Characteristics of dry-hot wind in the Huang-huai-hai plain and its effect on winter wheat

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Abstract: Climatic variations adversely affect crop production and, thus, tend to impose a key constraint on agricultural production, primarily on how to continuously enhance the yields of winter wheat worldwide. The high uncertainties in predicting the effects of climate change on wheat production are most likely attributable to a limited understanding of the responses of wheat production to extreme climatic factors, e.g., high temperatures, low humidity, and high wind speed. Dry-hot wind hazards represent one of the main natural disasters for Chinese winter wheat production, especially for the Huang-huai-hai plain. However, high uncertainties regarding the effects of dry-hot wind hazard on winter wheat production remain, mainly because of the gaps in long-term observations. Therefore, we selected Shangqiu as a case study area to determine the regularity of the occurrence of dry-hot wind hazards and its effects on winter wheat production on the Huang-huai-hai plain. Using regional meteorological data with a daily resolution in the later growth stage of winter wheat from 1963 to 2012, the distribution of annual average days of dry-hot wind in winter wheat growing seasons and the associated responses to the climate change were discussed, as were the relationships between dry-hot wind days and winter wheat yields. The results showed that the annual average days of light and severe dry-hot wind tended to decline in the most recent 50 years. Great inter-annual variations in light and severe dry-hot wind were observed. The significant inter-annual variations were related to the corresponding meteorological conditions of temperature, moisture and wind speed. The most serious damage from dry-hot wind occurred in the 1960s, whereas the damage appeared to be less intense in the 1980s and in the last decade, which could also be explained by the corresponding temperature, moisture and wind speed conditions. From 1963 to 2012, the wind speed at 2:00 pm, which was closely related to the wind hazard, declined significantly, and a climatic mutation point was found near 1985 ($p<0.05$); the variations in the other meteorological elements were not significant ($p>0.05$). The daily maximum temperature, the wind speed at 2:00 pm and the relative humidity at 2:00 pm played major roles in the decreasing trend of dry-hot wind disasters, and the significantly decreased wind speed at 2:00 pm was a main factor in Shangqiu. The yields of winter wheat were negatively correlated with annual average days of dry-hot wind in Shangqiu ($p<0.05$). Thus, improving the resistance of winter wheat to dry-hot wind hazards should proceed using biological measures, agriculture technology and chemical measures.

Keywords: climate change; Shangqiu; winter wheat; winter wheat yield; dry-hot wind

1. Introduction

Climate change has led to the frequent occurrence of extreme weather. Indeed, the 4th and 5th evaluation reports of the Intergovernmental Panel on Climate Change (IPCC, IPCC, 2007; 2013) noted that global warming has exerted widespread effects on agricultural ecosystems, brought increasing uncertainties to agricultural production, increased the frequency of regional occurrences of weather-related agricultural disasters, and altered the planting patterns of crops (Lobell et al., 1980;

Qin, 2009; Lobell et al., 2012; Ge et al., 2012). Dry-hot wind is a weather phenomenon involving high temperature, low humidity and high wind speed, which can cause strong evaporation from soil and crops. Strong evaporation leads to loss of the moisture balance within the body, crop blight and death (Meteorological Research Office of China, 1965). As one of the major meteorological disasters disrupting winter wheat growth and yield, dry-hot wind frequently occurs during wheat's flowering and grouting stages (mid May to early June), giving rise to a 10%-20% yield loss of winter wheat in the years when its disastrous effects are severe (Liu et al., 2012).

In recent years, some papers have been published in "*Nature*", that emphasized the effects of climate change and meteorological disasters on winter wheat, and found that climatic warming and extreme drought resulted in early maturation, yield loss, and decline in dry matter accumulation of wheat (Piao et al., 2010; Lobell et al., 2012; Pongratz et al., 2012;Basso et al., 2014; Asseng et al., 2015). Since the 1960s, Chinese agriculturalists and meteorologists have made significant advancements in dry-hot wind research (Meteorological Research Office, 1965; Chen et al., 2001; Liu et al., 2008; Wang et al., 2010; Liu et al., 2012; Zhao et al., 2012). Relevant research indicates that global warming and reduced precipitation have gradually intensified the disastrous effects of dry-hot wind, and the frequency of the regional occurrence of these effects has gradually increased, especially on the Huang-huai-hai plain (Liu et al., 2012). In Henan province, Chen et al. (2001) found that although the occurrence of dry-hot wind in wheat production gradually decreased from 1967 to 1996, the occurrence of dry-hot wind has increased in recent decades, such as in 1976-2005 and 1978-2007. Because dry-hot wind typically occurs locally and suddenly, this increase has caused severe harm during the grouting stage of winter wheat (Zhao et al., 2012). In other areas, such as Gansu province, as described by Liu et al. (2008) , the increasing frequency of dry-hot wind has caused relatively severe damage to winter wheat. Liu et al. (2008) and Zhao et al. (2015) comprehensively investigated the occurrence intensities of two types of dry-hot wind (light and heavy dry-hot wind). These scholars established indexes for evaluating occurrences and constructed models for the evaluation of loss in disasters according to the extent of the disasters impacting winter wheat (Pan et al., 2011; Wu et al., 2012; Lobell et al., 2011).

