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Surface wind observations affected by agricultural development over Northwest China

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Supplementary material for this article is available online

Abstract

Meteorological stations in Northwest China are surrounded by large proportions of cultivated land. The relations between the change of surface wind speed and the cultivated land fractions (CF) within a 4 km radius at 135 meteorological stations over arid Northwest China are investigated. Stations with larger CF experienced larger declines in surface wind speed from 1960 to 2007. Compared with the wind speed variation in the Tibetan Plateau where agricultural development is negligible, stations with low CF show similar variation, whereas the wind speed at stations with large CF illustrates a sharp decrease in the 1970s–1980s, during which irrigated agriculture developed rapidly. The observed wind speed at the station surrounded by irrigated fields in the Jingtai Irrigation District, shows a rapid wind speed decrease during the same period when the irrigated area expanded. By contrast, rapid wind decrease is not observed at a nearby station with minimal influence of agricultural development.

1. Introduction

Land surface exerts a frictional drag on the air blowing just above it, which can act to change the wind speed. In the dynamic sublayer, the mean wind speed can be described by the logarithmic velocity profile law:

$$U_m = \frac{u_*}{\kappa}\ln\left(\frac{Z - d_0}{Z_{0m}}\right) \quad (1)$$

where U_m is the mean wind speed (m s^{-1}), κ is the von Kármán constant (0.4), Z is the measurement height above the ground (m), d_0 is the displacement height, and Z_{0m} is the local roughness legnth (m). The difference in surface conditions directly affects how much friction is exerted. Increasing surface roughness forces the wind to slow down a much more (Vautard *et al* 2010, Wever 2012). Surface wind speed decline has been observed in many mid-latitude regions of both hemispheres (Vautard *et al* 2010, McVicar *et al* 2012). Vegetation-related roughness changes were considered as a main cause of lowering atmospheric wind (Vautard *et al* 2010, Cowie *et al* 2013). Agricultural development, such as land reclamation, extended irrigation, and enhanced fertilization, was the main cause of increases in vegetation activities (Fang *et al* 2004, Xiao and Moody 2004), which could increase surface roughness. Therefore, an intuitive relation between surface wind changes and agricultural development could be expected. Alpert and Mandel (1986) found a clear decreasing trend in normalized diurnal and inter-diurnal surface wind variability associated with agricultural development in south central Israel. Ozdogan and Salvucci (2004) found that the mean surface wind speed declined from 3 m s^{-1} in 1979 to 1 m^{-1} in 2001 along with rapidly irrigated agricultural development in southeastern Turkey. Nevertheless, most previous studies focused on observed regional wind speed changes without addressing the disturbances of agricultural development in the past decades.

The observed surface wind in China has declined rapidly since the early 1970s, and the weakening of atmospheric circulation, a north–south warming gradient, and sunlight dimming caused by air pollution were considered possible factors (Xu *et al* 2006, Jiang *et al* 2010, Guo *et al* 2011). Over Northwest China, observations have displayed a relatively larger decline magnitude of surface wind (Fu *et al* 2010, Guo *et al* 2011). However, the observed stilling over Northwest China is not well understood, which limits the understanding of the climate change. Besides, Northwest China has rich wind resources, and is experiencing rapid wind power development (Zhao *et al* 2009). Understanding the decline of surface wind observed in Northwest China is a potential concern for wind power electricity production. In addition, declining surface wind speed has been referred to as a major factor causing decreasing potential evaporation (Roderick *et al* 2007, Han and Hu 2012, Han *et al* 2012, McVicar *et al* 2012); understanding the observed surface wind variation is crucial for interpreting the evolution of the actual evaporation, as well as the hydrological cycle in Northwest China.

In the nearby Tibetan Plateau (TP), wind speed considerably declined over the last 30 years. Lin *et al* (2013) regarded changes in atmospheric circulation as the main driver of changes in surface wind speed compared with changes in surface roughness. Different from the TP, Northwest China has experienced rapid agricultural development from the 1970s (e.g., in Tarim River Basin (Liu et al 2014, Liu D et al 2015)), with greenness increasing considerably (Piao *et al* 2010). It was found that agricultural development has affected observations of surface air temperature (Han and Yang 2013). Enhanced declines in observed wind speed have been found in the main agricultural areas of Northwest China, such as the Tarim Basin (Han 2011) and the Hexi Corridor (Wang and Zhang 2007). Intuitively, a question may be aroused: are observed changes in surface wind speed in Northwest China disturbed by agricultural development? The current study aims to investigate the roles agricultural development on the observed surface wind speed changes, for a better understanding of the observed stilling in Northwest China.

