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Changes in Climate Factors and Their Impacts on Wind Erosion Climatic Erosivity in Farming-pastoral Zone of Northern China

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Abstract: Climate change can affect wind erosion power and hence induce changes in wind erosion rates. In this study, the wind erosion climate factor (*C*-factor), proposed by the Food and Agriculture Organization of the United Nations, was used to assess the impact of changes in climate on wind erosion climatic erosivity. The Mann-Kendall test was employed to detect trends in the *C*-factor during the period of 1961–2017 in the farming-pastoral zone of northern China. Sensitivity analysis was used to determine the sensitivity of the *C*-factor to changes in key climate factors. Furthermore, a comparison of the contributions of different climate factors was carried out to understand their impact on changes in the *C*-factor. The results indicated that most of the surveyed region exhibited decreasing trends in wind speed at a confidence level of 90%, while maximum and minimum temperatures showed increasing trends throughout the study area. As a consequence of decreasing wind speed, the annual *C*-factor exhibited significant decreasing trends, with a mean slope of –0.58/yr. Seasonal analysis revealed that in most regions, the changes in the *C*-factor had significant decreasing trends in spring, winter, and autumn, while in more than two-thirds of the study area, no significant change trends in the *C*-factor were detected in summer at a confidence level of 90%. Sensitivity analysis showed that the *C*-factor was most sensitive to wind speed, and that the sensitivity coefficients from July to September were much higher than those in other months. Contribution analysis revealed that, for most stations, wind speed (with greater values of sensitivity coefficients) was the dominant factor in the change of *C*-factor, while for some stations, the minimum temperature made the most contribution to the *C*-factor's change due to its dramatic changes during the study period. Although the minimum temperature sensitivity coefficient was the lowest of all the sensitivity coefficients, it is urgent to evaluate the expected impact of minimum temperature due to its possible changes in the future.

Keywords: climate factors; wind erosion climatic erosivity; sensitivity analysis; dominant factor; climate change

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1 Introduction

Wind erosion is the natural process of soil particle denudation, selection, and transportation by wind (Shi et al., 2003). Wind erosion removes the most fertile portion of soil from a field and, therefore, reduces land productivity (Daniel and Langham, 1936). It has caused severe land degradation and desertification, and is considered one of the most serious threats to the environment in arid and semi-arid areas all over the world, es-

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pecially in developing countries (Lal, 2001; Dearing and Jones, 2003; He et al., 2006; Tatarko et al., 2013). The land desertification area caused by wind erosion in China amounts to 182.63 × 10^4 km^2 in 2014, accounting for 69.93% of the total area of land desertification in China (Tu et al., 2016).

A report from the IPCC (Intergovernmental Panel on Climate Change) in (2018) indicated that the global warming of 1°C from the middle of the 19th century will reach 1.5°C between 2030 and 2052 based on the current warming rate. Global warming leads to changes in climate factors, such as wind speed, temperature, precipitation, and solar radiation. Continued warming and decreased precipitation can accelerate the process of wind erosion by reducing soil water content during dry and windy periods (He et al., 2013; Zhou et al., 2015). Recent researches have shown that wind speed, temperature, and precipitation play a determinant role in the change of wind erosion, although the dominant factors vary from place to place (Yang et al., 2016; Ren et al., 2017; Wu et al., 2018a; Lou et al., 2019; Qi et al., 2019; Wang et al., 2022). He et al. (2006) found that the soil erosion rate of the current period is much higher than that in the Quaternary due to the natural environment (rainfall, soil properties, vegetation covering) and human activity.

