more (less) rainfall in North China is associated with more (less) cold current coming from Xinjiang, an autonomous region in northwestern China, and meanwhile the subtropical high in northwestern Pacific lies in a further north (south) position than its climate. In August, the negative correlation center over Balkhash Lake becomes weak and the maximum center appears in the southwest of China. Therefore the rainfall primarily depends on the intensity of the warm and wet wind coming from the southwest of China. But the rainfall still needs the cold currents from western China. In September, the negative center moves onto the south nearby Baykal Lake, which indicates that the cold air activity from Mongolia is much more important for the rainfall in the month. By all accounts, the more intensive the cold air currents, the more the rainfall in North China, apart from the warm and wet wind from the south of China.

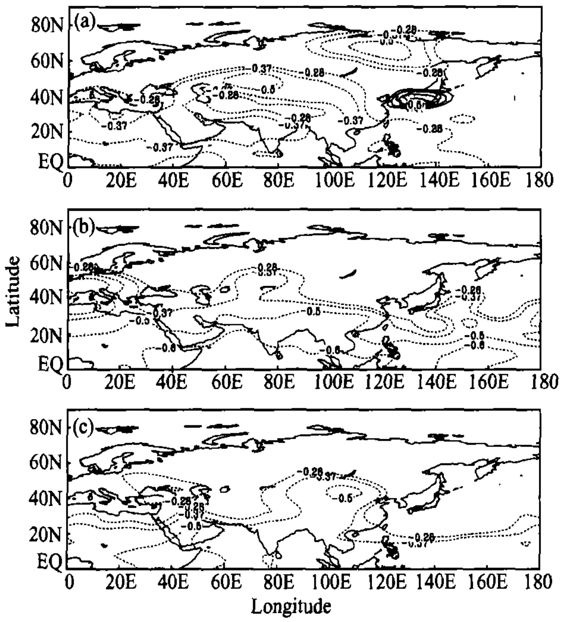

Fig. 3. Correlation between 3-year running-mean 500 hPa height field and monthly rainfall for 1951 ~ 2000. (a) July; (b) August; (c) September.

3 Drought and interdecadal change of height field

The correlation between the rainfall and 500 hPa height field (Fig. 3) reveals that the drought of North China corresponds to more positive anomalies of the height over northwestern China and Mongolia. We found that the interdecadal change could dominate the 500 hPa height departures[17] in China. For example, according to several box-mean sequences of 500 hPa height in eastern China more positive departures can be found after the abrupt change in 1977, and more negative ones appeared before 1977. Thus the interdecadal change of the atmospheric general circulation is one of the important causes that lead to the height ascending, which is associated with North China drought in recent 20 years.

Statistical testing demonstrates that the abrupt change of atmospheric general circulation in the late 1970s is the major one by comparing with others[18]. We cut the height sequences of every grid at 1977 to get two sequences for 1956 ~ 1976 and 1978 ~ 1998, respectively, and then make the average operations on each of them, and obtain two climate-mean height fields for the two periods. The difference field between them describes the distribution of the interdecadal change of 500 hPa height field in recent twenty years. The most pronounced feature shown in Fig. 4 is a large positive belt extended from Xinjiang to Baykal Lake, which evinces that the height over northern China, especially over northwestern China, has significantly ascended in recent 20 years. In the same month, the positive centers shown in Fig. 4 are approximately corresponding to the significantly negative correlation centers over northern China in Fig. 3. Therefore, the interdecadal ascending of the 500 hPa height over northwestern China and Mongolia is the main circulation background for the persistent drought in North China.

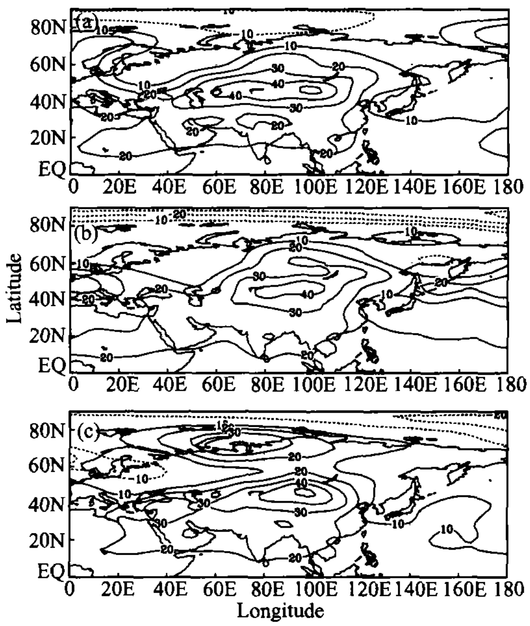

Fig. 4. Interdecadal change of 500 hPa geopotential height field represented by the difference between 1978 ~ 1998 mean and 1956 ~ 1976 mean. (a) July; (b) August; (c) September; unit: gpm.