Therefore, given the background of climatic change, scholars have conducted numerous research studies on such aspects as the rules of disaster occurrence in agricultural ecosystems and adaptations to climatic changes. However, because of the characteristics regional occurrence of agricultural meteorological disasters, the same disaster may vary between different regions. In recent years, the occurrence of meteorological disasters increased, and with the rapid development of agriculture in China, winter wheat production in the typical agricultural areas of the Huang-huai-hai region will encounter severe challenges because existing knowledge does not include the effects of climatic changes in different regions. Therefore, regional implementation of research on the rules governing the occurrence of meteorological disasters should support the safe production of winter wheat in these areas. This research also provides a theoretical basis for the prevention and alleviation of agricultural meteorological disasters.

Huang-huai-hai plain dominated by a winter wheat-summer maize double cropping system and is an important grain production base in China, which occupies an important position in the national food security strategy. Located in the typical agricultural area of the Huang-huai-hai plain, Shangqiu is a strategically pivotal city. Because of its unique geographical position, Shangqiu is a major region for agricultural development in Henan province and represents an important base for the production of marketable grain and subsidiary agricultural products in China. In Shangqiu, winter wheat damaged by cold and frost, and by drought and dry-hot wind throughout the growth period. Among these destructive forces, dry-hot wind represents a major agricultural calamity that severely damages winter wheat during its late growth period. The analysis in this paper used the daily-recorded meteorological data from 1963 to 2012 in combination with the index system for winter dry-hot wind to quantitatively analyze the features, effects, and changing trends of dry-hot wind on winter wheat production in Shangqiu within the past 5 decades. In the face of climatic change, this study provides a basis for policy-making to support the safe production of agricultural products, the avoidance of damage, and disaster prevention and alleviation.

2. Materials and methods

2.1. Site description

Located at 32°00′ N-40°30′ N, 113°00′E-121°00′E, the Huang-huai-hai plain has an area of approximately 38.7 km^2. It contains the Huanghe (the Yellow River), Huaihe, and Haihe rivers. The Huang-huai-hai plain represents an important base of agricultural production in China, with main crops of winter wheat, corn and cotton. This plain has a zonal brown or cinnamon soil type, a generally warm temperate humid or semi-humid climate, an average temperature of 14-15℃, a precipitation of 500-1000 mm (with large variations annually), and an annual accumulation temperature ≥ 0℃ that varies from 4500-5500℃. Located in the eastern area of Henan province, Shangqiu is a typical agricultural area on the Huang-huai-hai plain, and consists of an urban area (Shangqiu) and 7 counties. Located between 114°82′ E-116°64′ E, 33°71′ N-34°88′ N, Shangqiu has a total area of 10704 km^2 (Figure 1). The soil in the research area is moist, and the climate is a typical warm and semi-humid continental monsoon climate with an average annual temperature of 13.9℃-14.3℃, an average annual precipitation of 623 mm, an average annual sunshine duration of

2204.4-2427.6 hours, and an average frost-free period of 207-214 days. The test area is characterized by a warm and windy climate in the spring, warming and concentrated precipitation in the summer, cooling and long-term sunshine in the autumn, and cold, low-snow conditions in the winter.

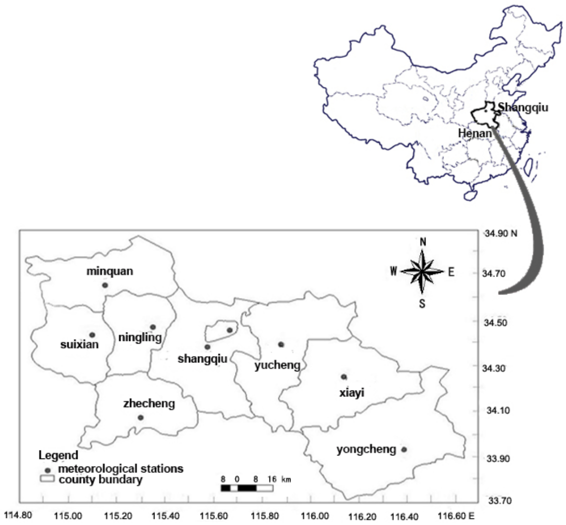


Figure 1. The study area

2.2 Data collection and methods

In Shangqiu, winter wheat enters the flowering stage from late April to early May, whereas in the western and northern areas of Henan province, it enters this stage approximately a week later (Cheng et al., 2011). In most of Henan province, winter wheat enters the grouting stage in the middle of May. Therefore, in this paper, the daily meteorological data of each year were selected from late May to early June (from May 21 to June 5). The effects of dry-hot winds on winter wheat from the grouting stage to the maturation stage (the late growth stage) were systematically analyzed. Daily meteorological data recorded from 1963 to 2012 at eight agricultural meteorological observatories in Shangqiu City, Minquan, Suixian, Ningling, Zhecheng, Yucheng, Xiayi and Yongcheng were selected. The meteorological data were provided by the meteorological bureau and agricultural bureau of Shangqiu City. All data were acquired from observations performed according to the requirements of the *Agricultural Meteorological Observation Standard* issued by the China Meteorological Bureau, and the methods for the observations were uniform.

