Spatial Distribution and Temporal Variation of the Winter Wheat Late Frost Disaster in Henan, China*

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ABSTRACT

The winter wheat late frost disaster (WFD) occurs mainly in the Yellow and Huaihe River area, of which Henan Province covers the most part. Henan is the major area of wheat production in China, but it is severely hit by the WFD. In this study, we construct a WFD index based on the minimum temperature and the winter wheat development period (WDP). The WFD degrees and days at 30 agrometeorological stations in Henan Province during the period of 1981–2004 are calculated. For the large-scale temporal variation analysis of WFD, the 24-yr WDP observation series is relatively short, so it is expanded by using the relation between the turning green date of winter wheat and the 5-day running mean temperature and that between the stem elongation phase and the effective cumulative temperature above a critical value of 2.5 °C. The WFD data are also expanded for the last 50 years and are analyzed by using the empirical orthogonal function (EOF) and the Morlet wavelet methods. Characteristics in the spatial distribution and temporal variation of WFD are revealed. The results show that the frequency of WFD is generally high, exceeding 40% in parts of Henan, and exhibits a rising trend in the period of 1970–1990. The variation trend of WFD degrees is similar to that of WFD days, and the areas with higher WFD degrees coincide the areas with more WFD days. Moreover, the WFD degree has a greater impact on the winter wheat yield than the WFD days. The areas with high WFD degrees lie in the southeast and southwest of Henan, and the areas with low WFD degrees lie in the south of the Huaihe River and parts of western Henan. Temporal variations of the first and second EOF modes of the WFD degree display 16- and quasi-22-yr periodicities, respectively. The areas of high (low) WFD frequency are distributed in the northern Henan and the southwest border of Henan (the northeast Henan and the middle part of southwest Henan). The temporal variation of the first (second) EOF mode of WFD days exhibits a periodicity (periodicities) of quasi-4 yr (quasi-3 and quasi-6–7 yr).

Key words: late frost disaster, frost index, EOF analysis, Morlet wavelet analysis

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1. Introduction

As one of the important wheat producing areas and the main demonstration zone for the implementation of the National High-yield Crop Science and Technology Project in China, the Yellow and Huaihe River region has more than 30% wheat plantation area and yield in the whole country. This greatly alleviates the grain shortage in China. The wheat yield in this region directly impacts the food reservation, acreage allotment, import and export planning, and future trading of wheat in China. However, the wheat

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agro-yield fluctuates greatly due to meteorological disasters. Frost, as one of the main agrometeorological disasters, has considerable influences on high and stable wheat yields in the wheat producing areas of the Yellow and Huaihe River. According to previous studies (Feng et al., 1999), more than 3.5×10^6 ha wheat plantation areas in China suffer from the frost disaster in a hard-hit year, which accounts for 70% of the total wheat plantation area. Consequently, the wheat yield decreases by 30%–50% in stricken provinces, and 60%–70% in hard-hit areas. The frequently-hit and hard-hit regions by frosts are concentrated in the Yellow and Huaihe River area. For example, in winter and spring 2005, 333333 ha area of wheat in the Yellow and Huaihe River area suffered frostbites. The hardest-hit province is Henan, of which 40% experienced severe frost, and some wheat fields even had no harvest.

Henan Province is located in the central part of the Yellow and Huaihe River area, covering nearly 50% of the whole area in size. It has the largest wheat plantation area in all provinces of China, and frequently suffers late frostbites. There are dense agrometeorological observation stations in Henan, which provide sufficient information and samples for the wheat development period (WDP) caculation. Therefore, in this study, we take Henan as an example to analyze the spatial distribution and temporal variation of the winter wheat late frost disaster (WFD).

2. Data and method

All daily meteorological data (1961–2004) and WDP data (1981–2004) are provided by the Henan Provincial Meteorological Bureau. The wheat regreening period data from 1961 to 1980 are obtained based on the temperature index, while the wheat jointing data during the same period are gained based on the accumulated temperature index over the regreening and regreening-jointing periods.

The Empirical Orthogonal Function (EOF) and Morlet wavelet analysis are employed to investigate the spatial distributions and temporal variations of WFD degree and occurrence days.

3. Construction of the WFD index

The WFD refers to the winter wheat suffering from frostbites in the jointing period when air temperature is lower than 0 °C or the leaf temperature is lower than −4 °C. The cold-resistant ability of winter wheat is closely related to the number of days after the jointing. The stricken wheat exhibts different degrees of severity in different parts and with various symptoms of being frosted. The winter wheat has the weakest cold-resistant ability during the wheat pistil and stamen differentiation period, 10–15 days after the jointing (namely the temperature sensitive period). During this period, low temperature may lead to severe frost.

The WFD is associated with the WDP and minimum temperature. The WDP is related to jointing days. Based on prior WFD indices (Shi and Mao, 1994; Han, 1999; Feng et al., 2000) and the relation between minimum temperature and minimum ground temperature (mainly used for late frost remote-sensing monitoring) (Zhang et al., 1991), the qualitative WFD index is calculated using minimum air temperature, minimum ground temperature, and minimum leaf temperature.

