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Effect of wind speed on sunshine hours in three cities in northern China

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ABSTRACT: There has been a drastic decline in sunshine hours in North China since the 1960s. Increased aerosol emissions driven by air pollution have been identified as the cause of sunshine decline in the region. The present study investigates the possible impact of wind speed on the extent of decline in sunshine hours in Shijiazhuang, Beijing and Tianjin (3 major cities in North China) during the period from 1960–2008. Among these cities, the smallest (largest) decline in sunshine hours was in the city with the highest (lowest) wind speed: Beijing (Shijiazhuang). Annual and monthly average daily sunshine hours for 1960–1969 (a period with low anthropogenic pollution and slow socioeconomic development) and 1999–2008 (a period with high anthropogenic pollution and rapid socioeconomic development) are compared with respect to low and high wind speeds. Extent of sunshine hours showed a positive correlation with wind speed. Analysis of the API (air pollution index) from 2000–2008 shows a discernible effect of wind speed on atmospheric pollution. Thus, we conclude that the decline in sunshine hours in the region is heavily influenced by wind speed. Low dispersion of air pollutants and their aerosol derivatives under low wind speed are likely the cause of the decline in sunshine hours.

KEY WORDS: Decline in sunshine hours · Wind speed · Air pollution · Aerosol

1. INTRODUCTION

Solar radiation on the surface of the earth's landmasses is an important factor influencing plant growth through photosynthesis and evapotranspiration and, therefore, indirectly influences the soil water available to plants. A decline in solar radiation, a phenomenon generally referred to as global dimming (Stanhill & Cohen 2001, Liepert 2002, Alpert et al. 2005, Wild et al. 2005), has been widely reported. Gilgen et al. (1998) investigated regional trends of annual global irradiance using data from the Global Energy Balance Archive (GEBA) and reported a decline in solar radiation at an average rate of 2% decade^{-1} over vast areas in Africa, Asia, Europe and North America. As in other parts of the world, a declining trend in long-term solar radiation has been reported for China as well (Kaiser & Qian 2002, Zhang et al. 2004, Che et al. 2005, Liang & Xia 2005, Ren et al. 2005, Qian et al. 2006).

Factors including anthropogenic disturbances and other natural processes influence global dimming. Liepert (2002) investigated the declining trend in surface solar radiation in a number of regions in the United States and around the globe for the period from 1961 to 1990 and determined anthropogenic disturbance to be the principle cause of global dimming. Furthermore, Alpert et al. (2005) reported that global dimming is predominant in large urban areas, with heavy atmospheric pollution, and Stanhill & Cohen (2001) suggested that increases in atmospheric aerosols

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and other air pollutants could be a cause of global dimming. Several other investigations have suggested various probable causes of global dimming, including interactions among aerosol loading, optical properties of the atmosphere and cloud cover (Nazarenko & Menon 2005); and increased cloudiness (Cutforth & Judiesch 2007).

Despite their importance, however, far fewer studies have analyzed the natural causes of the decline in solar radiation above and beyond the anthropogenic effects of aerosols. Thus, Yang et al. (2009) investigated the spatial and temporal correspondence between wind speed and the decline in sunshine hours and concluded that the interactions between wind speed and aerosol loading may be a major factor responsible for the decline in sunshine hours.

In the present study, the interactions among wind speed, air pollution and sunshine hours were analyzed for 3 cities (Shijiazhuang, Beijing and Tianjin) in North China. The main objective was to determine the effect of wind speed on the number of sunshine hours, and investigate possible driving mechanisms by analysing the effect of wind on air pollution.