The hazard indicators relating to the disaster grades of dry-hot wind based on the meteorological industry standard were released by the China Meteorological Administration in 2007 (Huo et al., 2007), and the 3 relevant meteorological factors were the daily maximum temperature, relative humidity at 2:00 pm, and wind speed at 2:00 pm. Meanwhile, Mann-Kendall mutation tests were applied to analyze of the timing rules of the meteorological factors of dry-hot wind disasters to analyze the trends of meteorological factors and climate mutation and identify the important period in which winter wheat production was influenced. The main reason for using Mann-Kendall mutation tests (non-parametric tests) is that compared with parametric statistical tests, non-parametric tests are thought to be more suitable for non-normally distributed data, and have been applied widely to time series of meteorological factors (Zhou et al., 2000; Wei, 2007). The threshold line of the Mann-Kendall mutation tests was set at Y=±1.96 (at the level of p=0.05), and the mutation points were systematically analyzed based on the form and directional trend of the cumulative departure curve to identify the genuineness of these points. A mathematical linear fitting equation was used to analyze the variation in the light and heavy dry-hot winds, and according to the variation, if necessary, we could segment a fitting equation to ensure the accuracy of the results. The statistical analysis was conducted using the SPSS 16.0 software package and Excel 2007. Origin 8.5 was used to create the figures.

2.3 Selection of dry-hot wind indexes

This work mainly analyzed dry-hot winds featuring high temperatures and low humidity. Such dry-hot winds are the main type of wind that damages to winter wheat in Shangqiu in the late growth period and generally occur at relatively high frequencies in middle and late May and early June (Zhao et al., 2012). The concrete indexes for the analysis are referred to in *Disaster Grades of Dry-hot Wind in Wheat* (Huo et al., 2007) (Table 1).

Table 1. Disaster grades of dry-hot wind

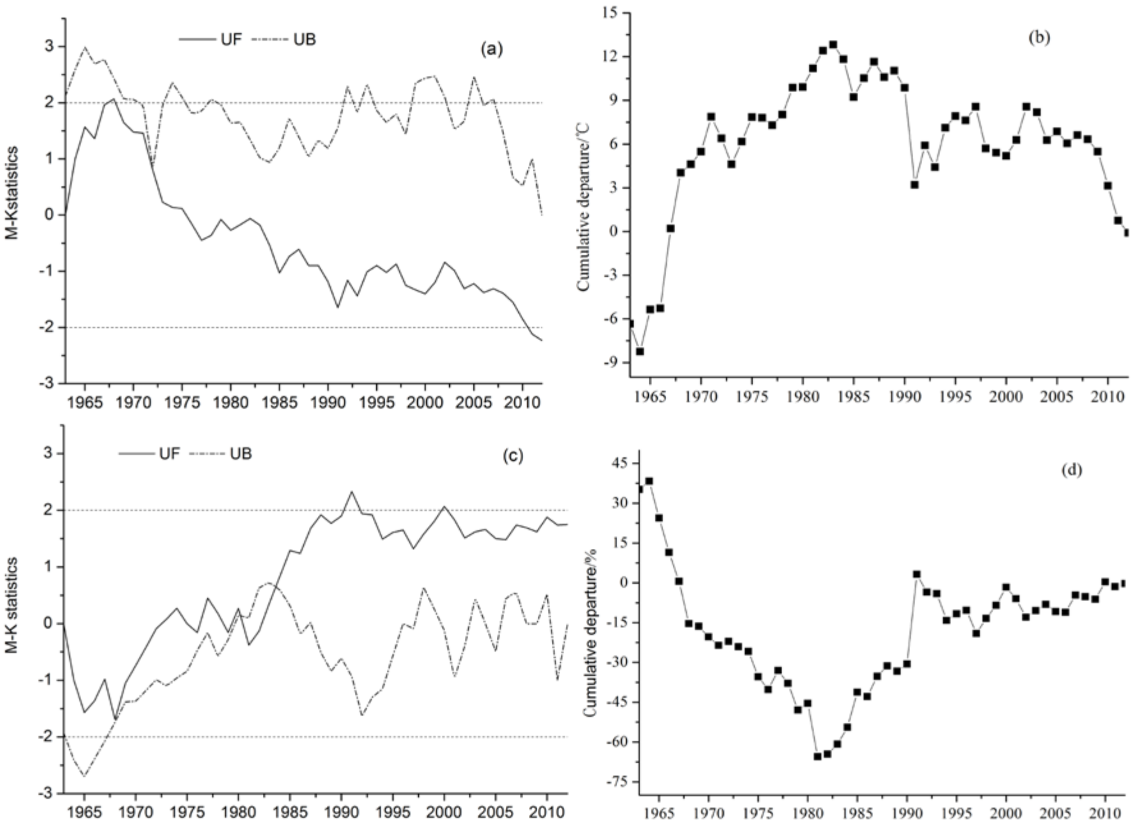
Light			Heavy		
daily maximum temperature (℃)	relative humidity at 2: 00 pm (%)	wind speed at 2: 00 pm (m/s)	daily maximum temperature (℃)	relative humidity at 2: 00 pm (%)	wind speed at 2: 00 pm (m/s)
≥32	≤30	≥3	≥35	≤25	≥3