As shown in Table 1, the WFD index is classified as light and hard. In order to analyze the late frost disaster quantitatively, we define a new frost index I that involves days (Δd) after wheat jointing and the minimum temperature ($T_{\min}$) as follows:

$$I = f(\Delta d) + g(T_{\min}), \tag{1}$$

Table 1. The WFD Index classified by different ranges of temperature (unit: °C)

WFD Index	Days after wheat jointing (Δd)	1–5 days	6–10 days	11–15 days	⩾16 days
Light	Minimum air temperature	–1.5–2.5	–0.5–1.5	0.5–0.5	1.5–0.5
	Minimum ground temperature	–3.1–4.1	–2.1–3.1	–1.1–2.1	0–1.1
	Minimum leaf temperature	–4.5–5.5	–3.5–4.5	-3.0–3.5	–3.0–1.0
Hard	Minimum air temperature	<–2.5	–1.5–2.5	–0.5–1.5	0.5–0.5
	Minimum ground temperature	<–4.1	–3.1–4.1	–2.1–3.1	–1.1–2.1
	Minimum leaf temperature	<–5.5	–4.5–5.5	–4.0–4.5	–4.0–1.5

where Δd is the number of days after wheat jointing, $\Delta d < 0$ represents the number of days before the jointing, and $\Delta d > 0$ represents the number of days after the jointing; $f(\Delta d)$ is the piecewise function related to Δd; $g(T_{\min})$ is the piecewise function related to $T_{\min}$, which is the minimum daily temperature.

The values of $f(\Delta d)$ and $g(T_{\min})$ are given in Table 2. They are classified as six levels (0–5) in sequence, corresponding to different ranges of values of Δd and $T_{\min}$, respectively. Table 2 shows that there is no frost when I is less than 5; otherwise, a frost disaster occurs. The higher the value of I, the more serious the frostbite is. $I = 5$ means a light frost while $I \geqslant 6$ means a hard one. In this way, the WFD indices are quantified.

The yearly maximum value of I is defined as the WFD degree in a specific year and the number of frost days of I are defined as WFD days in this year. They can be obtained by calculating the daily values of I according to Eq. (1) using the multi-year data. The WFD degree and the WFD days reflect characteristics of the local late frost of winter wheat.

Table 2. Values of the two piecewise functions $f(\Delta d)$ and $g(T_{\min})$

Values	0	1	2	3	4	5
Δd (day)	< 0	1–5	6–10	11–15	>16	
$T_{\min}$(°C)	> 1.5	$0.5 \leqslant T_{\min} <1.5$	$-0.5 \leqslant T_{\min} <0.5$	$-1.5 \leqslant T_{\min} <-0.5$	$-2.5 \leqslant T_{\min}<-1.5$	<-2.5

4. Annual mean WFD degree and WFD days

Analysis of the WFD characteristics needs long-term data series. The WFD is associated with the minimum daily temperature and the number of days after the jointing. In this paper, the minimum daily temperature data cover a long period of time (since the establishment of the observatory), while the WDP observations are not initiated until 1981 with missing data in the first few years. Therefore, it is necessary to process WDP data first so as to obtain a complete dataset with required length.

4.1 Data processing

In order to extend the wheat jointing period data series, daily meteorological data are first used to reckon the WDP data for 1961–1980 and some other years after 1980 with missing WDP data.

According to the accumulated temperature theory, the total daily average temperature above a critical temperature, namely the effective accumulated temperature, which is required over the period when a certain crop transforms from one development stage to the next, is always about the same. Therefore, the jointing period can be calculated from the regreening period if the effective accumulated temperature over the period between wheat regreening and regreening-jointing is known.

Based on the multi-year observation data and experimental results, the lower critical temperature during wheat regreening-jointing period in Henan Province is 2.5 °C. The WDP observational data from 1981 to 2004 at 30 agrometeorology observatories are used to calculate the effective accumulated temperature above 2.5 °C over the wheat regreening-jointing period for each year at each observatory. The multi-year arerage value at one agrometeorology observatory can be used as the theoretical effective accumulated temperature in winter wheat regreening-jointing period at this observatory.

Winter wheat regreening date at each agrometeorology observatory is obtained by using the meteorological index in regreening period, which is defined as the initial date of regreening when the 5-day moving average of temperature stably exceeds 0 °C. However, according to the "Criterion for Agrometeorological Observations" (China Meteorological Administration, 1993), the wheat regreening date is defined as the date when "wheat resumes growth in early spring with the length of interior leaf being 1.0–2.0 cm". Based on long-term observations, the interior leaf grows by 1.0–2.0 cm about 4 days after the temperature stably exceeds 0 °C. Combining the two definitions of the meteorological index, the wheat regreening date is therefore defined as the first day with the daily average temperature over 0 °C plus 4 days.