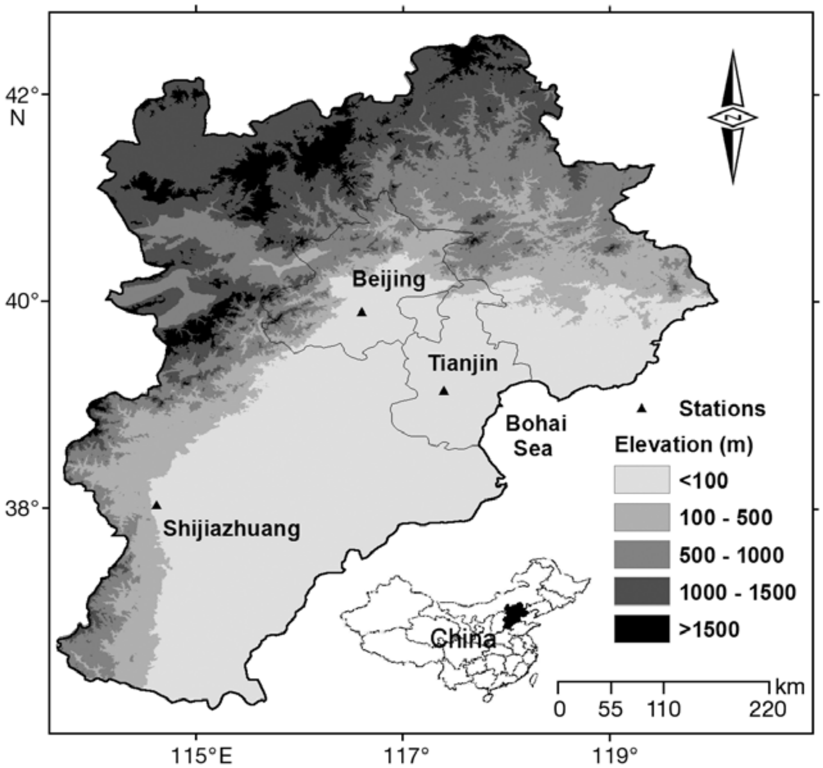

Fig. 1. Study area and locations of Shijiazhuang, Beijing and Tianjin stations, background topography and provincial boundaries

2. DATA AND METHODS

2.1. Study area and data collection

A survey was conducted in 3 major cities, Shijiazhuang, Beijing and Tianjin, with respective populations of approximately 12, 8 and 2 million. All 3 cities are in North China (see Fig. 1). High mountain ranges surround Beijing on the west, north and northeast and the North China Plain is in the south. The city area of Beijing encompasses 735 km^2. Tianjin is an important port city in North China, but its city area spreads well into the plains of North China, covering an area of 4334 km^2. Shijiazhuang is the capital of Hebei Province, with an approximate area of 174 km^2.

Following the survey, daily meteorological data were collected from 3 stations — 1 in each of the 3 cities. All 3 stations belong to the National Meteorological Information Centre (NMIC) of China. The locations of the stations are: 38.03° N, 114.42° E for Shijiazhuang, 39.79° N, 116.47° E for Beijing and 39.08° N, 117.07° E for Tianjin. The stations for Beijing and Tianjin are centrally located in the cities. The one for Shijiazhuang is located on the western outskirts of the city, not very far from the urban center. Since 1990, the population in these 3 cities has grown rapidly. The increase in the city population has stimulated real-estate development and accelerated urbanization. There has been a steady expansion in urban area, rapidly merging with the suburbs, in these cities. The rapid urbanization is a source of some degree of uncertainty in the long-term meteorological data. For example, heavy construction activity exacerbates air pollution problems and could also result in the decline of wind speed.

Data for both wind speed and sunshine hours for the period from 1960–2008 were analyzed on a daily basis and averaged to monthly and annual scales. To isolate the effect of wind speed on the decline in sunshine hours in each city, daily wind speeds (DWS) for each city were categorized into 2 ranges. For Shijiazhuang, DWS < 1.50 m s^{-1} were defined as low wind and DWS > 1.50 m s^{-1} were defined as high wind. For the cities of Beijing and Tianjin, DWS < 2.00 m s^{-1} were defined as low wind and DWS > 2.00 m s^{-1} were defined as high wind. Different daily wind speed ranges were used, because wind speeds for Beijing and Tianjin are much stronger than those for Shijiazhuang. For instance, days with wind speeds > 2 m s^{-1} are very rare in Shijiazhuang, especially in the low wind season of autumn. Conversely, days with daily wind speeds <1.5 m s^{-1} are rare in Beijing and Tianjin, especially in the high wind season of spring.

Data for the daily API (air pollution index) spanning from 5 June 2000 to 31 December 2008 (except for November 2006, for which period data were missing) were obtained from the National Environmental Daily Monitoring Database (NEDMD) of China. Based on the 3 principal pollutants SO_2, NO_2 and inhalable particulates (PM_{10}), API is defined as: API = max.(I_{PM10}, I_{SO2}, I_{NO2}). The sub-indices I_{PM10}, I_{SO2} and I_{NO2} were derived from observed mass concentrations of the 3 pollutants. It should be noted that PM_{10} is the most dominant of the 3 air pollutants in China. This is because PM_{10} API, including clean days, accounts for >90% of the total API days (Choi et al. 2008). Unfortunately, API data were not available until 2000, which represents a relatively short survey period compared with the available meteorological data for wind speed and sunshine hours. However, the 9 yr of data do reveal relevant information on the effect of wind speed on the API, via comparisons of the seasonal averages of the API under low and high winds from 2000–2008.

2.2. Statistical methods

The statistical methods used in the present study included the nonparametric Mann-Kendall test for determining the trends in wind speed and sunshine hours and the nonparametric Sen method for estimating the slopes of the linear trends.