3. Results and analysis

3.1 Changes in the meteorological factors of dry-hot wind

In this research, by analyzing ordinal sequence curves (UF curves) and inverse sequence curves (UB curves), in combination with cumulative departure curves, the genuine mutation points of every factor were analyzed and evaluated. The daily maximum temperature gradually decreased starting in 1975, and whereas the UF curve did not exceed the critical value line, and its decline was not significant (p>0.05; Figure 2a). The intersection point of the ordinal and inverse sequence curves of the maximum temperature appears in 1972, and the UF curve did not exceed the critical value line. The cumulative departure curve corresponding to the ordinal and inverse sequence curves of the maximum temperature had a low value in 1972, followed by an increasing trend (Figure 2b). Therefore, the increasingly abrupt timing of the maximum daily temperature occurred in approximately 1972 during the late growth stage of winter wheat, but this increase did not reach significance (p>0.05) (Figure 2b). The relative humidity at 2:00 pm gradually increased starting in 1983, the UF curve exceeded the critical value line in approximately 1991, and this increase was significant (p<0.05; Figure 2c). The sequence curves of the relative humidity at 2:00 pm intersect in the years 1968, 1981, and 1984, and the minimum value of the relative humidity at 2:00 pm occurred on the cumulative departure curve in 1981 (Figure 2d). After 1981, this value exhibited an increasing trend. Therefore, in approximately

1981, a gradual increase began in the abrupt timing of the value of the relative humidity at 2:00 pm (*p*>0.05). The wind speed at 2:00 pm gradually decreased starting in 1977, the UF curve exceeded the critical value line in approximately 1985, and this decline was significant (*p*<0.05; Figure 2e). No intersection point appears in the ordinal and inverse sequence curves (UF and UB curves) of the wind speed at 2:00 pm, and therefore, the mutation test failed (Figure 2e). However, the wind speed at 2:00 pm peaked in approximately 1985 (Figure 2f) and then exhibited a gradually declining trend. Therefore, in approximately 1985, a significant (*p*<0.05) abrupt time of gradual decline appears in the wind speed at 2:00 pm.



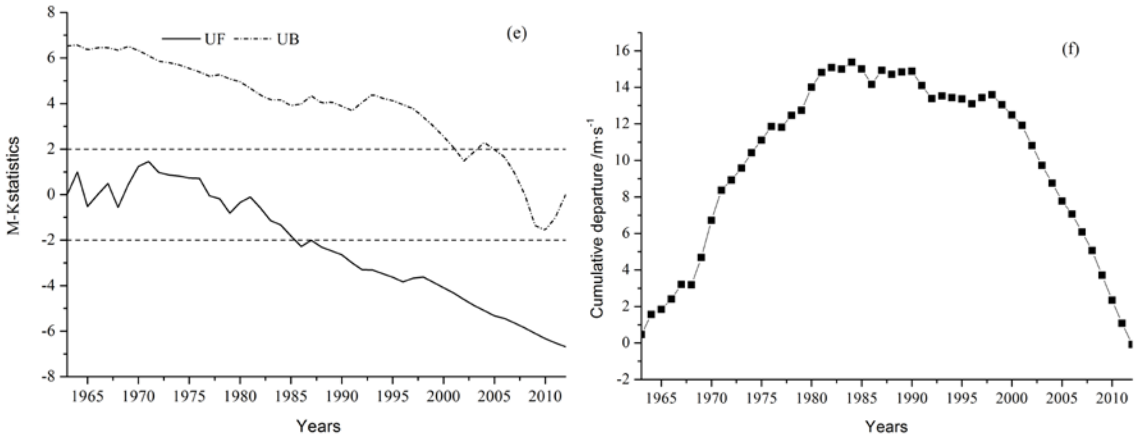


Figure 2. Mann-Kendall mutation test (a, c and e) and the cumulative effects of the daily maximum temperature, relative humidity at 2:00 pm and wind speed at 2:00 pm (b, d and f).

Note: the daily maximum temperature (a, b), relative humidity at 2:00 pm (c, d) and wind speed at 2:00 pm (e, f)

3.2 Days of dry-hot wind occurrence

3.2.1 Light dry-hot wind

From 1963 to 2012, the average number of days of the occurrence of high-temperature and low humidity light dry-hot wind affecting winter wheat exhibited a general trend of fluctuating decline (Figure 3). The number of days of light dry-hot wind fluctuated within 0-5.8 days, with an average value of 1.5 days, a coefficient of variation (CV) of 83.3%, and a standard error of 1.3 days. Over the past 50 years, relatively severe occurrences of light dry-hot wind appeared in 1965 and 1981, and relatively mild occurrences of light dry-hot wind occurred in 1993, 1996, 2007 and 2012. The maximum number of days of light dry-hot wind occurrence (5.8 days) was noted in 1965. According to the overall variation trend, to obtain a better fitting, we adjusted the data in three different regressions for different periods (Figure 3). Based on the three different linear fitting equations, the following can be concluded: From 1963 to 1980, the number of days of light dry-hot wind stabilized at a certain level. From 1981 to 1996, the number of days of light dry-hot wind decreased rapidly. In contrast, from 1997 to 2012, the number of days decreased more slowly. This decrease was correlated with the comprehensive effects of temperature, water, and wind speed after the winter wheat growth period.