Annual wheat jointing period can be determined according to theoretical effective accumulated temperature required in regreening and regreening-jointing periods. This method is validated by comparing the calculated wheat jointing period with the observations during 1981–2004. The results indicate that the average absolute error over 24 yr at 30 observatories in Henan Province is 4.7 days (table omitted). According to the classification of the WFD index, the interval of days after wheat jointing at different frost levels is 5 days, which is higher than the error. Therefore, this method can be used to determine the jointing period in 1961–1980.

4.2 Distributions of average WFD degree and WFD days

The late frost index I is calculated based on wheat jointing period data and annual and daily minimum temperature data. The annual maximum frost index (used as late frost degree in that year) and the number of frost days at each observatory are then obtained. The average degree and number of days of the late frost disaster in China are determined by their multi-year average values.

Figure 1 shows distribution of the WFD degree averaged over 1961–2004 in Henan Province. It is seen that the high WFD degree area lies in the boundary area of Henan Province, i.e., Nanyang Basin in southwestern Henan, western Anyang in northern Henan, and eastern Zhoukou in eastern Henan. The average frost indices in these areas are above 2.5, which is associated with the geographic location. The low WFD degree areas are mainly located along the two banks of the Yellow River and extend from northwest to the south of Henan. The average late frost indices are below 1.5. Besides geographic location, the WFD degree is also related to irrigation status. Relevant studies indicate that watering in advance can obviously alleviate WFD. Most of the rest regions and cities have intermediate frost, with the average WFD index of 1.5–2.5.

The number of WFD days in Henan has a "saddle" distribution (Fig. 2). The region with more WFD days corresponds to the region with high WFD degree. These regions include the northern, northeastern, and southwestern boundaries of Henan, with the average number of WFD days being 0.6. Light frost occurs in most parts of southwestern Henan with the average WFD days of 0.2. The rest of the province is intermediately frosted with the average WFD days of 0.2–0.6.

The annual WFD degrees at five agrometeorology observatories in Henan Province are plotted in Fig. 3. We see that there is no obvious change of annual WFD degrees in most areas from the 1960s to 1970s, but the annual WFD degree in the north of Henan shows a descending tendency. During the 1970s–1990s, annual WFD degrees in most areas have a rising tendency, among which the WFD occurs frequently with the frequency of 34%–45.5% in part of the southwest and north, about 27% in the middle and south, and about 16% in the east of Henan (Fig. 3).

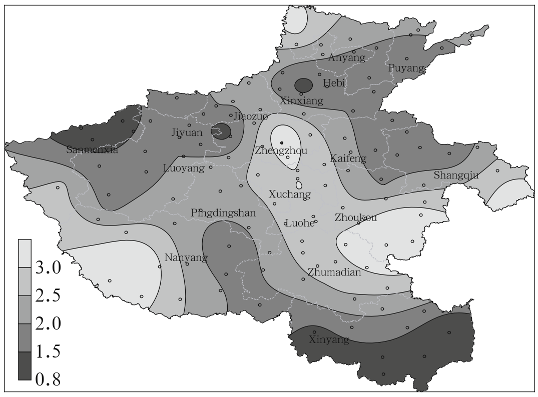

Fig. 1. Distribution of WFD degree averaged over 1961–2004 in Henan Province.

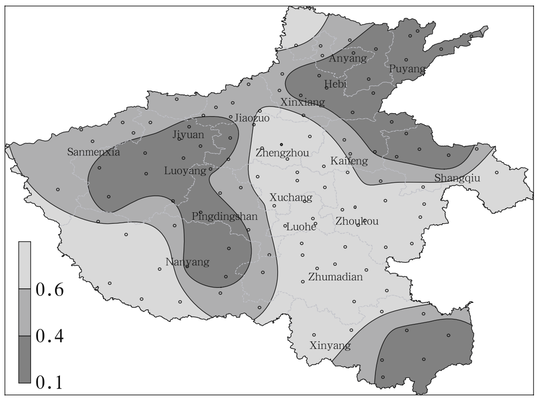

Fig. 2. Distribution of the number of WFD days averaged over 1961–2004 in Henan Province.

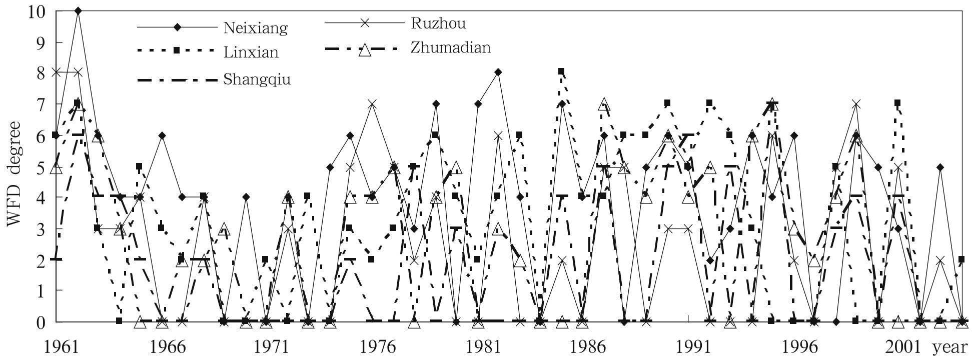

Fig. 3. Annual WFD degrees at five representative stations in Henan Province during 1961–2004.