Detecting the effects of agricultural development on wind speed observations in Northwest China is difficult due to two reasons: (1) meteorological stations of the China Meteorological Administration (CMA) are sparse in this region; and (2) the evolution of agricultural development near the stations is not monitored. In this study, 39 stations from the Climatic Center of Xinjiang, together with stations from CMA, were collected to increase the station intensity. The average cultivated land fraction (CF) within 4 km of the meteorological station from a land-cover map is used as a first-order index to approximate the intensity of agricultural influence around the stations. Using the denser station network and the agricultural development index, we presented a comprehensive analysis on the relations between agricultural development and surface wind speed variations from 1960 to 2007 over Northwest China.

2. Study area, data and methods

This study focuses on Northwest China, comprising the Xinjiang Autonomous Region, the Qaidam Basin and the Qinghai Lake Basin (the main agricultural region of Qinghai Province), the Hexi Corridor and a small part of Yellow River basin in Gansu Province. The nearby TP is used as a reference area. The climate of the study area is arid with a mean annual precipitation of less than 400 mm. The spatial patterns of mean surface wind speed in the study area are affected by the atmospheric circulation, topography, and land use/type. Generally, stations are located in oases, with lower elevation than the mountain regions but abundant cultivated lands, are characterized by smaller wind speed and enhanced surface wind decline in the past 50 years than those in the mountainous and desert regions (Li 2003, Chen 2010, Han and Hu 2012). The mean surface wind speed varies significantly across seasons, which is the largest in the spring, especially during April to May, followed by the summer, and the smallest in December to January of the winter because of the inversion layer (Chen 2010).

Single cropping wheat, maize, cotton and oil-bearing are the staple crops. The cultivated lands rely heavily on perennial irrigation. Since the early 1970s, Northwest China has experienced remarkable agricultural development with rapid increase in crop sown area (figure 2). The total crop sown areas increased from 4.10×10^6 ha in 1971 to 5.76×10^6 ha in 2007, whereas the area of grain crops decreased from 3.19×10^6 ha in 1971 to 2.17×10^6 ha in 2007, but with significant increase in the area of cotton and oil-bearing. The irrigated cropland increased from 2.96×10^6 ha in 1971 to 4.10×10^6 ha in 2007. Nevertheless, the proportion of irrigation relative to total cultivated area increased until the end of 1980s, and kept stable until 2001, but decreased later. In addition, the total consumption of chemical fertilizers increased rapidly. As a result, the crop production increased rapidly.

The daily wind speed data of 178 stations from the China daily surface meteorological dataset (V3.0) and monthly wind speed data of 39 stations from 1960 to 2007 across Xinjiang (from the Climatic Center of Xinjiang) were used in this study. The data were provided and controlled for quality by the Chinese National Meteorological Information Center. The wind speed was measured by anemometers 10 m above the ground surface. Although the series of *in situ* data on surface wind speed may be inhomogeneous because of non-climatic factors (Li *et al* 2008), the current study uses the unadjusted surface wind speed dataset since we aimed to evaluate the possible impacts of agricultural development on surface wind