There are many climate factors that affect wind erosion. In order to better understand the overall impact of climate factors on wind erosion, the concept of wind erosion climatic erosivity has been proposed, which is usually quantified by a wind erosion climate factor that varies with different computing methods. In the formula proposed by Chepil et al. (1962), soil moisture, wind speed, and Thornthwaite's Precipitation Effectiveness index (P-E Index) were used (Thornthwaite, 1931). However, in arid areas, as precipitation declines, the P-E index decreases, and the *C*-factor approaches infinity. To solve this problem, Chepil's index was modified by replacing the P-E index with the ratio of moisture deficit to potential evaporation. This meant that wind speed dominated the climate factors when precipitation approached zero (Food and Agriculture Organization of the United Nations (FAO), 1979). In 1986, using the parameters of topsoil moisture and wind force—along with the wind's main direction—Skidmore (1986) proposed a physically based *C*-factor that could be used in a wind erosion equation for long- or short-term soil loss estimates. Since Skidmore's *C*-factor does not require the use of Thornthwaite's P-E Index, it is highly sensitive to low precipitation. Despite this advantage, computing Skidmore's *C*-factor involves a large number of variables and data availability issues, which restricts its usage. Until now, the formula for calculating the *C*-factor proposed by FAO has been the most widely used formula—it can be computed using traditional observational data and satisfies the accuracy requirements of the wind erosion equation (Dong and Kang, 1994; Jia et al., 2017; Wu et al., 2018a; Qi et al., 2019; Yue et al., 2019).

The farming-pastoral zone (FPZ) of northern China is located in a transitional area between pastoral and agricultural activity. Due to the special climatic conditions and long-term anthropogenic intervention there, it is a vulnerable ecotone in which the ecological system is very sensitive to soil conditions, climate change, and human activity (Guo et al., 2013; Shi and Liu, 2018). Suffering from serious wind erosion and land degradation, this region has become a major origin of sandstorms (Zhao et al., 2002; 2003; Qin et al., 2007). The land surface is exposed for almost seven months every year, with the topsoil being dry and loose (Qin et al., 2007). Wind erosion and sand storms occur frequently in spring and winter, seriously affecting the FPZ environment (Wang et al., 2020; Liu et al., 2021). Recent studies have shown that the FPZ climate has changed significantly during the past few decades, which may substantially impact wind erosion climatic erosivity (Chen et al., 2007; Yan et al., 2008; Dong et al., 2010). The aims of this study are: 1) to detect the trends in climate factor and wind erosion climatic erosivity based on the non-parametric Mann-Kendall test; 2) to analyze the sensitivity of the *C*-factor to changes in climate factors using non-dimensional relative sensitivity coefficient analysis; 3) to quantify the climate factor contributions to the *C*-factor's change and identify the key factors affecting wind erosion climatic erosivity change.

2 Data and Methods

2.1 Description of study area

The farming-pastoral zone of northern China, covering an area of 72.4 × 10^4 km^2 and extending across 10 provinces (Fig. 1), is an ecotone that lies between the agricultural and pastoral areas of northern China (Deng

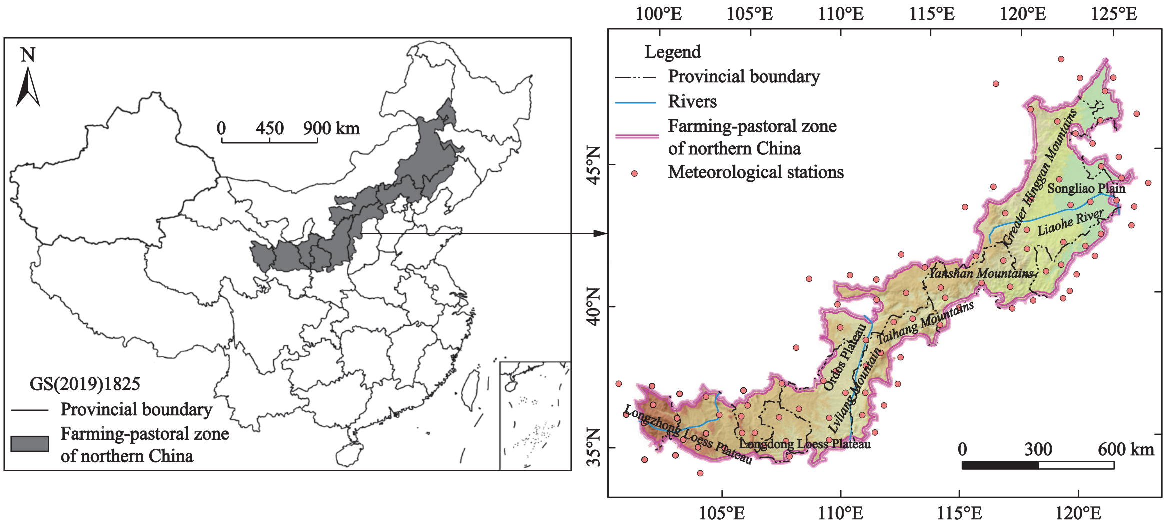

Fig. 1 Location of study area in China and spatial distribution of weather stations used in this study

and Zhan, 2004; Zhang and Guo, 2013). The mean annual precipitation there ranges from 250 to 500 mm, with approximately 60%–70% occurring in summer (Wang et al., 1999). The annual average temperature and annual wind speed are 6.9°C and 3.5 m/s, respectively, varying from place to place. The windy season usually occurs from March to June when bare ground and loose surface soil are prone to erosion (Zhao et al., 2002).