5. Temporal-spatial distributions of WFD degree and WFD days

The temporal-spatial variations of WFD degree and WFD days in Henan Province are analyzed by using the EOF method, which is commonly used for temporal-spatial analysis in the atmospheric sciences. This method is applied to studying the temporal-spatial structures of a single element time series F that is a vector collection. It can compress large amount of primary data by picking out the most frequent or dominant temporal-spatial variation patterns. It has the advantage of fast expansion and convergence and it can decompose of irregularly-distributed observations within limited areas (Zhang, 2005; Fang et al., 2004; You et al., 2003; Zhu and Zhang, 2004; Zhao et al., 2006; Chen et al., 2004).

5.1 EOF analysis of WFD degree

EOF analysis of the WFD degree at 30 agrometeorology observatories in Henan is carried out after normalizing the data series. Table 3 lists the variances of the first four dominant modes of the WFD degree. It is shown that the variances of the first four premier modes account for 64% of the total variance. Since the variances of the first and second modes contribute more than 50%, we only focus on the first two modes in this study.

Table 3. Variances of the first four premier modes of the WFD degree (%)

Mode	1	2	3	4
Variance contribution(%)	44.03	8.34	6.58	5.01
Cumulative variance (%)	44.03	52.37	58.95	63.96

5.1.1 The first mode of WFD degree

The variance of the first EOF mode of WFD degree contributes 44.03% to the total variance, which means that the first mode is the main WFD degree pattern in Henan Province (Fig. 4). The characteristic values of the first mode are all positive, so the varying trends of WFD degrees in this region are basically the same. The middle and east parts of Henan have high characteristic values, so the severe WFD appears in these regions. The low characteristic values are distributed in the north and west of Henan, so the first mode. The characteristic values of the second mode of WFD degree can be WFD in these regions are quite light. The WFDs in the rest regions are between these two types.

The time coefficients of the first mode of WFD degree fluctuate obviously from −10.73 to 26.91. This demonstrates that the WFD degree in Henan Province obviously changes with years. It exhibits an evident downtrend in 1961–1967. Most values of the WFD degree during 1965–1971 are negative, and the values in the rest of years fluctuate obviously between positive and negative values. Typical years with positive time coefficients are 1962 and 1991, while 1967 and 1986 are typical years with negtive time coefficents (Fig. 5).

5.1.2 The second mode of WFD degree

The variance contribution of the second EOF mode of WFD degree is 8.34%, which is obviously lower than that of the negative or positive, showing the opposite changing trends of WFD degree. The positive values are mainly distributed in the west and most of the north and northeast of Henan. The high

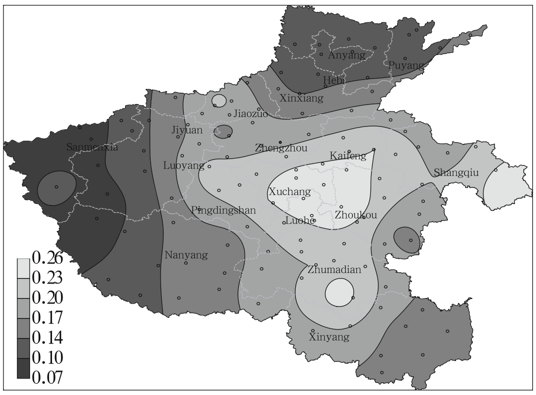

Fig. 4. Distribution of the first EOF mode of WFD degree in Henan Province.

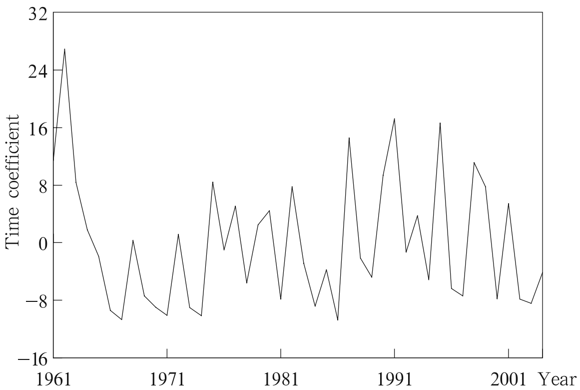

Fig. 5. The time coefficients of the first EOF mode of WFD degree.

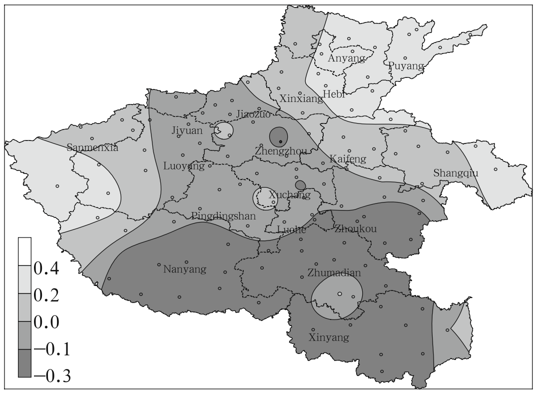

Fig. 6. Distribution of the second EOF mode of WFD degree in Henan Province.