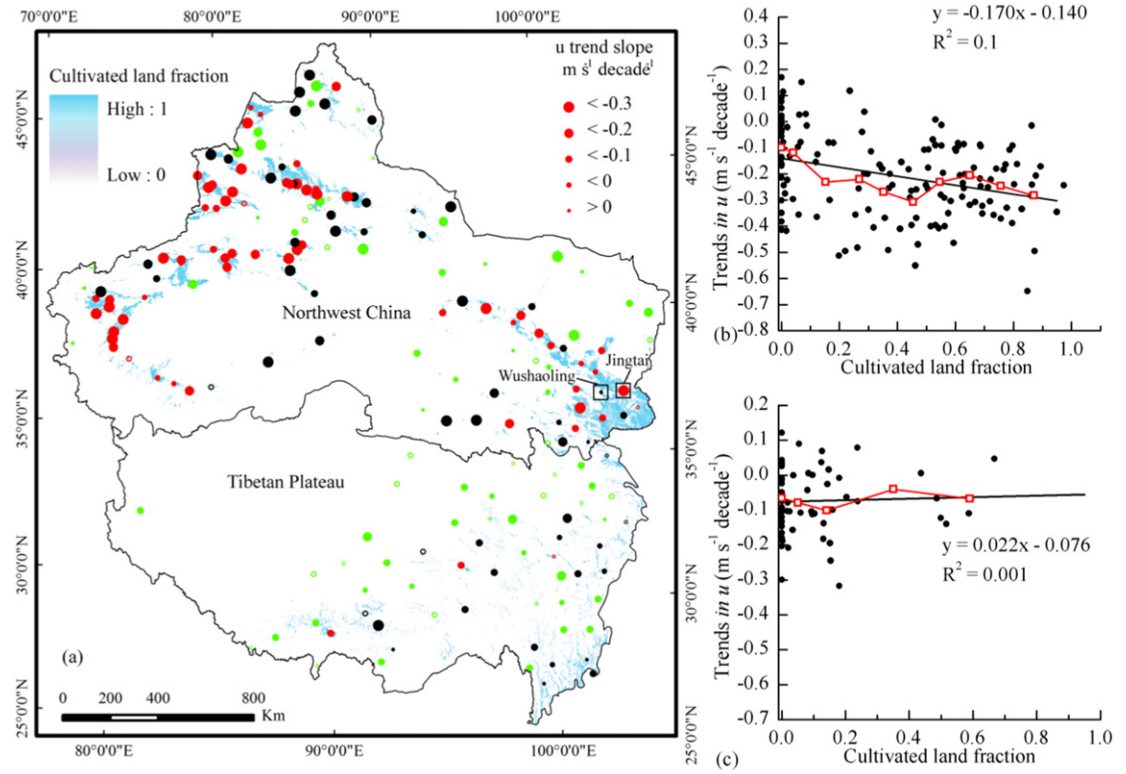

Figure 1. (a) Spatial distribution of the trends in growing season surface wind speed (m s^{-1} decade^{-1}) in 1960–2007 (the green, blue, and black marks correspond to the stations with CF > 0.5, CF < 0.1, and 0.1 < CF < 0.5; the solid marks show that the trends are significant at the 95% confidence level; and unfilled marks show that the trends are not significant at the 95% confidence level). Trends in growing season surface wind speed against the cultivated land fractions at the stations in (b) Northwest China and (c) Tibetan Plateau (the linear regression lines (solid lines) and equations, and the plots of average trends against average CFs between different intervals (dotted red lines) are shown in the panels).

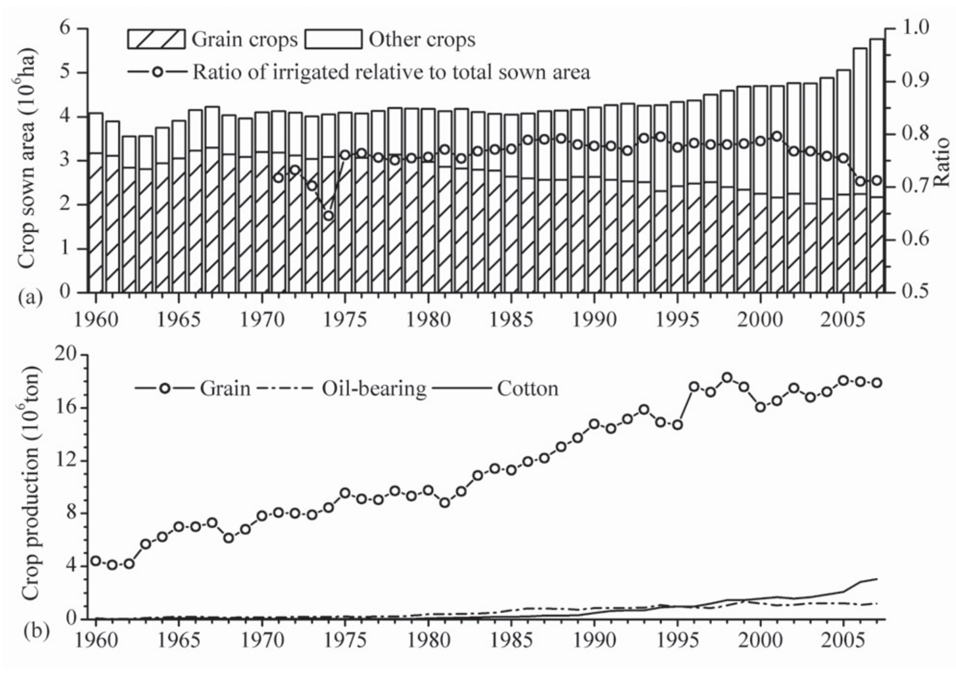

Figure 2. Time-series of (a) crop area, the ratio of irrigated to total sown area of the study area, and (b) sums of crops productions of the three provinces (Xinajign, Qinghai and Gansu).