The Mann-Kendall test (Mann 1945, Kendall 1975) is an established effective tool for trend detection based on correlations between time-series ranks and their order in time (Hamed 2008). It is commonly used to test the randomness of hydro-climatic time series (Zhu & Day 2005, Novotny & Stefan 2007). In this test, the null hypothesis H_0 states that a deseasonalized data set x_1 … x_n is an element of n independent and identically distributed random variables. The alternative hypothesis H_1 of a 2-tailed test states that the distribution of x_k and x_j are not identical for all $k,j \leq n$, with $k \neq j$. The test statistic S, with a mean of zero and variance computed as in Eq. (3), is asymptotically normal (Hirsch & Slack 1984) and can be calculated using Eqs. (1) and (2) as follows:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \mathrm{sgn}(x_j - x_k) \tag{1}$$

$$\mathrm{sgn}(x_j - x_k) \begin{Bmatrix} +1 \text{ if } (x_j - x_k) < 0 \\ 0 \text{ if } (x_j - x_k) = 0 \\ -1 \text{ if } (x_j - x_k) < 0 \end{Bmatrix} \tag{2}$$

$$\mathrm{var}(S) = [n(n-1)(2n+5) - \sum_t t(t-1)(2t+5)/18] \tag{3}$$

where sng is the signum function and var is the variance. The notation t is the extent of any given tie, and $\sum_t$ denotes the summation over all ties.

In cases where the sample size $n > 10$, the standard normal variate Z is computed in Eq. (4) (Kendall 1975) as:

$$Z = \begin{Bmatrix} \dfrac{S-1}{\sqrt{\mathrm{var}(S)}} \text{ if } S > 0 \\ 0 \text{ if } S = 0 \\ \dfrac{S+1}{\sqrt{\mathrm{var}(S)}} \text{ if } S < 0 \end{Bmatrix} \tag{4}$$

Thus, in 2-tailed trend test, H_0 is accepted if $|Z| \leq Z_{n/2}$ at 0.05 level of significance. A positive Z-value indicates an 'upward trend', while a negative Z-value indicates a 'downward trend'.

Sen's method for the nonparametric estimate of slope Q, as defined by Sen (1968), is given as:

$$Q = \mathrm{Median}\left(\frac{x_j - x_k}{j - k}\right) \qquad \text{for all } k < j \tag{5}$$

In addition, the SPSS (Statistical Package for Social Scientists) software was used to determine correlated relationships between sunshine hours and wind speed for the 49 yr period, along with linear regression tests, which defined the nature of the relation between the variables.

3. RESULTS

3.1. Annual average trends in daily sunshine hours

Fig. 2 is a time-series plot of the annual average daily sunshine hours for the 49 yr (1960–2008) period for Shijiazhuang, Beijing and Tianjin. The Mann-Kendall test and Sen's slope estimates were used to determine the trends in annual average daily sunshine hours for the 3 cities (see Table 1). The analysis showed a significant decline in annual average daily sunshine hours for all 3 cities ($p < 0.001$). The strongest trend in the decline of annual average daily sunshine hours was for Shijiazhuang, with a slope of –0.051 h yr^{-1}, i.e. 0.51 h decline $decade^{-1}$. In Fig. 2, a minimal sunshine duration gap is evident among the 3 cities prior to 1970, although Tianjin showed a slightly lower trend. The gap gradually widened after 1970, indicating varying degrees of decline in sunshine hours in the 3 cities. Shijiazhuang, the city in the southern part the study area (Fig. 1), had the same number of sunshine hours as Beijing in the 1960s. However, sunshine hours very rapidly declined after the 1980s in Shijiazhuang, becoming the lowest values in the region.

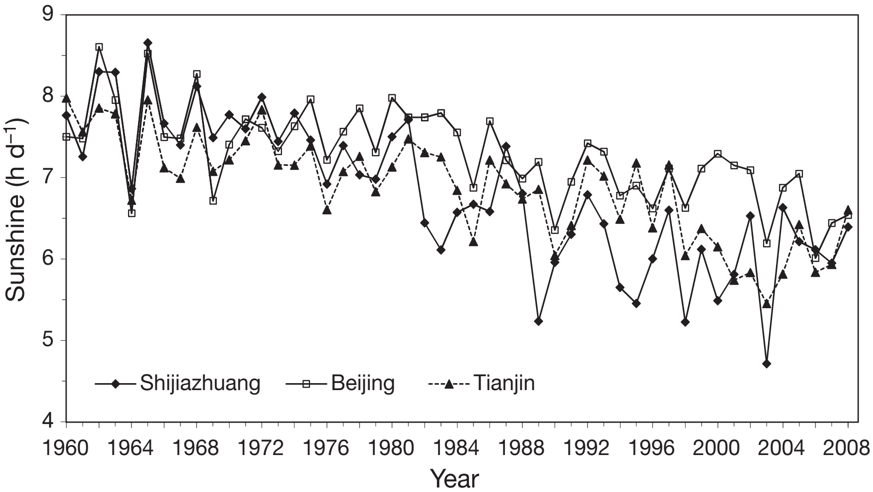

Fig. 2. Trends in annual average daily sunshine hours in Shijiazhuang, Beijing and Tianjin from 1960–2008

shine hours showed significant correlation, it seems hasty to conclude solely on the basis of regression analysis that wind speed is the primary driving factor of the decline in sunshine hours, as both variables (wind speed and sunshine hours) decline with time.