A dataset of weather stations with daily observations of wind speed (*WD*), sunshine duration (*SD*), relative humidity (*RH*), precipitation (*Pre*), maximum temperature ($T_{\max}$), and minimum temperature ($T_{\min}$) during the period of 1961–2017 was used in this study. These data were obtained from the Daily Observation Dataset (V3.0, http://www.nmic.cn/data/) archived at the National Meteorological Information Centre (NMIC) of the China Meteorological Administration. NMIC performs strict data quality control, and a quality assessment of data and data selection were done in this study. In order to analyze the temporal characteristics of climate factors and *C*-factor, stations with more than 50 years of data were retained, while the rest were excluded due to too much missing data. Because of the sparse and uneven distribution of the meteorological stations, the daily data of 101 observation stations in the study area and its surrounding regions and the kriging method were used in order to generate continuous spatial information (Fig. 1).

2.2 Calculation of wind erosion climatic erosivity

In this study, the wind erosion climatic erosivity was calculated using the equation proposed by FAO (1979). The *C*-factor is defined as follows:

$$C = \frac{1}{100}\sum_{i=1}^{12}\bar{u}^3\left(\frac{ETP_i - P_i}{ETP_i}\right)\times d_i \quad (1)$$

where C is the wind erosion climate factor; P_i is the precipitation (mm) in month i; d_i is the number of days in month i; ETP_i is the potential evapotranspiration (mm) in month i; and $\bar{u}$ is the average monthly wind speed at a height of 2 m, which is calculated using the daily wind speed measured at 10 m above ground level based on the following formula of FAO (Allen et al., 1998):

$$\bar{u} = u_z\frac{4.87}{\ln(67.8z - 5.42)} \quad (2)$$

where u_z is the wind speed measured at z m height above ground level. ETP_i (mm) in month i is estimated using the FAO56-PM function (Allen et al., 1998):

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma\left(\frac{900}{T+273}\right)u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (3)$$

where ET_0 is the daily reference crop evapotranspiration (mm/d), G is the soil heat flux density (MJ/(m^2·d)), R_n is the net radiation at the crop surface (MJ/(m^2·d)), u_2 is the daily wind speed at a height of 2 m (m/s), T is the mean daily air temperature at a height of 2 m (°C), e_s is the saturation vapor pressure (kPa), e_a is the actual vapor pressure (kPa), $e_s - e_a$ is the saturation vapor pressure deficit (kPa), γ is the psychrometric constant (kPa/°C), and Δ is the slope of the vapor pressure curve (kPa/°C). The calculation of each indicator in the

FAO56-PM equation is based on the guidelines and procedures given in Chapter 3 of FAO paper 56 (Allen et al., 1998; Gong et al., 2006).

2.3 Trend analysis

One of the most prevalent methods for monotonic trend detection in hydrological and meteorological time series, the nonparametric rank-based Mann-Kendall test, was used to investigate the temporal variability of wind erosion climatic erosivity and climate factors (Mann, 1945; Kendall, 1975). The Mann-Kendall test is considered to be the most suitable method for censored data, non-normal data, and data with missing values (Türkeş et al., 2009; Meusburger et al., 2012; Rehman, 2013). The Mann-Kendall test statistic Z is calculated, and positive Z indicates an increasing trend and negative Z a decreasing trend. Wind erosion climatic erosivity and climate factors will pass the significance test at confidence levels of 90%, 95%, and 99% when $|Z| \geq$ 1.65, 1.96, and 2.58, respectively (Amadi and Udo, 2015).