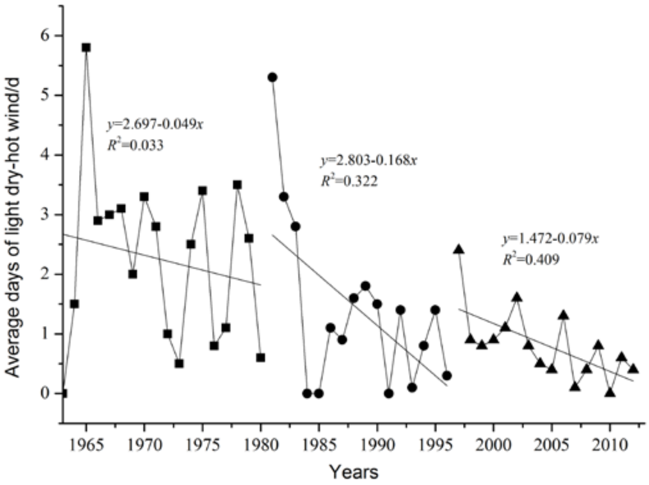


Figure 3. Changes in the annual average days of light dry-hot wind

Analyzing the characteristics of the annual changes in light dry-hot wind showed that in the 1960s, Shangqiu experienced the most severe occurrence of light dry-hot wind, with a total of 2.6 days. This occurrence was followed by occurrences of light dry-hot wind in the 1970s, 1980s and 1990s, with the numbers of days reaching 2.1 days, 1.7 days, and 0.9 days, respectively. The past 10 years have experienced the lightest damages caused by light dry-hot wind, with total of 0.8 days.

3.2.2 Heavy dry-hot wind

From 1963 to 2012, the average number of days on which heavy dry-hot wind occurred that affected winter wheat exhibited a general trend of fluctuating decline (Figure 4), with an average of 0.5 days. Based on calculations, it can be concluded that the CV was 98.9%, with a standard error of 0.8 days. Over the past 50 years, relatively severe occurrences of heavy dry-hot wind were found in 1967~1968, and 1994, peaking in 1968 at 3.5 days. From the fitted equations, the following can be concluded: From 1963 to 1981 and from 1997 to 2012, the occurrence of heavy dry-hot wind decreased slowly, whereas from 1982 to 1996, the occurrence increased slowly.

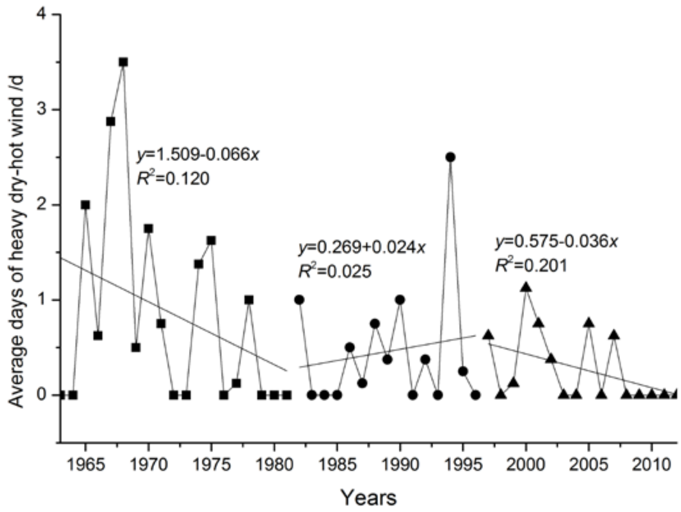


Figure 4. Changes in the annual average days of severe dry-hot wind

In the 1960s, Shangqiu experienced the most severe occurrence of light dry-hot wind in the late growth period of winter wheat, with an average of 1.4 days. This severe episode was followed by occurrences of heavy dry-hot wind in the 1970s, 1990s, and the past 10 years with the annual numbers of days of occurrence reaching 0.7 days, 0.5 days, and 0.4 days, respectively. In the 1990s, Shangqiu experienced the least damages caused by the occurrence of heavy dry-hot wind: 0.3 days in total.

3.3. Effects of climatic changes on meteorological disasters caused by dry-hot wind

The correlations between the number of days of dry-hot wind and climatic factors are shown in Table 2. The results indicated that the number of days of dry-hot wind was highly correlated with 10 meteorological factors, with coefficients ranging from -0.639 to 0.801. Furthermore, high temperature, low humidity and high wind speed strongly affect the number of days of dry-hot wind, and this effect is especially obvious effect for the wind speed at 2:00 pm (p<0.01) (Table 2).

The occurrence of dry-hot wind disasters exhibits the sensitive response of weather patterns to global climatic changes. The decreasing trends of the relative humidity and precipitation and the increasing trends of the average temperature, extreme temperatures and average evaporation lead to the occurrence of warming and drying weather. In this weather, dry-hot wind disasters occur with stronger intensities, are more frequent, and cause more severe damage (Table 2). In contrast, during periods of moderate and cooling weather, dry-hot wind disasters occur less frequently and have weak intensities.

Table 2 Correlations between the days of dry-hot wind occurrence and climatic factors

	Average temperature	Daily maximum temperature	Day number of maximum temperature≥32℃	Day number of maximum temperature≥35℃	Average relative humidity
Correlation Coefficient	0.612	0.632	0.753	0.594	-0.604
Sig.	0.01	0.01	0.01	0.01	0.01

	Relative humidity at 2:00 pm	Average precipitation	Average evaporation	Average day number of precipitation	Wind speed at 2:00 pm
Correlation Coefficient	-0.598	-0.497	0.408	-0.639	0.801
Sig.	0.01	0.03	0.05	0.01	0.01

3.4 Days of dry-hot wind and winter wheat yield

The correlation between winter wheat yields and the numbers of days of light and heavy dry-hot wind in the past 20 years (from 1991 to 2012) was investigated (Figure 5). The numbers of days of light and heavy dry-hot wind exhibited fluctuating declining trends, whereas the winter wheat yields exhibited a trend of enhanced fluctuations. After 2002, the days of light dry-hot wind were significantly negatively correlated with winter wheat yields (p<0.05). Additionally, the days of heavy dry-hot wind were significantly negatively correlated with winter wheat yields since 1999 (p<0.05). Overall, the yields of winter wheat were negatively correlated with days of dry-hot wind, especially in the 21st century.