4 East Asian monsoon

The East Asian monsoon is another important factor for North China rainfall. East Asia is one of the most famous monsoon regions in the world, where the monsoon has its own characteristics, different from others. There is a subtropical monsoon convergence zone along the northwestern edge of the subtropical high in northwestern Pacific Ocean, which is called Meiyu front in summer, made up by southwest monsoon and southward wind from high latitudes[21]. During the weak monsoon years, the Meiyu front is intensive and brings more rainfall to the valley of the Yangtze River and the Huaihe River, and meanwhile, a dry climate is dominant in North China, and *vice versa*. Our previous study shows that the summer monsoon lows in China and India apparently weakened in recent 20 years[17]. As mentioned above the monthly rainfall of North China is mostly decreased in July and August, which implies the importance of the monsoon weakening for the drought development. We will first calculate the correlation between the monthly rainfall and the meridional wind on 850 hPa, which approximately represents the summer monsoon intensity over East Asia, and then study the interdecadal change of the summer monsoon and its relationship with the drought of North China.

The intensity of the monsoon is usually defined by a monsoon index. There are several indices defined for East Asian monsoon[22, 23], such as using the surface pressure difference across the eastern coast of China[22]. Nevertheless, Li et al.[24] studied the rationality on description of monsoon by use of meridional wind on 850 hPa (hereafter referred to as MW). In this paper we employ the MW to represent the intensity of the East Asian summer monsoon.

The monthly rainfall of North China, as is expected, is significantly correlated with the MW in eastern China, an active region of the summer monsoon. It clearly shows that the more intensive the summer monsoon, the more the rainfall in North China. Hence the North China drought should correspond to a weak summer monsoon.

When comparing Fig. 5 with Fig. 3, one can find that their significant correlation regions are located in different regions, where the height-related correlation regions are in western and northwestern China, while the monsoon-related regions cover almost all the East Asian monsoon zone[24], including North China. So the monsoon variability is more directly associated with the North China drought in recent 50 years.

Though the East Asian monsoon experienced two interdecadal abrupt changes in the mid-1960s and the end of 1970s, respectively, which are very similar to the rainfall changes in North China, we here only analyze the latter and its impacts on the North China rainfall in rainy season. Employing a method that is the same as that given in the previous section we get the interdecadal difference of 850 hPa monthly MW (Fig. 6). It shows a negative difference over eastern China, which means that the East Asian summer monsoon weakened in recent 20 years. Considering the correlation pattern in Fig. 5 it turns out that the monsoon weakening is another important cause for North China drought.

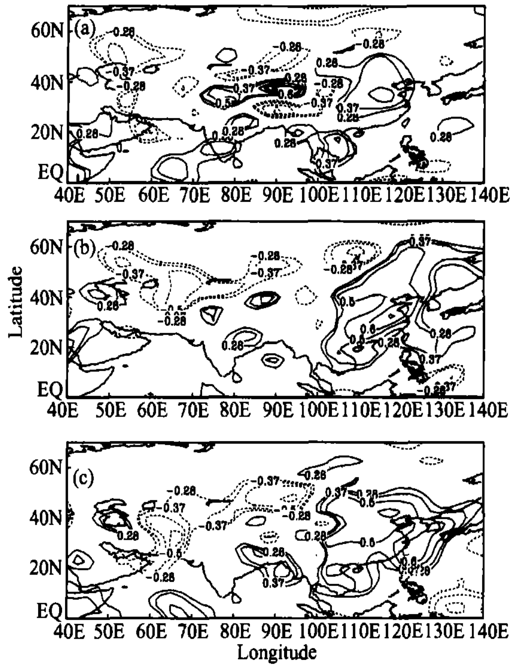

Fig. 5. Correlation between 3-year running-mean 850 hPa meridional wind and monthly rainfall for 1951 ~ 2000. (a) July; (b) August; (c) September.

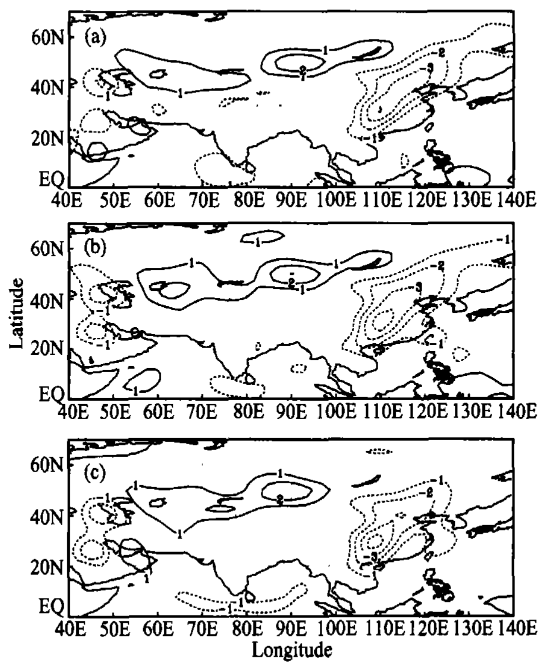

Fig. 6. Inderdecadal change of 850 hPa meridional wind field represented by the mean difference between 1978 ~ 1998 and 1956 ~ 1976. (a) July; (b) August; (c) September; unit: ms^{-1}.