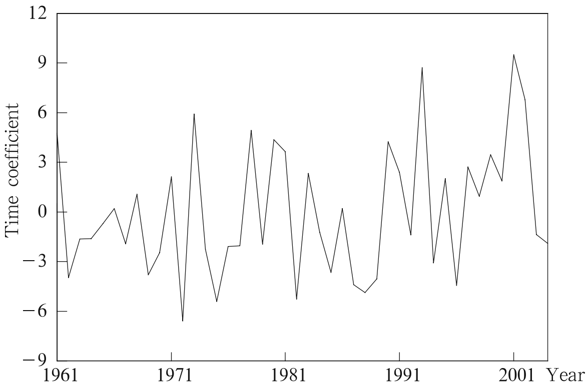

Fig. 7. The time coefficients of the second EOF mode of WFD degree.

value center corresponds to the harder-hit area in these regions. The negative values are distributed in large areas from the northwest to the north of Henan. The low value center corresponds to the lightly WFD hit area (Fig. 6).

The time coefficients of the second mode obviously fluctuate from –6.59 to 9.5. The typical years with positive time coefficients are 1993 and 2001 whereas the typical years with negative time coefficients are 1972, 1975, and 1982 (Fig. 7).

5.2 EOF analysis of WFD days

Table 4 shows the variance contribution of the first four modes in the number of WFD days by using the EOF decomposition. It is seen that the accumulative variances of the first four modes contribute 80% in total, so they can be used to basically describe the temporal-spatial distributions of the number of WFD days. Since the variance of the third and fourth modes contribute much less than the first two modes, we only consider the first two modes here.

5.2.1 The first mode of WFD days

As the main mode of WFD days, the first mode accounts for 52.2% of the total variance. The characteristic values of the first mode are negative, which means that the varying trends of WFD days in Henan are basically consistent. The fewer WFD days are distributed in Zhengzhou, Zhumadian, and Yongcheng (Fig. 8). The corresponding time coefficients are positive in most of the years with fluctuations from 0 to

Table 4. Variances of the first four modes of WFD days

Mode	1	2	3	4
Variance contribution (%)	52.2	19.11	7.77	7.4
Accumulative variance (%)	45.30	64.41	72.18	79.58

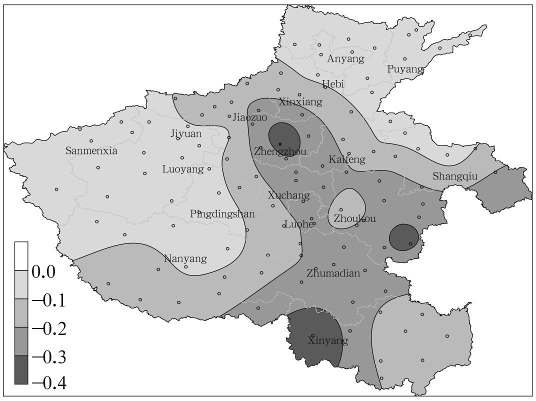

Fig. 8. Distribution of the first EOF mode of WFD days.

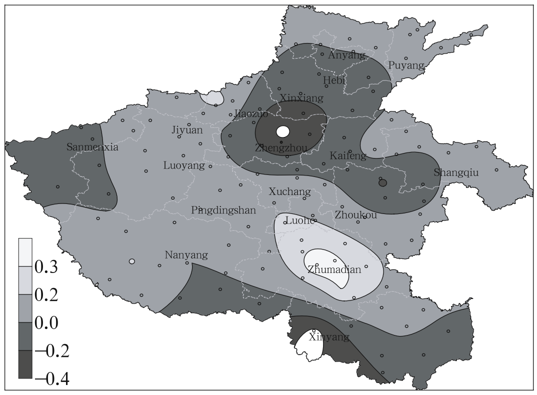

Fig. 10. Distribution of the second EOF mode of WFD days.

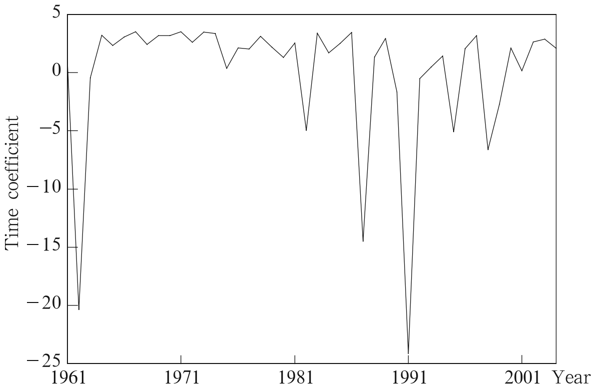

Fig. 9. The time coefficients of the first EOF mode of WFD days.

