Air pollution is pushing wind speed into a regulator of surface solar irradiance in China

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Abstract
Analysis in 27 cities across China shows that surface solar irradiance (SSI) and wind speed track similar decadal trends in 1961–2011, suggesting wind speed as a possible regulator of SSI. This assumption is further confirmed by the continuously widening gap in annually averaged daily SSI between windy and windless clear-sky days with worsening air pollution. Wider gaps are noted for more polluted cities and seasons. The gap in SSI between windy and windless conditions could therefore serve as a good indicator for air quality. The regulatory effect of wind speed on SSI starts to be important when air pollution index exceeds the boundary of 125. A plausible mechanism of wind speed regulating SSI through interactions with aerosols is proposed. There are two cut-off points of 2.5 m s⁻¹ and 3.5 m s⁻¹ wind speeds. Winds <2.5 m s⁻¹ noticeably disperse air pollutants and thereby enhance SSI. Above the 2.5 m s⁻¹ threshold, air pollution and SSI become largely insensitive to changing wind speeds. Winds in excess of 3.5 m s⁻¹ could enhance aerosol concentration probably by inducing dust-storms, which in turn attenuate SSI.

Keywords: air pollution index, solar dimming, clear-sky day

1. Introduction
Since the 1950s, the amount of solar irradiance incident on the Earth’s surface was not stable but underwent significant decadal fluctuations, constituting a decline until the late 1980s (global dimming) and a rise thereafter (global brightening) (Pinker et al. 2005, Wild et al. 2005). This phenomenon is widely attributed to air pollution linked aerosols, which have direct and indirect radiative forcings acting towards reducing radiation (Wild 2009, 2012). Direct radiative forcings include the scattering and absorption of radiation due to the nature of aerosol composition, while indirect radiative forcings include enhancement of cloud formation and lifetime by aerosols acting as cloud condensation nuclei and ice nuclei (Charlson et al. 1992, Ramanathan et al. 2001).

A strong dimming trend in surface solar irradiance (SSI) was also observed in China since the 1960s (Che et al. 2005, Liang and Xia 2005, Shi et al. 2008), especially under clear skies (Qian et al. 2006, 2007). This trend was increasingly noted to be related to wind speed, a possible other factor of SSI. Xu et al. (2006) detected that annual mean wind speed and SSI share similar decadal trends. Correlation of sunshine hours (a common proxy for SSI) with a range of meteorological parameters suggested that sunshine hours are most strongly influenced by wind speed in North China (Yang et al. 2009a), Southwestern China (Li et al. 2012, Yang et al. 2012) and even the whole of China (Yu et al. 2011).
These studies laid the basis for further research into the connections between SSI and wind speed at different temporal and spatial scales.

As winds disperse and alter frequency distributions of pollutants and aerosol derivatives, previous studies suspected that the interactions between wind speed and aerosol loading may be the enabling force behind the influence of wind speed on sunshine hours (Yang et al. 2009a,b, Li et al. 2012). The fundamental process by which wind–aerosol interactions regulate SSI, however, remains largely unexplained.

Thus this study aims to: (1) clarify the magnitude and direction of the regulatory effect of wind speed on SSI; and (2) lay the conceptual framework of solar dimming driven by wind–aerosol interactions under varying degrees of air pollution.

2. Data and analysis procedure

2.1. Data and quality control

Based on the availability of meteorological (wind speed and total cloud cover), solar irradiance and air pollution index (API) data, the study covered a total of 27 cities across longitudes 87°39′–126°46′ E and latitudes 20°00′–45°45′ N in China (figure 3).