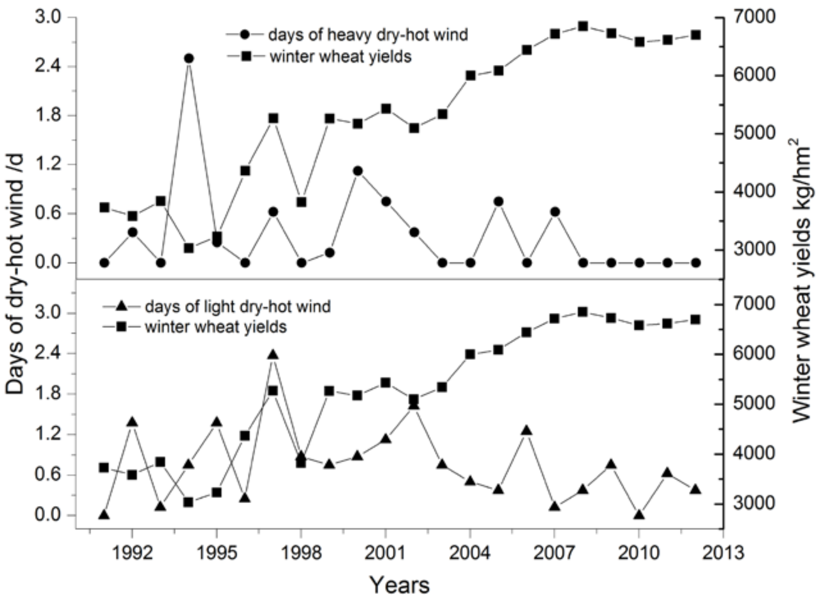


Figure 5. The relationship between the days of light and heavy dry-hot winds and the yields of winter wheat

4. Discussion

In Shangqiu, the range and frequency of dry-hot wind occurrences during the growth period of winter wheat generally exhibited gradually decreasing trends. The increasingly abrupt timing of the maximum daily temperature occurred in approximately 1972, but this change did not reach significance (p>0.05). In approximately 1981, a gradual increase in the abrupt timing was found for the relative humidity at 2:00 pm (p>0.05), whereas a significantly (p<0.05) abrupt timing of the gradual decline of the wind speed at 2:00 pm appeared around 1985. The magnitude of the temperature increase in China was 0.22℃/10 years and reached 0.25℃/10 years from 1963 to 2012 on the Huang-huai-hai plain (Tan et al., 2009; Zhu et al., 2012a). The average temperature in Shangqiu exhibited an obviously increase (Shi et al., 2012). However, the trend of the change in the maximum daily temperature varied at different at different stages during the winter wheat growth period (Tan et al., 2009; Xiong et al., 2010). In Shangqiu, during the late growth period of winter wheat, the maximum daily temperature did not significantly increase with the average temperature (Zhu et al., 2012b), which was beneficial for winter wheat at the grouting stage. In the context of global climatic change, the decreased relative humidity in the air is the main reason for drought (Jin et al., 2009). In our study, from 1963 to 2012, the relative humidity at 2:00 pm increased slowly, which was in accordance with the results reported by Zhao et al.(2012) and Cheng et al. (2011). Thus, the comprehensive effect of the three climatic factors (daily maximum temperature, relative humidity at 2:00 pm and wind speed at 2:00 pm) determined the decreasing trend of dry-hot wind disasters affecting winter wheat yield. The significant reduction of wind speed also played a major role in the overall weakening of the effect of dry-hot wind disasters.

Over the past 50 years, the overall disasters caused by dry-hot wind in winter wheat exhibited a gradual decreasing trend. Periodic disasters of dry-hot wind still occurred because of differences in matching the meteorological factors of temperature, water, and wind speed at different times. Therefore, to minimize the harmful effects of dry-hot wind on winter wheat during the late growth period, emphasis should be placed on the prevention of dry-hot wind disasters, and research concerning aspects other than climatic factors should be intensified (Sridhar et al., 2006). In recent years, the existing indexes of dry-hot wind and the concomitant research results have been insufficient to meet the requirements of regional food production and to prevent agricultural meteorological disasters. Relatively large differences exist in the climatic environments, soils, and crop types in different regions in China (Zhao et al., 2012). In addition, because the mechanisms underlying the effects of dry-hot wind on different food crops also differ and given improvement in breeding technology and planting level, new generations of experimental research investigating the indexes of dry-hot wind should be continuously implemented. The harmful effects of dry-hot wind disasters have been correlated with the physiological and structural features of agricultural crops, the developmental processes, and the degrees of regional environmental effects. Therefore, the influences of human activity, field management strategies, and resistance levels of different varieties of winter wheat should also be considered (Jung et al., 2010;Zhu et al., 2012b).