To better understand the effect of wind speed on the decline of sunshine hours, annual average daily sunshine hours under different wind speeds were analyzed for the period from 1960–1969 (a period with less anthropogenic pollution and slow socioeconomic development) and from 1999–2008 (a period with strong anthropogenic pollution and

3.2. Wind speed analysis

Fig. 3 shows the annual average wind speed for the 3 cities. The trends were determined by the Mann-Kendall test and Sen's slope estimates (Table 1). A significant decline in wind speed ($p < 0.01$) was observed for all 3 cities, although the trend in the decline was stronger for Tianjin ($Q = -0.018$ m s^{-1} yr^{-1}) than for Beijing ($Q = -0.010$ m s^{-1} yr^{-1}) and Shijiazhuang ($Q = -0.009$ m s^{-1} yr^{-1}). For the entire observation period, Shijiazhuang had the lowest annual average wind speed. Beijing and Tianjin showed a relatively stronger wind speed, which may have been induced by their geographical location. The annual average wind speed and daily sunshine hours generally reflected similar trends, especially after 1992. Beijing, for instance, showed the highest wind speed and daily sunshine hours after 1992. On the other hand, Shijiazhuang had the lowest wind speed and daily sunshine hours during the same period. This presumably reflected some degree of correlation between wind speed and sunshine hours in the region.

Table 1. Mann-Kendall test and Sen's slope estimate for annual average daily sunshine hours and wind speed in Shijiazhuang, Beijing and Tianjin (1960–2008). Negative values denote declining trends. *Q*: linear regression slope (h yr^{-1} for annual average daily sunshine hours and m s^{-1} yr^{-1} for wind speed); *B*: linear regression constant. Significance $^{**}p < 0.01$; $^{***}p < 0.001$

	Z-test	*Q*	*B*
Sunshine hours			
Shijiazhuang	−6.15***	−0.051	7.95
Beijing	−4.87***	−0.026	7.95
Tianjin	−5.77***	−0.036	7.72
Wind speed			
Shijiazhuang	−2.97**	−0.009	1.99
Beijing	−2.80**	−0.010	2.74
Tianjin	−3.73***	−0.018	2.92

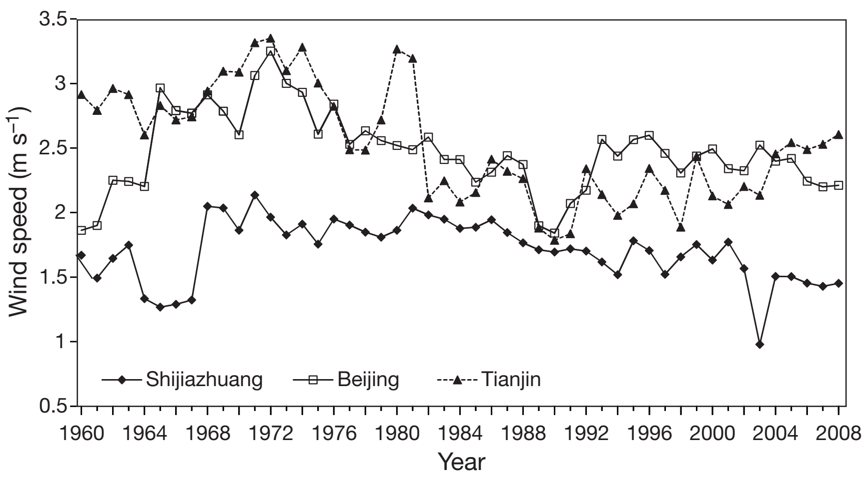

Fig. 3. Trends in annual average daily wind speed in Shijiazhuang, Beijing and Tianjin from 1960–2008

3.3. Sunshine hours and wind speed

Using regression equations (Table 2), the relationships between annual average daily sunshine hours and annual average wind speeds for the 3 cities were determined and the coefficient of determination (R^2) was calculated. Though wind speed and sun-

Table 2. Regression relationships between annual average daily sunshine hours and wind speed for the 3 cities from 1960–2008 (equation significant at $p < 0.01$). Sh: sunshine hours; Ws: wind speed; R^2: coefficient of determination

Station	Regression relation	R^2
Shijiazhuang	Sh = 4.944 + 1.093 Ws	0.083
Beijing	Sh = 5.696 + 0.643 Ws	0.125
Tianjin	Sh = 4.671 + 0.868 Ws	0.354

rapid socioeconomic development); the results are presented in Fig. 4.

From Fig. 4, the influence of wind speed on sunshine hours was very explicit. In Shijiazhuang, for instance, when wind speed dropped below 1.50 m s^{-1}, annual average daily sunshine hours dropped to lower values for the same period. This was even more explicit for 1999–2008, a period of relatively rapid development, when the city is reported to have had a greater pollution problem than in the 1960s. Under low wind conditions, the difference in sunshine hours between the 2 periods was high and vice versa. This implied that low wind speed resulted in a strong decline in sunshine hours. The same phenomenon has been noted for Beijing and Tianjin (Fig. 4B,C). However, as wind is stronger in Beijing and Tianjin than in Shijiazhuang (Fig. 3), the differences in sunshine hours between days with high and low wind were not as high as those for Shijiazhuang. From 1999–2008, the average differences in sunshine hours between days with high and low wind speeds for Shijiazhuang, Beijing and Tianjin were, respectively, 2.46, 1.72 and 1.28 h. This further suggests that low wind speed strongly influenced the decline of sunshine hours in the region.