2.4 Sensitivity analysis

In order to quantitatively evaluate the effects of changes in climate factors on wind erosion climatic erosivity, sensitivity analysis was carried out in this study. For the FAO56-PM model and FAO C-factor equation, different variables have different dimensions and ranges of values, which makes it difficult to compare the sensitivities of the C-factor to changes in climate factors using partial derivatives. Moreover, the relative magnitudes of the C-factor and climate factors have significant impacts on the sensitivity coefficients (Beven, 1979; Gong et al., 2006). Therefore, this study used the non-dimensional relative sensitivity coefficient recommended by McCuen (1974):

$$SC_{x_i} = \lim_{\Delta x_i \to 0} \left(\frac{\frac{\Delta C}{C}}{\frac{\Delta x_i}{x_i}} \right) = \frac{\delta C}{\delta x_i} \times \frac{x_i}{C} \quad (4)$$

where Δx_i is a unit change in a climate factor, ΔC is the change in the C-factor induced by Δx_i, and SCx_i are the sensitivity coefficients of the C-factor to x_i. It is worth noting that Eq. (4) is the first-order term of Taylor's expansion (Saxton, 1975; Lenhart et al., 2002; Darshana et al., 2013; Mosaedi et al., 2017). A positive value of SCx_i indicates that the C-factor increases as a particular climate factor increases, and a negative value indicates that the C-factor decreases as the climate factor decreases. Moreover, the larger the value of SCx_i, the greater the effect a given climate factor has on the C-factor. If SCx_i is 0.2, it means that a 10% increase in x_i causes a 2% change in the C-factor, while the other climate factors are held constant (Gong et al., 2006; Huo et al., 2013).

In this study, SCx_i was conducted from −10% to +10% with an interval of ±1% (20 scenarios) for each of the climate factors (WD, SD, RH, Pre, $T_{\max}$, and $T_{\min}$) while keeping the other factors constant. On a monthly basis, sensitivity coefficients were calculated for all weather stations in the farming-pastoral zone of Northern China, and yearly average values were computed based on monthly sensitivity coefficients.

2.5 Attribution analysis

As mentioned above, sensitivity analysis (SA) is helpful in that it roughly determines the change in the C-factor due to the change in each climate factor. Combined with known changes in climate factors, SA can quantify the contribution of each climate factor to the change in wind erosion climatic erosivity. Yin et al. (2010) proposed an approach for attributing changes in ET_0 to climate factors; this can be obtained by calculating the sensitivity coefficient multiplied by the relative change of climate factors. In this study, the contribution of each climate factor on the wind erosion climatic erosivity can be estimated as follows (Zhang et al., 2018):

$$RC_{x_i} = \frac{n \times Trend_{x_i}}{|\overline{x_i}|} \times 100\% \quad (5)$$

$$CA_{x_i} = SC_{xi} \times RC_{xi} \quad (6)$$

where n is the number of years, $\overline{x_i}$ is the average value of each climate factor x_i for n years, $Trend_{x_i}$ is the trend in $\overline{x_i}$ over the past 57 yr calculated using the least-squares linear fitting method, RCx_i is the relative change in climate factor x_i, and CAx_i is the contribution of climate factor x_i.

3 Results and Discussion

3.1 Trends in climate factors

The results of the Mann-Kendall test on climate factors are presented in Fig. 2. The analysis shows that for most

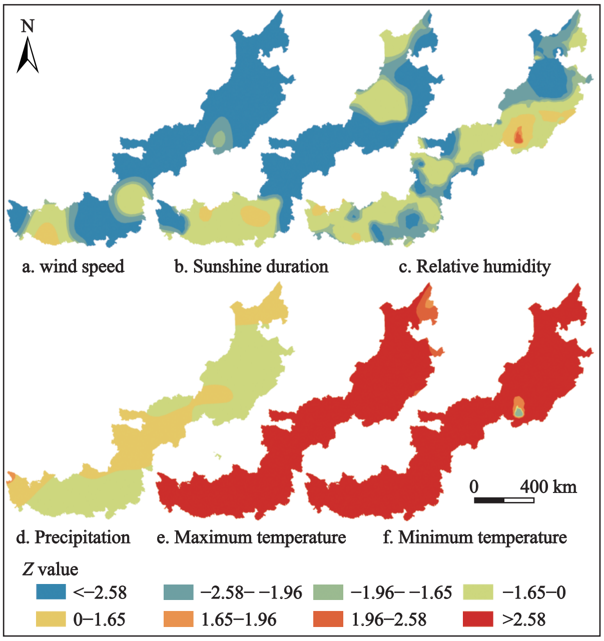

Fig. 2 Spatial patterns of the Z values for changes in different climate factors during the period of 1961–2017 in the farming-pastoral zone of northern China