Dry-hot wind generally occurs during the late growth period of winter wheat and poses relatively severe threats to winter wheat at the grouting stage (Chen et al., 2001; Zhao et al., 2012). When it occurs, dry-hot wind exerts extremely strong effects on the yield, 1000-seed weight, and quality of winter wheat (Benzian et al., 1986; Li et al., 2003). These impacts are in accordance with previous indicating that in Shangqiu, the average annual number of days of dry-hot wind was significantly negatively correlated with the winter wheat yield. However, numerous factors influence the yield of winter wheat, including biological technologies, investments in agricultural production (including agricultural chemicals and fertilizers), and other meteorological factors. In this research, only the effects of dry-hot wind on the winter wheat yield were analyzed. In the future, such effects should be comprehensively analyzed in combination with other factors, including biological gene technologies, crop cultivars, and crop diseases and pests.

5. Conclusions

The range and frequency of dry-hot wind tended to decline over the past 50 years. The significant inter-annual variations were related to the corresponding meteorological conditions of temperature, moisture and wind speed. The most damage caused by light and severe dry-hot wind occurred in the 1960s, with less damage recorded in the 1980s and the last decade, which could be explained by the corresponding temperature, moisture and wind speed conditions. The comprehensive effects of daily maximum temperature, relative humidity at 2:00 pm, and wind speed at 2:00 pm showed that in Shangqiu, disasters caused by dry-hot wind affecting winter wheat generally exhibited a gradually declining trend, and a remarkably decreased wind speed played the main role in mitigating the overall disasters resulting from dry-hot wind. The annual average days of dry-hot wind strongly influenced the yields of winter wheat in Shangqiu.

Acknowledgements

The study was supported by the Natural Science Foundation of China (41140019 and 41501263); the Key Program of Higher Education of Henan Province of China (No. 15A180054), and the Foundation for Shangqiu University Key Teacher of Ministry of Education of China (2015GGJS15). The authors wish to thank the two anonymous reviewers for their useful comments and suggestions regarding the manuscript.

References

Asseng, S., Ewert, F., Martre, P., Rötter, R. P., Lobell, D.B., Cammarano, D., Kimball, A.A., Ottman, M.J., Wall, G.W., White, J.W., Reynolds, M., Alderman, P.D., Prasad, P.V.V., Aggarwal, P.K., Anothar, J., Basso, B., Biernath, C., Challinor, A.J., De Sanctis, G., Doltra, J., Fereres, E., Garcia-Vila, M., Gayler, S., Hoogenboom, G., Hunt, L.A., Izaurralde, R., Jabloun, M., Jones, C.D., Kersebaum, K.C., Koehler, A.K., Muller,C., Naresh, K.S., Nendel, C., O'Leary, G., Olesen, J.E., Palosuo, T., Priesack, E., Rezaei, E.E., Ruane, A.C., Semenov, M.A., Shcherbak, I., Stockle, C., Stratonovitch, P., Streck, T., Supit, I., Tao, F.L., Thorburn, P., Waha, K., Wang, E., Wallach, D., Wolf, J., Zhao, Z.G., and Zhu, Y.: Rising temperatures reduce global wheat production. Nature Climate Change, 5, 143-147, 2015.

Basso, B., and Ritchie, J. :Temperature and drought effects on maize yield. Nature Climate Change, 4, 233, 2014.

Benzian, B., Lane, P. W.: Protein concentration of grain in relation to some weather and soil factors during 17 years of english winter-wheat experiments. J. Sci. Food Agr., 37, 435-444,1986.

Chen, H. L., Zou, C. H., Fu, X. J, and Guan, W.Y.: The EOF analysis on wheat dry-hot-wind in Henan province. J Nat. Resour., 16,59-64,2001.

Cheng, L., Zhang, Z. H., Chang, J.: Analysis on the change of dry-hot wind hazard for winter wheat in last 47 years in

Henan province. Chinese J. Agrometeorol., 32, 456-460, 2011.

Ge, Q. S., and Zheng, J. Y.: Progress on the study of the forcing and impacts of the warm periods in China during the past 2000 years. Geogr. Res., 31, 769-769,2012.

Huo, Z. G., Jiang, Y., Li, S. K., and Bai, Q.F.: Disaster grade of dry-hot wind for wheat. Beijing: China Meteorological Press, 1-3, 2007.

IPCC. Working Group Ⅰ Contribution to the IPCC Fifth Assessment Report, Climate Change 2013: The Physical Science Basis: Summary of for Policymakers [R/OL]. [2013-10-28]. Http://www.climatechange2013.org/images/uploads/WGIAR5-SPM_Approved27Sep2013.pdf

IPCC. Climate Change 2007: the Physical Science Basis, Summary for Policy Makers. Paris: IPCC WGI Fourth Report, 195-199,2007.

Jin, Y. H., Lian, S. H., Zhou, D. W., and Xu, J.B., Peng, C.: Study on change of relative humidity in semiarid region under global climate change. J. Northeast Norm. U., 41, 134-138, 2009.

Jung, M., Reichstein, M., Ciais, P., Seneviratne, S.I., Sheffield, J., Goulden, M.L., Bonan, G., Cescatti, A., Chen, J.Q., Richard de Jeu, Dolman, A.J., Eugster, W., Gerten, D., Gianelle, D., Gobron, N., Heinke, J., Kimball, J., Law, B.E., Montagnani, L., Mu, Q.Z., Mueller, B., Oleson, K., Papale, D., Richardson, A.D., Roupsard, O., Running, S., Tomelleri, E., Viovy, N., Weber, U., Williams, C., Wood, E., Zaehle S., and Zhang, K.: Recent decline in the global land evapotranspiration trend due to limited moisture supply. Nature, 467, 951-954,2010.