Fig. 5 provides a comparison of average monthly daily sunshine hours under different wind speeds (low and high winds) for the periods from 1960–1969 and 1999–2008. The difference in daily sunshine hours between the 2 periods was largest at low wind speeds. Using Shijiazhuang as an example (Fig. 5A), when wind speed was <1.50 m s^{-1}, the difference in sunshine hours was greatest in June (4.08 h d^{-1}); the difference in average daily sunshine hours for the 2 periods was 2.23 h. In contrast, when wind speed was >1.50 m s^{-1}, the difference in average daily sunshine hours for the 2 periods was only 1.08 h. The same was true for Beijing and Tianjin (Fig. 5B,C). On days with low wind speeds, average monthly daily sunshine hours declined by 1.14 and 1.58 h for Beijing and Tianjin, respectively. Moreover, the largest differences in sun-

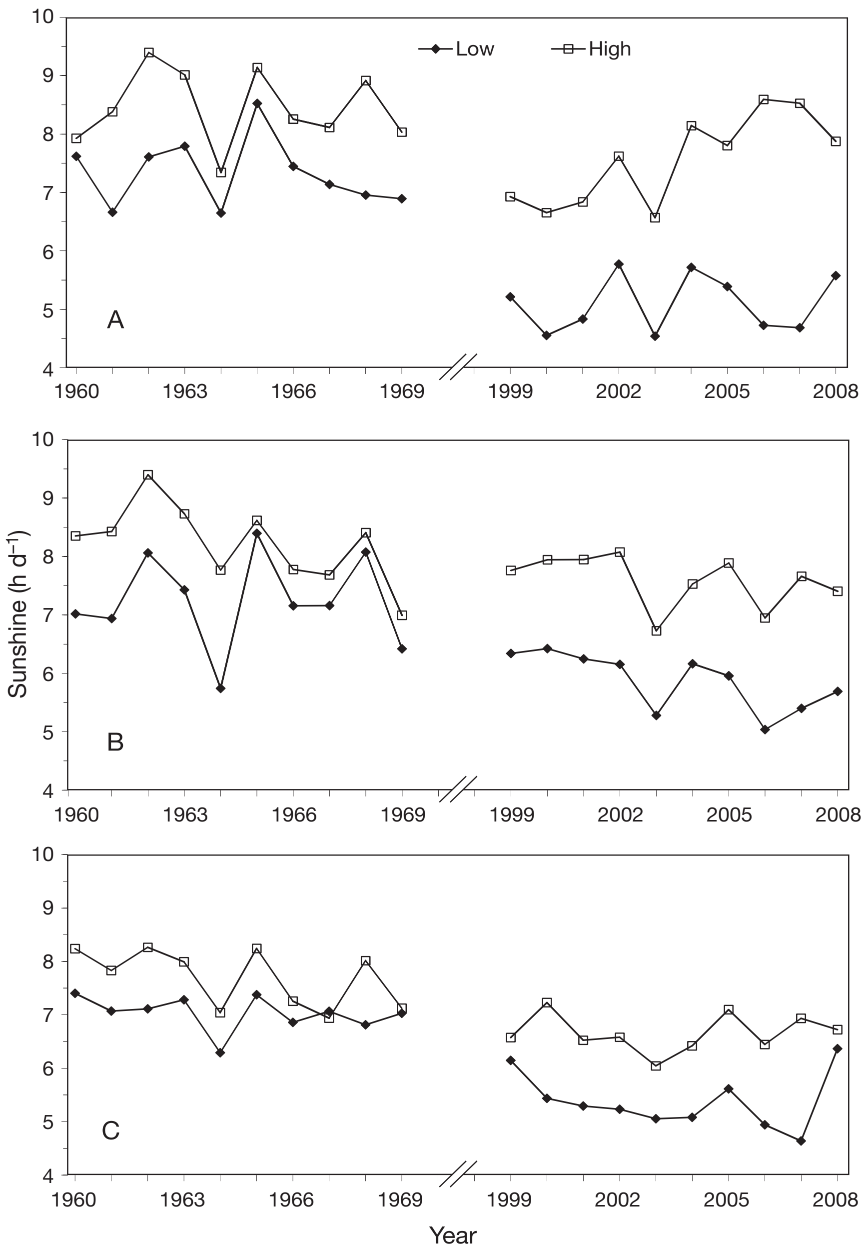

Fig. 4. Comparison of annual average daily sunshine hours under low and high wind speeds for the periods 1960–1969 and 1999–2008 in the 3 cities. For Shijiazhuang (A), low wind speed is a daily wind speed (DWS) of <1.50 m s^{-1} and high wind speed is a DWS of >1.50 m s^{-1}. For Beijing (B) and Tianjin (C), low wind speed is a DWS of <2.00 m s^{-1} and high wind speed is a DWS of >2.00 m s^{-1}