of the study area, the annual wind speed decreases at a confidence level of 90% (Fig. 2a). Significant decreasing trends in sunshine duration occur in the middle area (Fig. 2b). Trends in the relative humidity vary greatly spatially, with a significant decreasing trend in the Great Hinggan Mountains and Songnen Plain and a significant increasing trend in the Yanshan mountainous area (Fig. 2c). No significant trends in the annual precipitation are observed across the study area, with a few exceptions in the southwest (Fig. 2d). Due to global warming, both the annual minimum temperature and the annual maximum temperature show an increasing trend almost throughout the study area. This is especially true for the annual minimum temperature, which increases sharply in several regions (Figs. 2e and 2f).

3.2 Trends in wind erosion climatic erosivity

The results of the Mann-Kendall test on wind erosion climatic erosivity are depicted in Fig. 3. Seasonal analysis of the changes in the C-factor reveals that most regions in the study area have significant decreasing trends in spring, winter, and autumn, while in more than two-thirds of the area, no significant trends are detected in summer at a confidence level of 90% (Figs. 3a–3d). Similar to what is observed for the trends in wind speed (Fig. 2a), significant decreasing trends are found in the

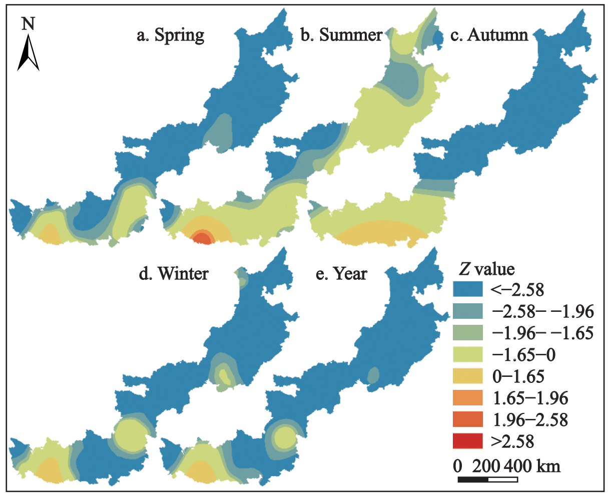

Fig. 3 Spatial patterns of the Z values for changes in seasonal and annual C-factors in the farming-pastoral zone of northern China

C-factor at the annual time scale almost throughout the study area (Fig. 3e). Previous studies have shown that the C-factors of most arid and semi-arid areas in northern China have had a decreasing trend in recent decades (Jiang et al., 2013; Qi et al., 2015; 2019; Li et al., 2018), which leads to increasing vegetation coverage and decreasing of wind erosion (Dong et al., 1996; Zhao et al., 2005; Li et al., 2018). Additionally, because it is the main driving force of land desertification disaster, an annual decrease in wind erosion climatic erosivity will reduce the risk of land desertification (Shen et al., 2017).

3.3 Sensitivity of wind erosion climatic erosivity to climate factors

The results for the average monthly C-factor sensitivity to changes in climate factors are shown in Fig. 4: the wind speed, sunshine duration, and minimum and maximum temperatures are positive, while the precipitation and relative humidity are negative. Overall, the average monthly C-factor is most sensitive to a change in wind speed. Sensitivity values fluctuate over time, between 3.21 and 3.79, indicating that a 1% increase in wind speed leads to more than a 3% change in wind erosion climatic erosivity. Our findings that wind speed might be a crucial factor underlying changes in the C-factor are consistent with the results of other studies (Dong and Kang, 1994; Yang and Lu, 2016; Niu et al., 2017; Li et al., 2018). Recent studies have shown that decreasing trends in wind speed are mainly caused by changes