observations. The observed hours, frequency and statistical methods are consistent after 1960. In the period from 1960 to 2007, the surface wind observing instruments varied mainly around 1969 when wind pressure anemometers were replaced by EL or EN electric wind anemometers (Li *et al* 2008), which was thought as the main reasons for a sharp step change of annual wind speed in 1969 (Fu *et al* 2010, Jiang *et al* 2010). So in the present analysis, the Mann–Kendall non-parametric method (Mann 1945, Kendall 1975) was applied to establish trends in surface wind speed using all the available data, as the results are less influenced by the presence of outliers in the data (Jhajharia and Singh 2011). In order to eliminate the influences of possible faked abrupt changes, we have paid special attention to the differences of the surface wind speed changes between the stations with or without significant agricultural influences, especially after 1970. After eliminating stations with less than 35 years of records, 195 stations were left. Nevertheless, two stations (51495 and 51886) were eliminated because the data jump is virtually impossible, and anemometer changes, station changes, and/or other reasons must occur. The annual mean wind speed jumped from 4.7 m s^{-1} in 1998 to 8.7 m s^{-1} in 1999 at Station 51495 (Fu *et al* 2010), and the annual wind speed at Station 51886 decreased from 4.56 m s^{-1} in 1987 to 2.67 m s^{-1} in 1989. The remaining 193 stations were analyzed, with 135 located in Northwest China and 58 in the TP (figure 1).

The spatial distribution of cultivated land for 2000 were obtained from the Data Center for Resources and Environmental Sciences of the Chinese Academy of Sciences (Liu *et al* 2003). The data were based on a 1:100 000 land use map, in which the area proportions of cultivated land were provided at each 1 km grid. The average CF within 4 km of the meteorological stations is calculated to denote the agricultural land use at these stations. Although cultivated lands constitute only a small proportion of the total land area, the CFs of stations in Northwest China ranged from 0% to 97%, with a mean value of 41%, which is larger than that in the TP, with an average CF of 12.6%. Generally, stations surrounded by large CF experienced more influences of agricultural development. Therefore, we use CF to denote the agricultural development around the stations.

The biweekly NDVI data obtained from the Global Inventory Monitoring and Modeling Studies (GIMMS) database, with a spatial resolution of 8 km, were used to denote the vegetation variations from 1982 to 2007. Here, we used the third-generation GIMMS-NDVI3g data. At each selected site, the averaged NDVI in the 3 pixel × 3 pixel window surrounding the site was calculated. The time series of growing season (May–September) mean NDVI from 1982 to 2007 were then calculated for each site. In Northwest China, agricultural development is the main cause of increases in NDVI (Fang *et al* 2004, Xiao and Moody 2004), while the NDVI in areas with natural vegetation is much lower. Therefore, the values of CF and NDVI around the stations are related. The stations with larger CFs are characterized with larger average NDVI values and more significant increasing trends (correlation coefficients are 0.44 and 0.51, respectively). However, the temporal evolution of agricultural development cannot be inferred because the land use map is unavailable before the satellite era. Therefore, the annual variations of NDVI from 1982 to 2007 are used to demonstrate the temporal evolution of agricultural development indirectly.

A station in the Jingtai Irrigation District (figure 1), where the data on irrigated area around the station are available from the 1960s, is used to demonstrate the relations between the changes of wind speed and agricultural development. The Jingtai Irrigation District is a proluvial plain surrounded by mountains with bare land and is near the upstream Yellow River. After the construction of an irrigation pumping project from the Yellow River in the early 1970s, the irrigated land area rapidly expanded from nearly 0 km^2 to 200 km^2 (Han *et al* 2014). The Jingtai meteorological station (104°3'E and 37°11'N) is located approximately at the center of the irrigation district. The data of the Wushaoling station (102°52'E and 37°12'N), a station approximately 96 km away from the irrigation district, were used for comparison as the reference station with little influence from agricultural development (Wang and Zhang 2007).

The rawinsonde wind data of 21 sites are gathered in the China monthly sounding dataset of assigned height layer. The rawinsonde stations are listed in table S1. Monthly averaged values of upper-air wind speed at pressure levels of 850 and 700 hPa were used. Given that the data before 1980 have missing information for many stations, we focused on data from 1980 to 2007.

The non-parametric Mann–Kendall trend test method with a trend-free, pre-whitening procedure (Yue *et al* 2002) was used to identify the wind speed trends. The linear regressions of wind speed trends on the CFs were computed. The sensitivity of observed wind speed trends to the agricultural land use were then evaluated based on regression slopes and linear correlation coefficients. The statistical significance of the correlation coefficient was evaluated using *t*-test.