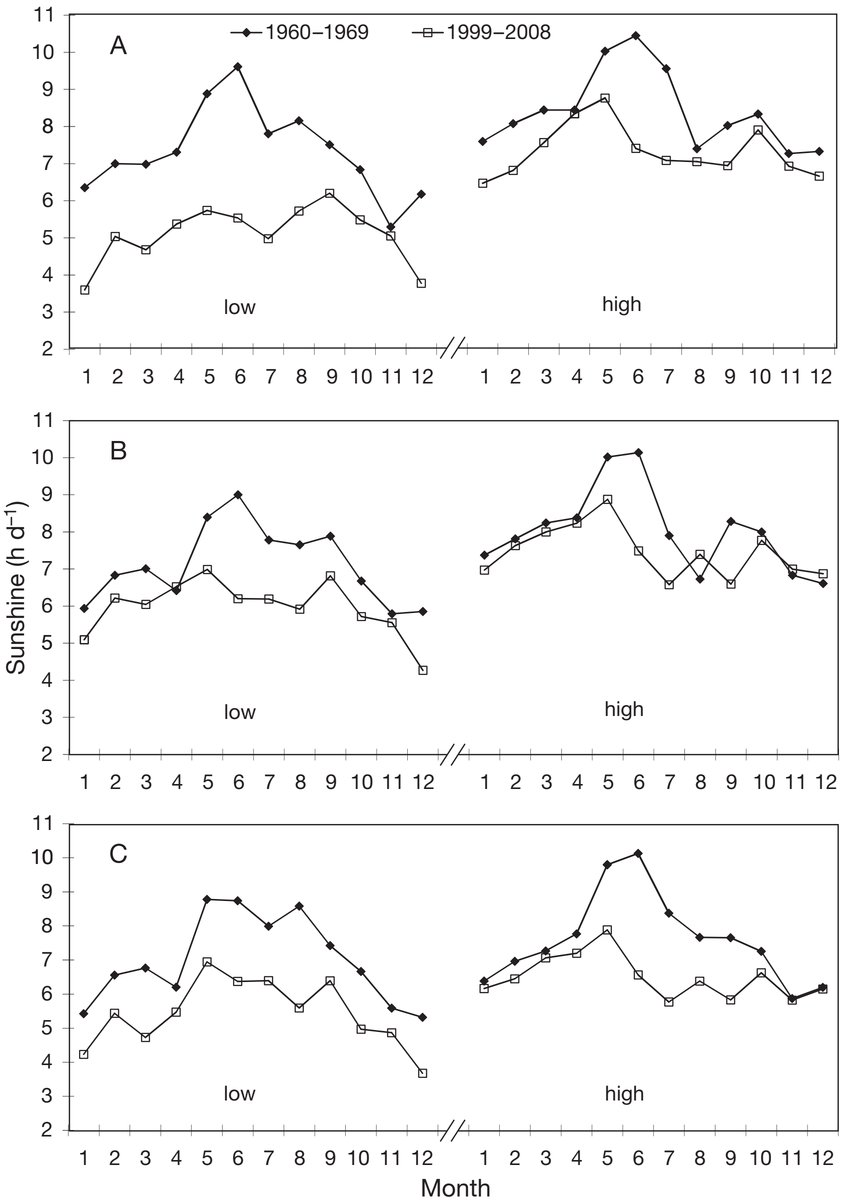

Fig. 5. Comparison of monthly average sunshine hours between 1960–1969 and 1999–2008 under low and high wind speeds for Shijiazhuang (A), Beijing (B), and Tianjin (C). Wind speed ranges are defined in Fig. 4

shine hours for the 2 periods were in May, June and July. This may have been due to longer sunshine durations and greater amounts of water vapor in warmer conditions. The mixture of pollutants with water vapor could easily have resulted in increased aerosol concentrations. However, there was an exception in August. Under high wind speed, the average monthly sunshine hours in the 1999–2008 period for Shijiazhuang was only slightly lower than that in the 1960–1969 period, and for Beijing it was actually higher than in the 1960–1969 period.

The findings suggest a significant correlation between low wind speed and the decline in sunshine hours. It is highly possible that pollution is an important factor driving the decline in sunshine hours in this region. This is because on days of low wind conditions, atmospheric pollution is hardly dispersed. Thus, the relationship between wind speed and pollution was further analyzed.

3.4. Wind speed and air pollution index

Based on the separation of the 4 seasons (spring: from March to May; summer: from June to August; autumn: from September to November; and winter: from December to February), Fig. 6 depicts the mean seasonal API (2000–2008) under low and high wind conditions for Shijiazhuang, Beijing and Tianjin. In general, seasonal variations exist in the API, with maxima in winter and minima in summer. Fig. 6 clearly illustrates higher API values at low wind speeds than at high wind speeds for all 3 cities. Among the cities, the average differences in API values between days with low and high winds were 16, 12 and 6 for Shijiazhuang, Beijing and Tianjin, respectively. This corresponded to average API values (for the 9 yr period) of 107, 103 and 90, respectively. This also suggested that the influence of low winds on API was stronger in the more polluted cities of Shijiazhuang and Beijing. Tianjin had the lowest API, possibly due to its large city area and low population density.