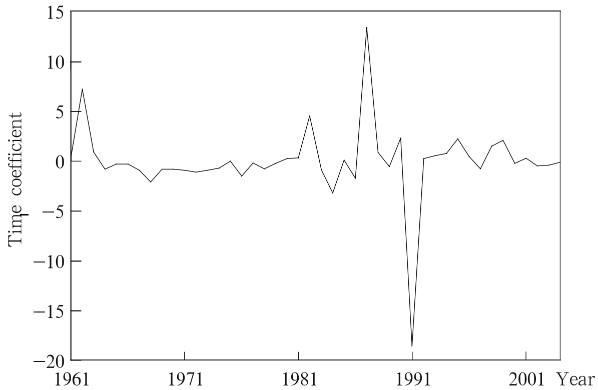

Fig. 11. The time coefficients of the second EOF mode of WFD days.

5, which indicates that the variation of first mode of WFD days has consistent trends in most of years. The typical years with different trends are 1962, 1987, and 1991 (Fig. 9).

5.2.2 The second mode of WFD days

The variance contribution of the second mode of WFD days is 19.11%, and its characteristic values can be negative or positive. Positive values are distributed in most of Henan, with high value center located in part of Zhumadian where WFDs frequently happen. The negative values are in the west, such as Sanmenxia, Xinxiang, Zhoukou, and Xinyang, where WFDs rarely occur (Fig. 10). The corresponding time coefficients in most years are near zero with small fluctuations. The typical years with positive time coefficients of WFD days are 1962 and 1987, while the typical year with a negtive value is 1991 (Fig. 11).

6. Multi-scale analysis of WFD degree and WFD days

Wavelet analysis is an integration of functional analysis, Fourier analysis, spline analysis, harmonic analysis, and numerical analysis. It is a powerful tool to analyze the periodicity and non-uniformity embeded in meteorological data. This method can be used to make detailed multi-scale analysis of functions or signal series by scaling and translation in order to find out the temporal distributions of different scale (period) signals (Tan, 2002; Niu et al., 2004; Dai et al., 2007).

In the EOF analysis, the time coefficients of each mode of the typical field represent temporal variation features of the field series. The multi-scale variations of WFD degree and number of days from the main

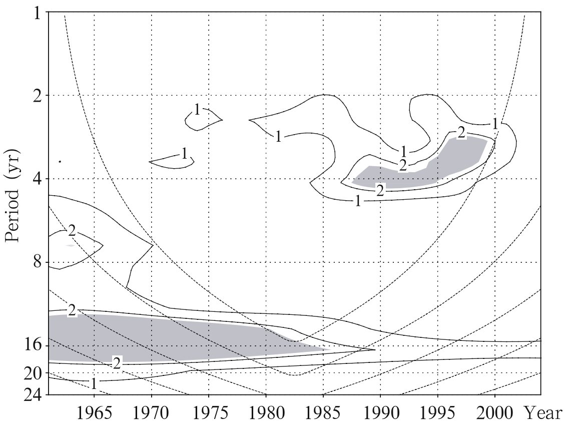

Fig. 12. Morlet wavelet of time coefficients of the first EOF mode of WFD degree.

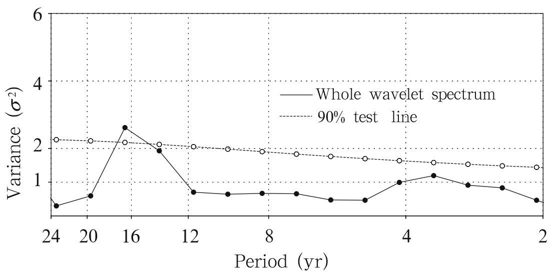

Fig. 13. Whole Morlet wavelet spectrum of time coefficients of the first EOF mode of WFD degree.

modes of the EOF analysis in time and frequency domains can be revealed by the wavelet analysis.

6.1 Wavelet analysis of WFD degree

Local Morlet wavelet variation of time coefficients of the first mode of WFD degree is shown in Fig. 12. It can be seen that there are two big value areas, which pass the white noise test at the 0.1 significance level. One appeared in 1987–1999 with a periodicity of 3 yr, and the other appeared in 1961–1985 with a periodicity of quasi-16 yr (some data are affected by the boundaries). The whole Morlet wavelet spectrum of time coefficients of the first mode of WFD degree (Fig. 13) exhibits decadal variations in different periods. There is a peak value at 16 yr, which is above the significance level of 0.1 (possibly influenced by boundary data). The peak value at quasi-3 yr is not obvious and is below the significance level of 0.1, so this time period only features a local variation. The results can be used to further analyze the climate characteristics and the WDP in 1987–1999 in order to provide better prediction and prevention of the WFD in future.