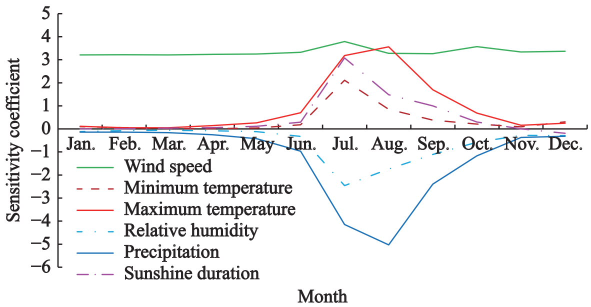

Fig. 4 Sensitivity coefficients of *C*-factor to changes in climate factors during the period of 1961–2017 in the farming-pastoral zone of northern China

in large-scale atmospheric circulation and human activities, including the weakening of East Asian monsoons, sea surface temperature anomalies, urbanization, changes in land use and cover, and the global warming caused by anthropogenic emissions (Zhao et al., 2016; Wu et al., 2017; 2018b; Hu et al., 2019; Li et al., 2019; Ding et al., 2020). Long-term decreasing wind speed will not only have a direct impact on the *C*-factor, but also an indirect impact via the reduction in solar radiation received at the land surface, which influences water evaporation and hydrologic cycles (McVicar et al., 2012a; 2012b; Liu et al., 2014).

Fig. 4 shows that the *C*-factor value is least sensitive to changes in the minimum temperature. According to recent studies, a change in the minimum temperature leads to a change in the potential evapotranspiration (Jiang et al., 2013; Li et al., 2018; Han, 2019), which will further affect the change in the *C*-factor. However, previous studies have found that the potential evapotranspiration is not sensitive to variation in the minimum temperature (Yin et al., 2010; Zhang et al., 2017). Therefore, the sensitivity coefficient of the minimum temperature is much lower than other climate factors. The sensitivity values of the other factors vary dramatically throughout the year, with larger values occurring in the hot season from July to September. For example, the sensitivity coefficient of T_{max} increases from 0.05 in February to 3.56 in August and then drops sharply after September. The sensitivity coefficient of the precipitation also increases, but in the opposite direction, from 0.14 in January to a maximum of 5.03 in August (Fig. 4). Wind speed and precipitation have a strong influence on the potential evapotranspiration in several months, leading to a change in the *C*-factor. Fig. 4 shows that the sensitivity coefficients of precipitation are higher than those of wind speed in July and August.

Fig. 5a shows that, although the sensitivity value of the wind speed in a number of research areas is above 3.25, it varies greatly spatially. High sensitivity coefficients are observed in the Greater Hinggan Mountains, Songnen Plain, Lvliang Mountains, Longdong Loess Plateau, and in the Ordos Plateau, while low sensitivity coefficients are observed in the Yanshan Mountains. As shown in Fig. 5b, the sensitivity coefficient of the sunshine duration also varies substantially from place to place, high in the Yanshan Mountains and Longdong Loess Plateau, and low in the Longzhong Loess Plateau, Northeastern Ordos Plateau, and Southern Greater Hinggan Mountains. Similarly, the sensitivity coefficients of the precipitation and relative humidity vary dramatically spatially, with relatively large values generally in the Greater Hinggan Mountains, upstream of the Liaohe River, in the Longdong Loess Plateau, and in the Yanshan and Lvliang Mountains. Relatively small values are observed in the Ordos Plateau and Longzhong Loess Plateau (Figs. 5c and 5d). In this study, the spatial distribution for the sensitivity value of the maximum temperature is similar to that for the minimum temperature, with relatively high values in the Songnen Plain, upstream of the Liaohe River, and in the Longdong Loess Plateau, and relatively low values in the Ordos Plateau and Longzhong Loess Plateau (Figs. 5e and 5f).

3.4 Contributions of climate factors to changes in wind erosion climatic erosivity

The sensitivity coefficients and relative changes in climate factors, as well as their influence on the annual *C*-factor, are summarized in Table 1. Among all the climate factors, wind speed makes the greatest contribution to the decrease in the annual *C*-factor due to its high sensitivity coefficient (3.34) and high relative change (–24.82%). The minimum temperature makes the second largest contribution owing to its high relative change (59.75%), although its sensitivity coefficient is the lowest (0.36). Precipitation makes a small contribution to the change in annual *C*-factor (4.56%), with a sensitivity coefficient of –1.29 and a relative change of –2.45%. In comparison, the contributions of sunshine duration and relative humidity are almost negligible, as the changes in the annual *C*-factors are all below 3%.