There were, however, some exceptions for Beijing and Tianjin, as observed in the spring of 2001 and 2002. This was due to the frequent dust storms in these 2 yr. From Fig. 6B, strong dust storms along with high winds triggered a dramatic rise in API (to nearly 150) in the spring of 2001 and 2002 in Beijing and in 2001 in Tianjin (Fig. 6C).

4. DISCUSSION AND CONCLUSIONS

As data analysis for Shijiazhuang, Beijing and Tianjin indicated, there has been a significant decline in daily sunshine hours in North China. This is similar to the trends that have been observed in other regions of China (Zhang et al. 2004) and elsewhere around the globe (Alpert et al. 2005).

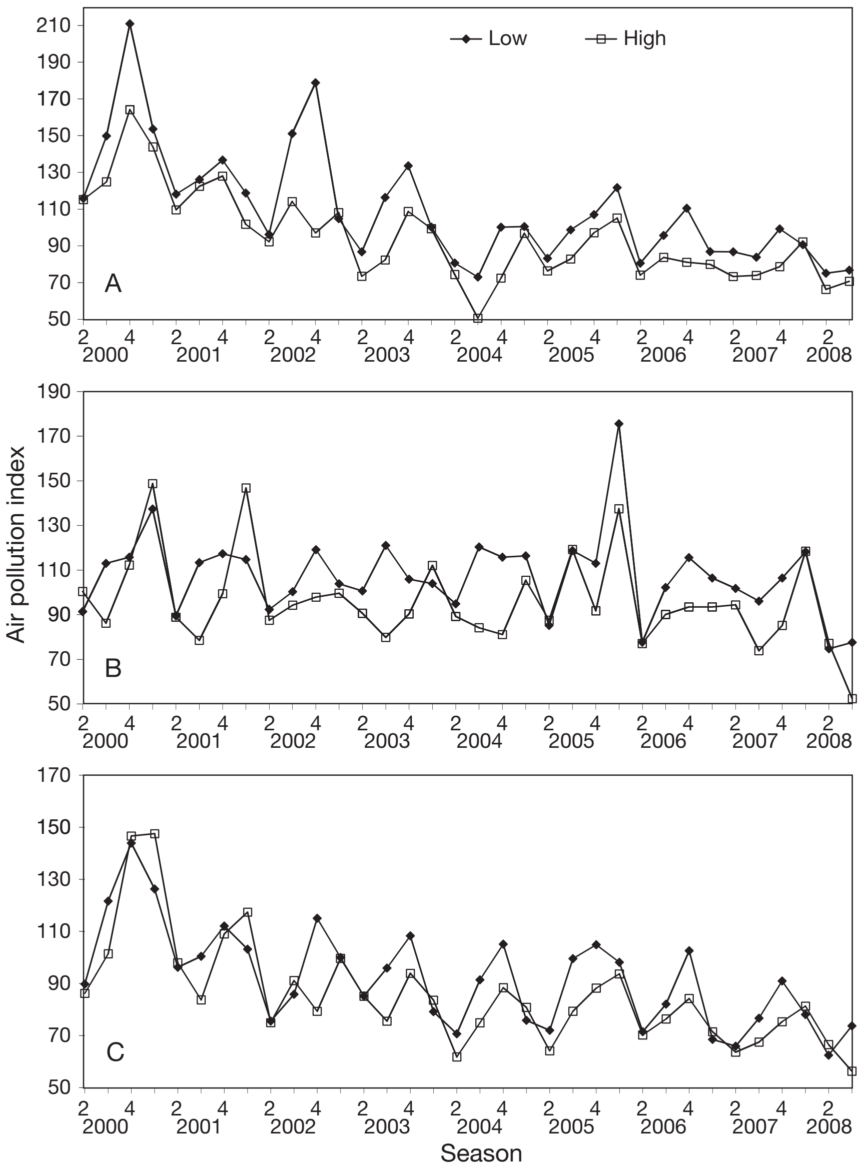

Fig. 6. Comparison of seasonal average air pollution index under low and high wind speeds for Shijiazhuang (A), Beijing (B) and Tianjin (C) from the summer of 2000 to the autumn of 2008. Wind speed ranges are defined in Fig. 4. The abscissa is labeled by year and season notation, where 1, 2, 3 and 4 denote spring, summer, autumn and winter, respectively

Our study showed that wind speed has a strong influence on daily sunshine hours. Furthermore, there was a significant decline in wind speed over the 49 yr period (Fig. 3). This trend is quite similar to that observed by Xu et al. (2006), where a steady decline was noted for the East Asian monsoon winds from 1969–2000. It is also possible that the decreasing wind speed is, to some degree, caused by the rapid urbanization of Chinese cities. While Fig. 2 shows that, of the 3 cities, the largest decline in daily sunshine hours was in Shijiazhuang, Fig. 3 also shows the lowest annual average wind speed in the city (only 1.71 m s^{-1}). Furthermore, in the comparison between 1960–1969 and 1999–2008 (Fig. 4), the latter period revealed a dramatic decline in daily sunshine hours on low windy days. In Fig. 5, the trends confirm that daily sunshine hours were heavily influenced by low wind conditions, especially in May to July. This finding is in agreement with our earlier study (Yang et al. 2009), in which we observed that wind speed was an important driving factor for the number of sunshine hours in North China.