3. Results

The trends of yearly mean surface wind speed in the growing season (from May to September), non-growing season (from October to April), and in all 12 months of the 193 stations are analyzed for the period of 1960–2007. The trends in the growing season wind speed are displayed in figure 1. Of the 135 stations in Northwest China, 111 stations (82%) exhibit a significant decreasing trend at 95% confidence level for the growing season wind speed, whereas only 35 of 58

Table 1. Comparison of trends in surface wind speeds m s^{-1} $decade^{-1}$ from 1960 to 2007 of station groups with CF larger than 0.5 and smaller than 0.1 in Northwest China and the TP.

			Station-averaged trend slopes			Trends of station-averaged time series*		
Region	Group	Number of stations	Annual	May-Sep.	Oct.-Apr.	Annual	May-Sep.	Oct.-Apr.
Northwest China	All	135	−0.187	−0.209	−0.165	−0.183	−0.202	−0.161
	CF < 0.1	36	−0.102	−0.108	−0.096	−0.133	−0.145	−0.109
	CF > 0.5	61	−0.212	−0.236	−0.189	−0.213	−0.234	−0.189
	All	58	−0.094	−0.074	−0.100	−0.113	−0.082	−0.121
Tibetan	CF < 0.1	36	−0.098	−0.071	−0.108	−0.122	−0.090	−0.134
Plateau	CF > 0.5	3	−0.099	−0.081	−0.097	−0.115	−0.090	−0.101

stations (60%) in the TP exhibit a significant decreasing trend. The decreasing trends of surface wind speed (with an average trend slope −0.209 m s^{-1} $decade^{-1}$ in growing season) are higher in Northwest China than those in the TP (with an average trend slope −0.074 m s^{-1} $decade^{-1}$ in the growing season). In Northwest China, the decreasing trends in the growing season are more significant than the trends in the non-growing season (with an average trend slope −0.165 m s^{-1} $decade^{-1}$), which is different from those in the TP.

In Northwest China, surface wind speed trends are sensitive to the CFs of stations, which can be detected using linear regression. The trend slopes of the 135 stations are negatively correlated with the CFs. The regression slope (−0.17 ± 0.09 m s^{-1} $decade^{-1}$) and correlation coefficient (−0.32, $p < 0.0001$) during the growing season are more significant compared with those in the non-growing season (the regression slope is −0.12 ± 0.07 m s^{-1} $decade^{-1}$ and the correlation coefficient is −0.28, $p < 0.001$). By contrast, no significant correlation exists between surface wind speed trend slopes and CFs in the TP. The trend slopes of the growing season surface wind speed of the stations in the two regions are plotted against the CFs in figure 1. Although the relationships are scattered, in Northwest China, the stations with a large CF are expected to experience more significant atmospheric stilling (i.e., declines in wind speed) than the stations with a small CF.

To further evaluate the different variations of surface wind speeds of stations with different influences of agricultural development, all the 135 stations in Northwest China are roughly classified into three groups: 36 stations with CF < 0.1 are taken as with minimal influences of agricultural development, 61 stations with CF > 0.5 are taken as with significant influences of agricultural development, and the other 38 stations with 0.1 < CF < 0.5 are taken as the rest of the group. As shown in table 1 and figure 1(b), on which the average surface wind speed trends of stations with different levels of CF (0%, 0%–10%, 10%–20%, up to 90%–100%) are plotted against the average CFs, the average decreasing trends in surface wind speed of the station group with CF < 0.1 are much weaker than the other groups, but are close to those in the TP, where the agricultural development is negligible. In Northwest China, the station group with CF > 0.5 experienced a more rapid decline in wind speed than that with CF < 0.1, especially in the growing season. Therefore, the 36 stations with CF < 0.1 in Northwest China provide a reference of background wind speed change, while the 61 stations with CF > 0.5 are analyzed with special attention.

The time series of station-averaged growing season wind speed of the station groups with CF < 0.1 and CF > 0.5 in 1960–2007 in Northwest China are compared. The time series of station-averaged growing season surface wind speed of the stations with CF < 0.1 and all stations in the TP are also calculated for comparison. The variation of station-averaged surface wind speed for the group CF < 0.1 in Northwest China is close to those in the TP (the correlation coefficient between them is 0.88). At stations rarely affected by agricultural development, surface wind speed showed a steep increase in the early 1970s, followed by a significant decline until the early 2000s and a slight recovery thereafter. Despite the decline in wind speed, the deviation from the mean of the 1960s is positive in the 1970s–1980s and is small in the 2000s. By contrast, surface wind speed at stations largely affected by agricultural development (i.e., CF > 0.5) in Northwest China dropped off sharply from the early 1970s to the 1980s, resulting in a pronounced negative deviation from the mean of the 1960s. The deviations of the surface wind speed from the mean of the 1960s are shown in figure 3(a).