Wavelet analysis of time coefficients for the second mode of WFD degree is shown in Fig. 14. The results indicate that the high value passing the white noise test at the significance level of 0.1 is at quasi-2 yr, which mainly appeared in 1970–1975, 1980–1984, and 1991–1994. The whole Morlet wavelet (Fig. 15) demonstrates that one peak value is at about 2 yr at the significance level of 0.1, and another peak is at about 10 yr but below the significance level of 0.1. The results can be used as reference to prediction of WFD degree. If the weather system has the same periods as above, the second mode of WFD degree may occur with an approximate 2-yr period.

6.2 Wavelet analysis of WFD days

Wavelet analysis of time coefficients for the first mode of WFD days is plotted in Fig. 16. We see that the peak value is at quasi-4 yr and appears in 1981–

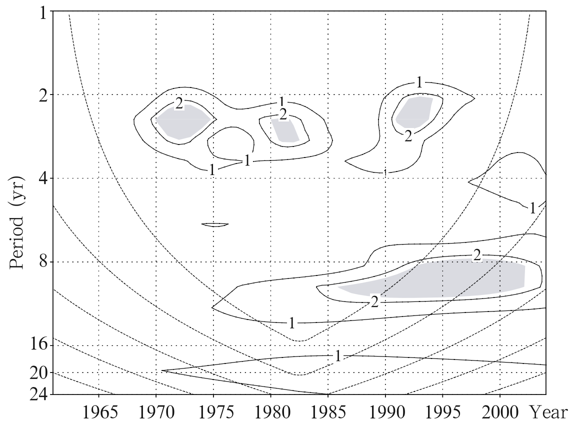

Fig. 14. Morlet wavelet of time coefficients of the second EOF mode of WFD degree.

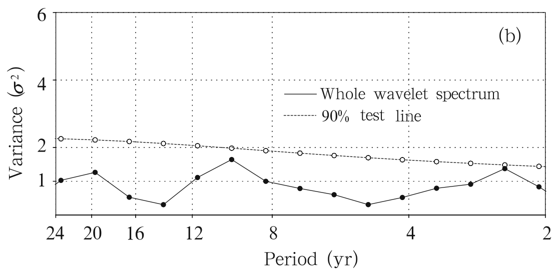

Fig. 15. Whole Morlet wavelet spectrum of time coefficients of the second EOF mode of WFD degree.

1995, which passes the white noise test at the significance level of 0.1 and is also shown in the whole wavelet spectrum (Fig. 17).

Figure 18 presents the local wavelet of time coefficients for the second mode of WFD days. It shows that the peak values passing the 0.1 significance white noise test appear at quasi-3 yr (in 1985–1994) and quasi-6–7 yr (in 1981–1995). This is also clearly illustrated in Fig. 19.

7. Effect of WFD on winter wheat yield

7.1 Effects of WFD degree and WFD days on winter wheat yield

Both WFD degree and WFD days can influence wheat yield. Taking Zhengzhou city as an example, we calculate the correlation between WFD degrees/number of days and wheat yield per hectare (Table 5).

The correlation coefficient between wheat yield

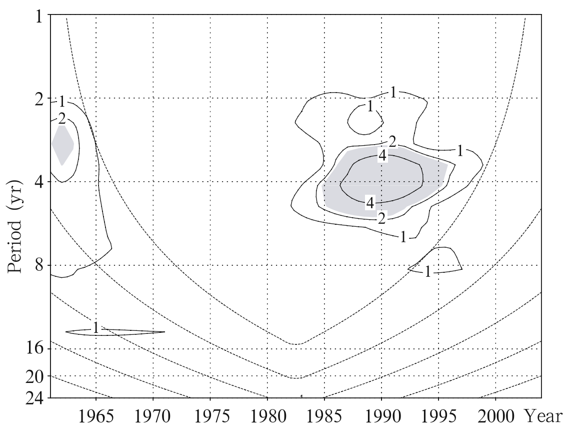

Fig. 16. Morlet wavelet of time coefficients of the first EOF mode of WFD days.

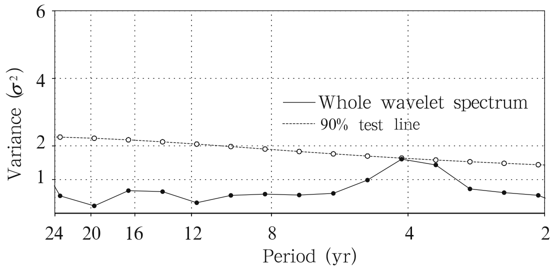

Fig. 17. Whole Morlet wavelet spectrum of time coefficients of the first EOF mode of WFD days.