Despite that, on average, the decrease in *C*-factor resulting from a reduction in wind speed is great as

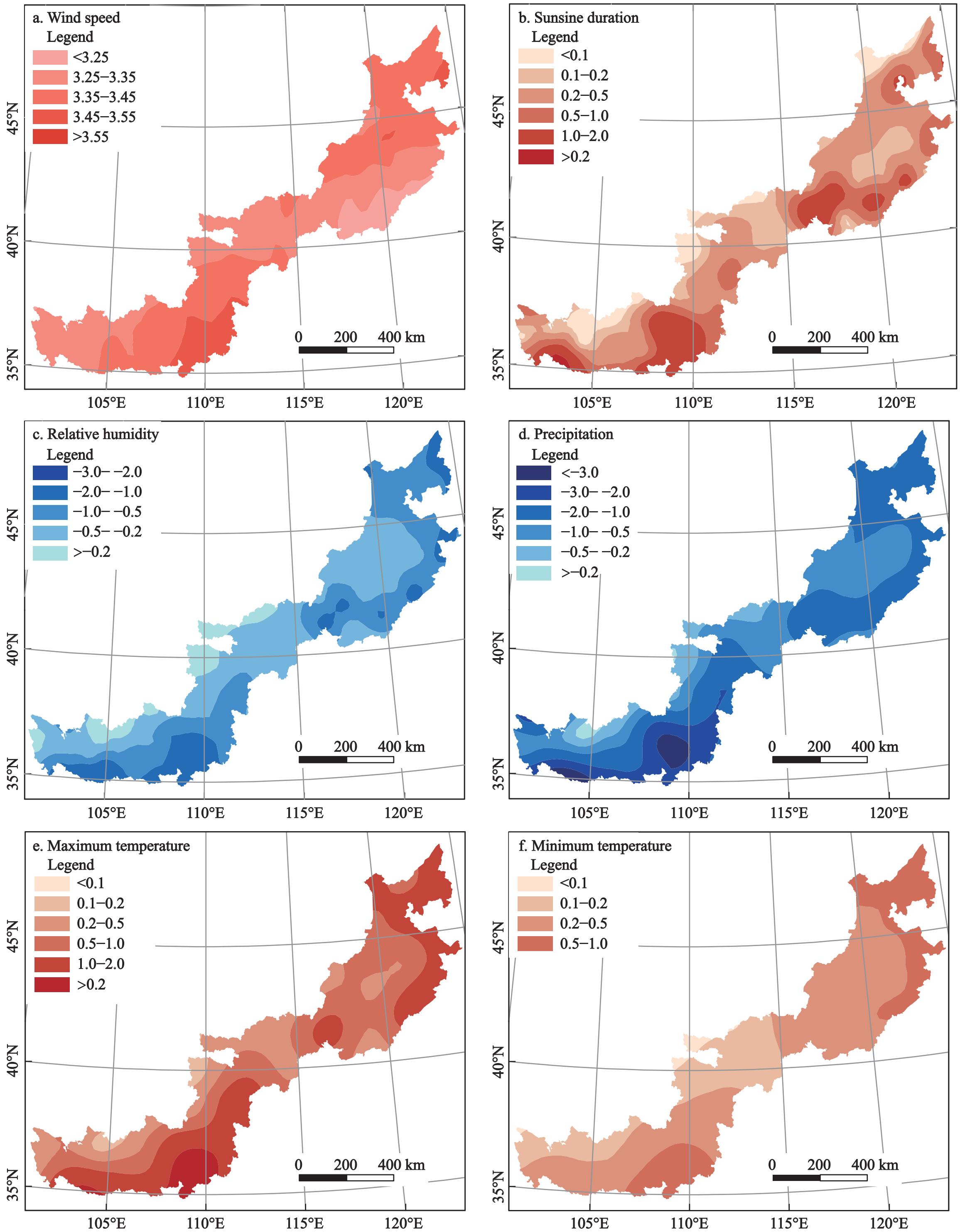

Fig. 5 Spatial distribution for the sensitivity coefficients of the average annual *C*-factor to changes in climate factors during the period of 1961–2017 in the farming-pastoral zone of northern China

81.70%, dominant factors vary across the research area. Fig. 6 shows that a decrease in wind speed is the leading factor in variation of the *C*-factor at 86% of the stations; at the other stations, the minimum temperature is the dominant contributor to changes in the annual *C*-factor.