Large-scale changes in atmospheric circulation may explain wind speed variations at the stations with small CF but are unlikely the main cause at the stations with large CF, and agricultural development may be an important influencing factor of the observed wind speed changes. The distinct surface wind speed variations at two stations (figure 1) around the Jingtai Irrigation District demonstrate how agricultural development may affect observed growing season wind speed (figure 3(b)). The wind speed at the Wushaoling station, that was barely influenced by agriculture activities, increased in the early 1970s and decreased slightly thereafter. The wind speed did not drop compared with that in the 1960s. The growing

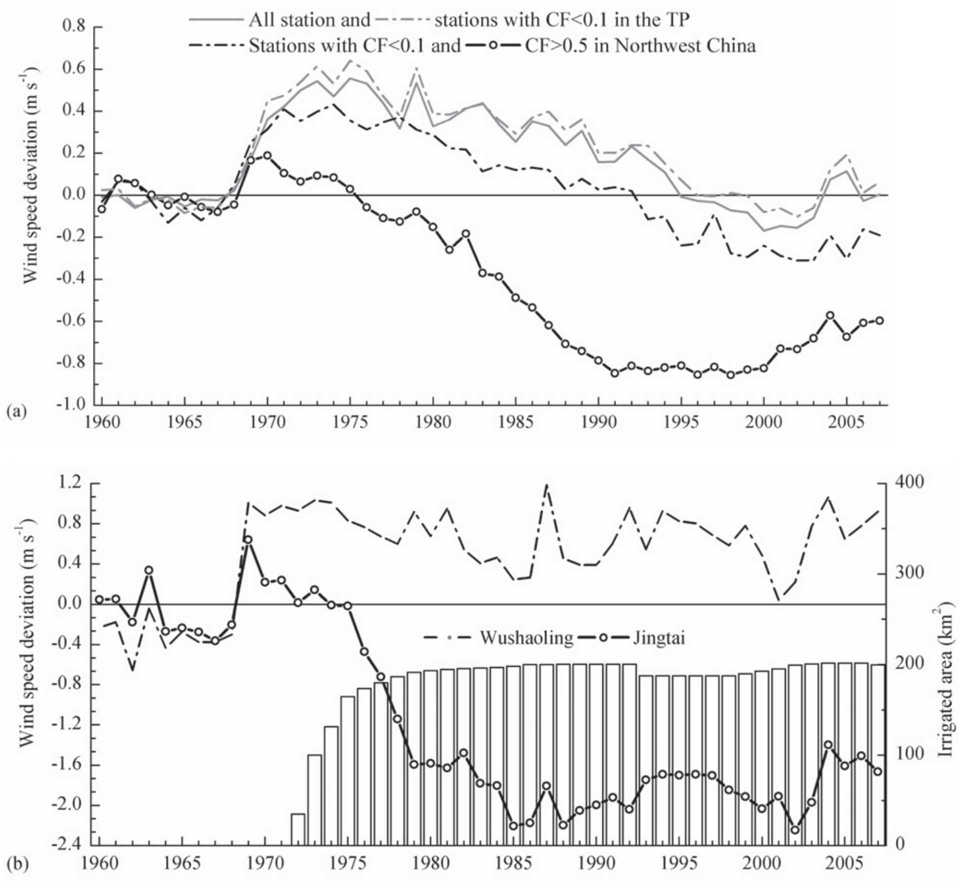

Figure 3. (a) Time-series of the average growing season surface wind speed deviation from the mean of the 1960s of the station groups with CF < 0.1 (3.44 m s^{-1}) and CF > 0.5 (2.14 m s^{-1}) in Northwest China as well as all stations and stations with CF < 0.1 in the TP from 1960 to 2007; (b) time series of the growing season surface wind speed deviation from the mean of 1960–1971 of station Jingtai (3.79 m s^{-1}) and Wushaoling (4.30 m s^{-1}) and changes in irrigated acreage in the Jingtai Irrigation District from 1960 to 2007.

season wind speed variation of the Jingtai station was closely related to the variation of the Wushaoling station before the early 1970s when agricultural development around the Jingtai station was absent. From the 1970s, the irrigated area around the Jingtai station increased from nearly 0 km^2 to 200 km^2, and irrigation water withdrawal had increased to 150×10^6 m^3. Furthermore, the growing season surface wind speed at the Jingtai station decreased sharply by approximately 2 m s^{-2}. By contrast, the sharp decrease of wind speed was not observed at the Wushaoling station. The expansion of irrigated land around the Jingtai station halted after 1980. After 1980, the annual wind speed variation of the Jingtai station became similar to that of the Wushaoling station again, although the wind speed at the Jingtai station had slowed.