5 Quasi-stationary waves

The anomaly of the quasi-stationary wave (hereafter referred to as QSW) on boreal westerlies may influence the rainfall of North China. The interdecadal change of the geopotential height or pressure can affect the QSW amplitudes and phases, which are related to the zonal distribution of dry or wet climate in northern China. Since the height difference fields of July and August (JA) are very similar (Fig. 4 (a), (b)), and so do their interdecadal changes (Fig. 1), we only study the JA mean QSW. The QSW is usually defined by the height departures from a reference state that, usually, is the climate height averaged on a latitude ring. However, to well display QSW and its anomaly over Euro-Asian continent, the reference state used here is JA-mean climate height averaged on a domain 10°E ~ 180° at a latitude ring, in which the departures just represent the QSW on the domain. The QSW in 1956 ~ 1976 is very different from that in 1978 ~ 1998 (Fig. 7). Before 1977 there was a very large trough over northern China, Mongolia and West Siberia, while after 1977 the trough greatly weakened and became a very narrow belt from the Korean Peninsula to Indian subcontinent. Meanwhile a QSW ridge evolves over northwestern China, Mongolia and West Siberia due to the height ascending there in recent 20 years. In other words the boreal QSW had declined and shifted eastward. This change can also be clearly shown by the comparison of several climate mean isohypses before and after 1977[17] on 500 hPa. In consequence, the ascending of the height over northern Asian continent restrained the boreal cold air currents from entering the North China and, therefore, reduced the North China rainfall in rainy season.

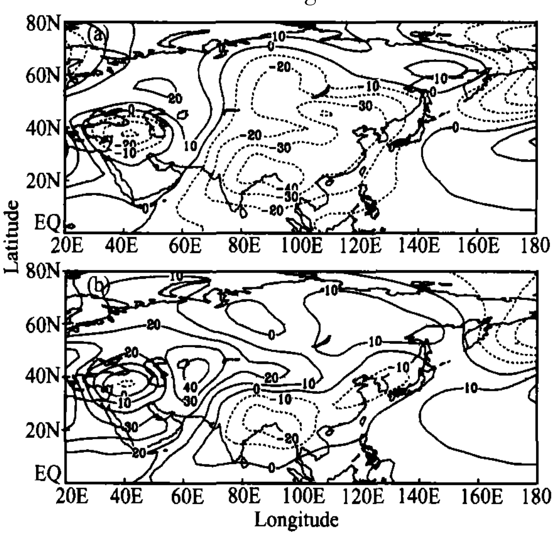

Fig. 7. Quasi-stationary waves of 500 hPa height fields for July and August. (a) 1956 ~ 1976; (b) 1978 ~ 1998; unit: gpm.

Moreover, the height ascending in the northwest of China produced a geostrophic wind southward over eastern China, which partly offsets the East Asian summer monsoon and consequently decreases the rainfall in North China. Besides, the strengthening of the westlies and QSW weakening confine not only the cold air activity but also the advancement of the summer monsoon. So, the abnormal QSW is also one of the important causes for North China drought in recent 20 years.

6 Conclusion and discussion

In recent 20 years the North China rainfall significantly decreased in rainy season and its interannual variability became weakening since the mid 1960s according to the wavelet analysis. The spectrum abrupt change occurred in the mid-1960s with a sudden disappearance of 5-year spectrum. And then the biennial oscillation had gradually declined since 1970.

We find that the interdecadal change of atmospheric general circulation and the East Asian summer monsoon have important effects on the rainfall spectrum abrupt change and the drought of North China. Due to interdecadal change, the geopotential height ascended in northern and northwestern China, the quasi-stationary waves became weak and shifted eastward, which restrained the summer monsoon and the cold air activity from driving the North China rainfall. The correlation analysis shows that the dry climate corresponds to a weak summer monsoon over East Asia, and the wet climate is coupled with intensive monsoon. The sharply decaying of the summer monsoon in the mid-1960s was almost coincided with rainfall spectrum abrupt change. In recent 20 years both the East Asian summer monsoon and quasi-stationary waves in middle and high latitudes had became very weak, when North China experienced a severe drought. Consequently, the monsoon decaying and the weak cold air activity on boreal westerlies are the major causes for the persistent drought in North China during recent 20 years.

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