C-factor change is a complicated issue and depends on the individual and combined effects of various climate variables. For an individual climate factor, its contribution is not only determined by the magnitude of the

Table 1 Variations of climate factors and their contribution to *C*-factor change

Climate factors	Sensitivity coefficient	Relative change / %	Changes in *C*-factor / %
Wind speed	3.34	–24.82	–81.70
Minimum temperature	0.36	59.75	24.33
Maximum temperature	0.91	12.34	11.11
Precipitation	–1.29	–2.45	4.56
Sunshine duration	0.51	–7.03	–2.64
Relative humidity	–0.60	–4.18	2.32

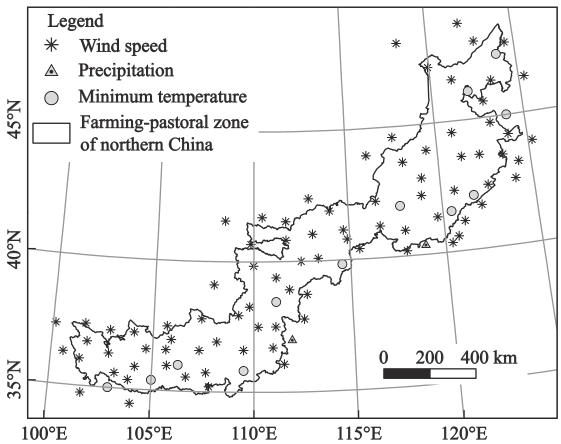

Fig. 6 Dominant factor of *C*-factor change in different stations in the farming-pastoral zone of northern China

change in climate factors over time, but also by its sensitivity coefficient. Uncertainties in the *C*-factor are compounded by the combination of different climate factors. As shown in Fig. 6, due to its substantial increase in the past decades, the minimum temperature is the dominant factor affecting changes in the *C*-factor at 10 stations. However, the effect of increasing minimum temperature is offset by the negative impact of other climate factors, leading to an overall decreasing trend in the *C*-factor (Table 1). It is worth noting that, as the second dominant factor, the minimum temperature will make an increasing contribution to changes in the *C*-factor because of global warming. Thus, further research is needed to evaluate the impact of minimum temperature on the *C*-factor in the future.

4 Conclusions

The *C*-factor is a crucial parameter in the assessment of the possible effects of climatic conditions on wind erosion. Using daily meteorological data, we studied changes in climate factors and their impact on the *C*-factor in the farming-pastoral zone of northern China. The main findings are summarized as follows:

(1) Significant decreasing trends in wind speed were detected in many regions, especially in the northeastern part of the study area, while the minimum and maximum temperatures showed increasing trends throughout the study area. Significant decreasing trends in the annual *C*-factor were also found in most regions. Seasonal analysis on the changes in the *C*-factor revealed that most regions in the study area had significant decreasing trends in spring, winter, and autumn, while in more than two-thirds of the area, no significant trends were detected in summer at a confidence level of 90%.

(2) Sensitivity analysis showed that the *C*-factor was most sensitive to wind speed and least sensitive changes in minimum temperature. The sensitivity values of the wind speed varied from 3.21 to 3.79, and the sensitivity coefficients for July to September were much higher than those of the other months.

(3) The *C*-factor was affected by a wide variety of climate factors. While wind speed, maximum temperature, minimum temperature, and sunshine duration made positive contributions changes in the *C*-factor, the other factors, including precipitation and relative humidity, made negative contributions. Comparing the contributions of different climate factors showed that changes in the *C*-factor were mainly caused by a decrease in wind speed in most areas, followed by an increase in the minimum temperature; relative humidity made the smallest contribution.

(4) Since our investigation was based on observational climate data from weather stations, the uneven distribution and sparse coverage of weather stations in some areas may have led to uncertainties that affect the analysis. Gridded climate data, such as data from CLDAS (China Meteorological Administration Land Data Assimilation System), HRCLDAS (High-Resolution Land

Data Assimilation System), and LIS (Land Information System), with high spatial and temporal resolution, may be used to downscale the analysis output in future research. In this study, the impacts of climate change on the *C*-factor were evaluated using meteorological data observed over the past few decades. Due to rapid changes in the climate of the study area, more studies, focusing on the response of the *C*-factor to future climate scenarios, need to be conducted to develop policy recommendation.

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