4. Discussions

In Northwest China, the surface wind speed trends are highly positively correlated with the altitude of stations (during growing season, the regression slope is 0.08 ± 0.03 m s^{-1} $decade^{-1}$ km^{-1} and the correlation coefficient is 0.43), indicating that surface winds declined more intensely for stations at lower elevations than those at higher elevations. This result is opposite to that in the TP (during the growing season, the regression slope is -0.01 ± 0.04 m s^{-1} $decade^{-1}$ km^{-1} and the correlation coefficient is −0.09), which was also pointed out by Lin *et al* (2013). Our result is also opposite to those in two mountainous regions (Yellow River Basin and Switzerland) found by McVicar *et al* (2010). In Northwest China, most of the cultivated land is distributed at low elevation, making the CFs of stations negatively correlated with the altitude (correlation coefficient is −0.34). For all 80 stations with altitudes between 700 and 1800 m, the decline in surface wind speed trends at stations with CF > 0.5 (42 stations, with the average growing season trend slope of −0.24 m s^{-1} $decade^{-1}$) remain more significant than that at stations with CF < 0.1 (16 stations, with the average growing season trend slope of −0.13 m s^{-1} $decade^{-1}$). However, the difference of altitude (average values are 1183 m and 1253 m, respectively) is negligible. Therefore, the difference between surface wind speed change rates at stations with high and low CFs in Northwest China is not caused by altitude differences.

Table 2. Correlation coefficients between surface wind speed and NDVI and upper-air wind speed for different groups.

	NDVI			850 hPa upper-air wind speed			700 hPa wind upper-air speed		
	Annual	May-Sep.	Oct.-Apr.	Annual	May-Sep.	Oct.-Apr.	Annual	May-Sep.	Oct.-Apr.
TP	−0.44**	−0.47**	−0.22	—	—	—	0.71**	0.63**	0.69**
CF < 0.1	−0.39**	−0.61**	0.01	0.44**	0.67**	0.37**	0.18	0.50**	0.23*
CF > 0.5	−0.85**	−0.86**	−0.63**	0.00	0.03	−0.10	−0.02	0.09	−0.03

**Significant at 99% confidence level, * significant at 95% confidence level, and the others are not significant at 90% confidence level.

As deduced by Lin *et al* (2013), the surface winds in the TP are coincident with changes in the upper-air winds, which can be detected from the large correlations between the surface wind speed and the upper-air wind speed at a pressure level of 700 hPa (table 2). Likewise, the station-averaged surface wind speed of the station group with CF < 0.1 in Northwest China is highly correlated with the upper-air wind speed at pressure levels of 850 and 700 hPa from 1980 to 2007 (table 2 and figure S1). By contrast, no statistically significant correlation exists between the surface and upper-air wind speed for the station group with CF > 0.5 in Northwest China. Instead, the positive elevation dependence of observed surface wind trends in Northwest China suggests higher influences from the land surface at stations with large CFs.

This finding can be confirmed by the changes of corresponding averaged NDVI of 1982–2007 in the 3 pixel × 3 pixel window surrounding the meteorological stations. Compared with the station group with CF < 0.1, the station-averaged growing season NDVI of the station group with CF > 0.5 in Northwest China is larger and increased more rapidly from 1982 to the end of the 1990s, followed by a more rapid decrease (figure S2(a)). The variations of station-averaged growing season surface wind speed of the station group with CF > 0.5 in Northwest China are significantly negatively correlated with changes of corresponding NDVI (correlation coefficient is −0.85, table 2 and figure S2(b)). By contrast, no statistical correlations exist between the surface wind and the NDVI for the station groups with CF < 0.1 in Northwest China and in the TP. Given that NDVI is related with the surface roughness (Vautard *et al* 2010), an intimate link between the surface wind speed for stations with CF > 0.5 in Northwest China and the land surface can be detected.