Li, Y. G., Jiang, G. M., Yang, J. C.: Effects of temperature on carbon and nitrogen metabolism, yield and quality of wheat. Chinese J. Plant Ecol., 27, 164-169, 2003.

Liu, D. X., Sun, L. D., Ning, H. F.: Characteristics of dry-hot wind in Gansu province and its response to climate change. J. Glaciol. Geocryol., 30, 81-86, 2008.

Liu, L., Liu, J. D., Wu, D. R., and Xu, Y.L.: Temporal and spatial variation of dry-hot windy days in North China under the condition of climatic change in the future. Sci. Tech. Rev., 30, 24-27,2012.

Liu, J., Ma, L.W., Zhang, X.Y., Liu, Y.L., Wu, W.L., and Sun, Y.C.: A method for monitoring dry-hot wind of spring wheat and estimating its yield losses: an example in irrigated areas of Ningxia. J. Appl. Meteorol. Sci., 15, 217-225, 2004.

Lobell, D. B., Schlenker, W., and Roberts, J. C.: Climate trends and global crop production since 1980. Science, 333, 616-620, 2011.

Lobell, D. B., Sibley, A., and Ortiz-Monasterio, J. I.: Extreme heat effects on wheat senescence in India. Nature Climate Change, 2, 186-189,2012.

Meteorological Research Office of China: Investigation on the defensive dry-hot wind of winter wheat. Scientia Agricultura Sinica, 11, 28-32, 1965.

Pan, G. X., Gao, M., Hu, G.H., Wei, Q.P., Yang, X.G., Zhang, W.Z., Zhou, G.S., Zou, J.W.: Issues and challenges on mitigation of climate change impacts on china's future agriculture. J. Agro-Environ. Sci., 30, 1707-1712,2011.

Piao, S. L., Ciais, P., Huang, Y., Shen, A.H., Peng, S.S., Li, J.S., Zhou, L.P., Liu, H.Y., Ma, Y.C., Ding, Y.H., Friedlingstein, P., Liu, C.Z., Tan, K., Yu, Y.Q., Zhang, T. Y., and Fang, J. Y.: The impacts of climate change on water resources and agriculture in China. Nature, 467,43-51,2010.

Pongratz, J., Lobell, D. B., Cao, L. and Caldeira, K.: Crop yields in a geo-engineered climate. Nature Climate Change, 2,101-105,2012.

Qin, D. H.: Climate change: regional response and prevention and mitigation of disaster. Beijing: Science Press, 17-19,2009.

Shi, B. L., Zhu, X. Y., Li, H. Z., and Zhang, Y.: Impacts of climate change on winter wheat yield in central plains of China: case study of Shangqiu. Geogr. Res., 31, 14-22,2012.

Sridhar, V., Loope, D. B., Swinehart, J. B., Mason, J.A., Oglesby, R.J., and Rowe, C.M.: Large wind shift on the Great

Plains during the medieval warm period. Science, 313,345-347,2006.

Tan, F. Y., Wang, J. L., Song, Y. B., and Shen, S.H.: Analysis of changing characteristics of agricultural climate resources over last 45 years in north China plain. Chinese J. Agrometeorol., 30,19-24,2009.

Wang, Z. W., Miao, A. M., Li, Y. F., Chen, Y.B., Li, H.L., and Wang, S.F.: Prediction of wheat dry-hot wind in Changzhi city. Chinese J. Agrometeorol., 31, 600-606,2010.

Wei, F. Y.: Modern climatic statistical diagnosis and forecasting technology (Second Edition). Beijing: China Meteorological Press, 69-72,2007.

Wu, D. R., Liu, J. D., Liu, L., and Jiang, C.Y.: Regionalization study on dry-hot windy days in North China plain using CAST model. Sci. Tec. Rev., 30, 19-23, 2012.

Xiong, W., Lin, E. D., Jiang, J. H., Li, Y., and Xu, Y.L.: An integrated analysis of impact factors in determining China's future grain production. Acta Geogr. Sinica, 65, 397-406,2010.

Zhao, J.F., Zhao, Y.X., Guo, J.P., and Fang, S.B.: Spatial-temporal changes of dry-hot wind for winter wheat in Huanghuaihai plain during the past 50 years. Agr. Sci. China, 45, 2815-2825, 2012.

Zhao, J.F., Zhao, Y.X., Guo, J.P., and Mu, J.: Assessment of the yield loss of winter wheat caused by dry-hot wind in Huanghuaihai Plain based on the hazard index of dry-hot wind. Acta. Ecol. Sin., 35, 5287-5293, 2015.

Zhou, C. H., Wan, Q., Huang, S. F., and Chen, D.Q.: A GIS-based approach to flood risk zonation. J. Geogr. Sc., 55, 15-23,2000.

Zhu, Q., Jiang, H., Peng, C. H., Liu, J.X., Fang, X.Q., Wei, X.H., Liu, S.R., and Zhou, G.M.: Effects of future climate change, CO2 enrichment, and vegetation structure variation on hydrological processes in China. Gl. Planet. Change, 80-81, 123-135, 2012a.

Zhu, X. Y., Liu, J., Shi, B. L., and Zhang, Y.: Variation of climate suitability of winter wheat in central plains under the condition of climate warming. Geogr. Res., 31, 1479-1489, 2012b.