Table 5. Correlation coefficients between WFD degrees/number of days and wheat yield per hectare in Zhengzhou city

	Degrees	Number of days	samples
Correlation coefficient	–0.3757*	–0.1659	44

*exceeding the significance level of 0.05

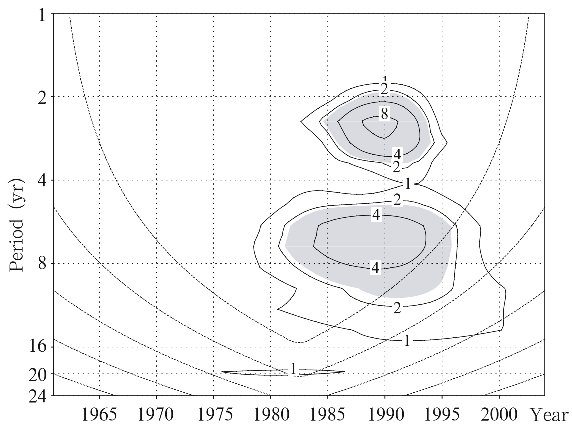

Fig. 18. Morlet wavelet of time coefficients of the second EOF mode of WFD days.

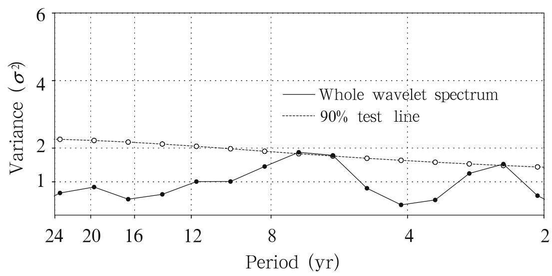

Fig. 19. Whole Morlet wavelet spectrum of time coefficients of the second EOF mode of WFD days.

per hectare and WFD degrees/number of days is negative, and the coefficient related to the WFD degrees passes the 0.05 significance test. This indicates that WFD is harmful to wheat yield and the WFD degrees exert a greater influence on wheat yield than the number of WFD days. This is consistent with the actual situation, namely, the harder the frostbite is, the greater the influence on wheat yield. If the WFD degree is small but the number of WFD days is large, there is no obvious influence on wheat yield. Therefore, it is more effective to protect winter wheat from WFD in harder-hit areas with fewer WFD days than in lightly hit area with more WFD days.

7.2 Effects of different spatially distributed WFD degrees and days on wheat yield

Different spatially-distributed WFDs have different influences on wheat yield. In order to analyze these effects, we separate wheat yield in 1961–2004 in Henan into trend yield and meteorological yield with the moving average method. Meteorological yield is the subyield under the weather condition of whole wheat development, and the time coefficients for degrees and days of different modes of WFD reflect variations of differently distributed WFD. Therefore, it is feasible to explore the influence of WFD on wheat yield by analyzing the correlations between time coefficient of degrees/days of WFD and the meteorological yield.

As shown in Table 6, except the first mode, the correlation coefficients between the second mode time coefficients for degrees/days of WFD and the meteorological yield fail the 0.05 significance test. This indicates that the first mode of WFD degree impose a negative influence on wheat yield, while other modes of WFD degree have no obvious influence on wheat yield.

Table 6. Correlation coefficients between time coefficients of degrees/days of different mode WFDs and wheat meteorological yield

Mode	1	2
WFD degrees	–0.322*	–0.006
WFD days	0.267	0.074

*above the significant level of 0.05.

The small correlation coefficient between WFD days and wheat meteorological yield shows that the number of WFD days has no obvious effect on wheat growth, which is in agreement with the real situation. WFD degrees have greater effects on wheat growth than the number of WFD days does. Since wheat has a strong reviving ability due to long development period and effective field management, the influence of light frostbites on final wheat yield would be small.

8. Conclusions

The variation trend of WFD degree is similar to that of the number of WFD days, namely, the region with higher WFD degree corresponds to the region with more WFD days. The frequency of WFD occurrence is as high as above 30% in the southwest and north, about 20% in the middle and south, and about 16% in the east of Henan Province, and has a rising trend in most areas during the 1970s–1990s. The shortened development period of wheat, advanced jointing in early spring caused by climate warming, and frequent cold air attacks in spring are the main reasons for increased WFDs. In addition, some farmers plant high-yield spring species instead of winter or semi-winter species, which are easily attacked by the WFD, i.e., the frostbite, in the Yellow and Huaihe River area in 2005.

The harder-hit areas of average WFD degrees are locally distributed in the southwest, north, and southeast of Henan; lightly-hit areas are distributed along the two banks of the Yellow River and extend from the northwest to southeast of Henan. The first EOF mode of WFD degree is dominant, with high values in the middle and the east and low values in the rest of Henan, and with a quasi-16-yr periodicity in its temporal variation. The second EOF mode of WFD degree has positive value centers located in the west and northeast of Henan and negative value centers in the southwest and south of Henan with a quasi-2-yr periodicity in its temporal variation.

The high value areas of average number of WFD days are located in the boundary between the north and southwest of Henan, and the small value areas lie in the northeast and the middle southwest of Henan, with the periodicity of quasi-4 yr in the 1980s–1990s. The high value center for the second mode of WFD days is located in Zhumadian and the middle of Henan, while the low value center is located in Sanmenxia, Zhengzhou, Xinxiang, etc., with obvious periodicities of quasi-3 and quasi-6–7 yr in the 1980s–1990s.

The number of WFD days in Henan Province have a small influence on wheat yield, while the WFD degrees have a relatively great influence on wheat yield.

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