Agricultural development, as the most distinct alternation of the land surface around stations, can affect surface wind speed from several aspects (Ozdogan and Salvucci 2004). First, the enhanced irrigation and fertilization may cause the increase of vegetation activities of crops around the stations. Although a quantitative relationship between NDVI and roughness length is difficult to establish, the corresponding increase surface roughness of which would contributed to the more significant surface wind decline (Vautard *et al* 2010). Second, agricultural development in Northwest China has accompanied shelterbelt expansion. Taking Xinjiang as an example, the proportion of shelterbelt to cultivated land increased from 2.2% in 1977 to 5.0% in 1989 (Sun 1991) and to 9.5% in 2008 (Zheng *et al* 2013), and 95% of the current cultivated land is protected by shelterbelt. In the Jingtai Irrigation District, the shelterbelt area has also rapidly increased to nearly 10% of the total irrigated area along with irrigation expansion (Han *et al* 2014). In addition, the development of irrigated area in the large oasis regions may be associated with local circulations that led to the 'oasis effect', especially in the growing season, which in turn resulted in the decrease in wind speed (Oke 1978, Ozdogan *et al* 2006). The surface wind speed changes accompanying agricultural development are possible composite effects of the above aspects.

According to the observations, the average surface wind speed in the main growing and non-growing seasons in Jingtai during 1985–1999 are 46.7% and 53.0% of those during 1970–1971. By contrast, those values in Wushaoling are 94.5% and 87.9%. The impacts of irrigation expansion on the surface wind speed in Jingtai could be quantitatively analyzed according to the surface roughness length. In the oases of the Heihe River Basin (approximately 400 km away from the Jingtai), the roughness length estimated by the data of the Heihe Basin Field Experiment (HEIFE) in the field of bare land is 0.04 m, while it is 0.17 m and 0.33 m in the fields of wheat and maize (Jia *et al* 1999), both of which are also the main crops in Jingtai Irrigation District. Before the irrigation project, the near field of Jingtai station can be regarded as 'open' with a roughness length of 0.03 m according to the Davenport classification of terrain roughness (Davenport *et al* 2000), while the surface was transformed to be 'rough' with a roughness length of 0.25 m after the project. Supposing a constant friction velocity, the average surface wind speed at 10 m height after the irrigation expansion is approximatly 57.9% of that before, assuming the displacement height is related with the roughness length (Allen *et al* 1998). The results are consistent with the observation in Xinjiang, where the surface wind speed at cultivated land inside the shelterbelt with a height of 0.5–2 m was 46.2%–81.2% of that at the bare land (Liu *et al* 1991).

The results suggest that the evolution of agricultural development has affected observed surface wind speed in Northwest China. If the differences of trends in surface wind speed between the station groups with CF > 0.5 and CF < 0.1 are taken as the influences of agricultural development, the results (table 1) suggest that agricultural development could explain 37.8%–54.2% of the observed stilling in the growing season, and 42.4%–49.0% in the non-growing season. Although the 'oasis effect' is weak in the non-growing season, the shelterbelt and crop residue cover still work on reducing the surface roughness. The results indicate that the impacts of vegetation related roughness changes on the surface wind speed are beyond the main growing season (Zender and Kwon 2005, Cowie *et al* 2013).

However, the temporal evolution of agricultural development was not inferred in this study because land use maps are unavailable before the satellite era. The land use in 2000 is applied under the assumption that stations with a large CF are characterized by a significant increase in agricultural development. Only one example from Jingtai has been shown. More examples would reinforce the conclusion. Although the agricultural development may largely reduce the observed wind speed, the cultivated land area is only approximately 3.7% of the land in Northwest China. Out of the agricultural area, the changes in NDVI, and the declines in the surface wind speed are not as significant as those in the agricultural area. Agricultural development has likely affected the wind speed observations at the stations surrounded by the irrigated fields but does not necessarily significantly affect the area-averaged surface wind speed. Considering that most meteorological stations were surrounded by the cultivated lands in Northwest China (61 out of 135 stations in this study), caveats must be made when interpolating wind speed from the station observations.

5. Conclusions

The above analysis demonstrates that observations of surface wind speed in Northwest China were disturbed by agricultural development. Stations surrounded with large fractions of cultivated land experienced more rapid declines in surface wind speed from 1960 to 2007. The average surface wind speed of 61 stations with CF > 0.5 exhibited variations associated with agricultural development, which were obviously different from those at stations with CF < 0.1 and at the TP. The observed surface wind speeds rapidly decreased from the early 1970s to the 1990s, corresponding to the rapid agricultural development in Northwest China. In light of this scenario, the agricultural development around meteorological stations should be seriously considered to better understand observed surface wind speed. The results indicate that the background atmospheric stilling is not as large as we seen from observations at the meteorological stations. The evaluation of regional surface wind speed changes in Northwest China may be inappropriate without adjusting for the effects of agricultural development.

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