However, the mechanism behind the effect of wind speed on sunshine hours needs to be further clarified. The factors affecting sunshine hours have been summarized by a number of scholars (Ertekin & Yaldiz 1999, Stanhill & Cohen 2001). Among these factors — including astronomical, geographical, geometrical (surface azimuth, surface tilt angle, solar altitude and solar azimuth), physical (scattering of air molecules, water vapor content, dust and other atmospheric constituents like O_2, N_2, CO_2, O_3, etc.) and meteorological (effect of cloudiness and reflection from the environs) factors — the most probable causes of the decline in sunshine hours are increased cloud and aerosol loading.

It does not appear that cloud cover has been a major cause of the decline in sunshine hours. Kaiser (1998, 2000) reported a decreasing trend in total cloud cover at most of the observation stations (over 196 observation stations) in China for the period from 1954–1996. Qian et al. (2006) carried out a follow-up study (cf. Kaiser 1998, 2000) by analyzing both total cloud and low cloud cover through 2001 and expanding the number of observation stations to 537, and came to similar conclusions. Specifically, most stations have registered statistically significant drops (1 to 3% $decade^{-1}$) in cloud cover in North China. The decrease in sunshine hours could, therefore, not be driven by decreasing cloud cover.

As reported in many previous studies, increased aerosol loading, resulting from human-induced air pollution, has been considered one of the main causes of the decline sunshine hours and global dimming (Stanhill & Cohen 2001, Liepert 2002, Alpert et al. 2005). Fig. 6 suggests that wind speed is one of the factors influencing API in the 3 cities between 2000 and 2008. On days with high winds, the API for Shijiazhuang, Beijing and Tianjin were all lower than for low-wind days. Similarly, Chan & Yao (2008) showed that the air pollutant concentration decreased with increasing wind speed in Beijing. Since air pollution was the main driver of aerosol formation, increased air pollution under low winds should, to some extent, result in an increase of aerosol concentration, causing a decline in sunshine hours.

However, our analysis also showed that API was influenced by several factors other than wind speed itself. For instance, API clearly showed seasonal variations, with the highest API in winter and the lowest in summer. Several studies on the seasonal change in PM_{10} also showed similar trends (He et al. 2001, Niu et al. 2006). The high API in winter was largely ascribed to coal combustion in the region. The low API in summer, on the other hand, was generally attributed to frequent rainfall, which scrubs the air of pollutants (Wang & Yang 2007). In in Beijing and Tianjin in spring of 2001 and 2002, the API for the days with high winds was higher than for the days with low winds. This may have been due to sandstorms and dust in the driest season of spring. Dust, but not human air pollution, was one of the main contributors of natural aerosols (Satheesh & Moorthy 2005). Similarly, several studies showed that aerosol optical thickness in North China was mainly influenced by sandstorms in spring and air pollution from coal burning in winter (Qiu & Yang 2000, Cheng et al. 2006, Che et al. 2009). This explains why the highest API in spring did not result in the greatest decline in sunshine hours in the region. In Fig. 5, May to July was the period with the highest difference in daily sunshine hours between 1960–1969 and 1999–2008, because May to July had the highest aerosol optical thickness (Cheng et al. 2006). Both Che et al. (2009) and Qiu & Yang (2000) suggested that the highest aerosol in summer was possibly due to pollutant growth in the high water vapor conditions. This may explain why, under the lowest API, the decline in sunshine hours was highest in May to July.

It is generally recognized that wind can directly affect aerosol dispersion. Naturally, low winds are hardly strong enough to blow away aerosols and other air pollutants. In Beijing, hazy days (which are generally related to atmospheric aerosols), with a visibility of <10 km and a relative humidity of <80% usually occur on days with low wind speeds (<2 m s^{-1}) and stagnant and sometimes foggy weather conditions (Xie et al. 2005, Wang et al. 2006). Similarly, Fu et al. (2008) suggested that the causes behind heavy air pollution days in the Yangtze River Delta are the prevailing and unusually stagnant dispersion conditions when winds are <1.0 m s^{-1}. Incecik (1986) observed a strong pollution problem along the Golden Horn of Turkey, where surface winds >2.0 m s^{-1} are very rare.

In summary, it is likely that wind speeds are generally too weak to disperse pollutants and their derivates (aerosols) in Shijiazhuang. Furthermore, the effect of low wind speeds on air pollution and aerosol dispersion have likely resulted in a decline of sunshine hours in the 3 studied cities in North China.

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