Daily meteorological and solar irradiance data for 1961–2011 were collected from China Meteorological Data Sharing Service System at http://old-cdc.cma.gov.cn/, governed by China Meteorological Administration (CMA). Wind speed was measured by anemometers at 10 m height above the ground while total cloud cover was by visual inspection based on the World Meteorological Organization Standards (see documented dataset interpretation). Observation times used to calculate daily mean values of wind speed and total cloud cover were 0200, 0800, 1400 and 2000 h. The Yanishevsky thermodiometric pyranometer (modeled on that used in the former Soviet Union) was used to record SSI prior to 1993, and the DFY-4 pyranometer (manufactured by China) used after 1993 (Xia 2010, Ye et al. 2010, Tang et al. 2011). Estimated error in the two types of pyranometers at daily scale was less than 5% (Shi et al. 2008). As the CMA preliminary quality checks on the data are simple, potential impacts of instrument modification, operation error and station location change on the datasets are difficult to eliminate (Shi et al. 2008). Thus the SSI data were further checked following the two criteria established by Shi et al. (2008) and Tang et al. (2010): (1) the measured SSI should neither exceed solar irradiance at the top of the atmosphere \( (R_{s}) \) nor fall below the lower bound \( (0.03R_{s}) \), and (2) the measured SSI should not exceed 10% of the clear-sky daily irradiance \( (R_{\text{cw}}) \). Both \( R_{s} \) and \( R_{\text{cw}} \) were calculated using the FAO-56 method (Allen et al. 1998). It is noteworthy that the inputs for estimating \( R_{\text{cw}} \) were \( R_{s} \) and station elevation. This implies that the effects of turbidity and water vapor were not considered in physical threshold tests of the SSI data.

Daily API data for 2001–2011 were derived from China National Environmental Monitoring Center at http://www.cnemc.cn/, managed by State Environment Protection Administration. API is the generalized mode of gauging air quality in China. It converts the levels of three fundamental atmospheric pollutants of \( \text{SO}_2 \), \( \text{NO}_2 \) and suspended particulates (PM\(_{10}\)) into a non-dimensional number with a range of 0 to 500. The calculation starts by quantifying sub-indices \( I_{\text{PM}_{10}}, I_{\text{SO}_{2}} \) and \( I_{\text{NO}_{2}} \) on the basis of 24 h (daily) average mass concentrations \( (C, \mu \text{g m}^{-3}) \) of PM\(_{10}\), \( \text{SO}_2 \) and \( \text{NO}_2 \), respectively.

\[
I = \frac{I_{\text{high}} - I_{\text{low}}}{C_{\text{high}} - C_{\text{low}}} (C - C_{\text{low}}) + I_{\text{low}} \tag{1}
\]

where \( I \) is the air pollution sub-index, \( C \) is the pollutant concentration, \( C_{\text{high}} \) and \( C_{\text{low}} \) respectively denote the concentration breakpoints \( \geq \) and \( \leq \), \( I_{\text{high}} \) and \( I_{\text{low}} \) are the index breakpoints respectively corresponding to \( C_{\text{high}} \) and \( C_{\text{low}} \). It should be noted in table 1 that the concentration breakpoints and corresponding index breakpoints are defined for each pollutant separately. The maximum sub-index of the three pollutants is defined as API, where

\[
\text{API} = \max \{ I_{\text{PM}_{10}}, I_{\text{SO}_{2}}, I_{\text{NO}_{2}} \}. \tag{2}
\]

The corresponding pollutant is defined as the ‘key pollutant’. PM\(_{10}\) is the most dominant urban pollutant in China (Wang et al. 2013a). In urban environments, diurnal cycle of pollutant concentration is characterized by two peak values in the morning and evening (Zhao et al. 2009). In terms of radiation, both total aerosol content and constituent concentration are important. Thus in contrast to aerosol concentration analysis which is definitive, API analysis is generally exploratory.

2.2. Analysis procedure

In order to minimize possible influence of changing clouds on SSI, this study was performed only for clear-sky (i.e., total cloud cover \( \leq 10\% \)) days. In China, clear-sky days are more frequent in winter than in summer. Thus weighted daily SSI data (obtained by multiplying the ratio of average annual/seasonal to average monthly values) were used to derive annual/seasonal trends. Although this process minimizes the effect of annual solar cycle on SSI, it might induce possible cloud effect. Changes in cloudiness could also occur through changes in the number or timing of clear-sky days. Therefore, the effect of clouds on the analyzed trends could not be completely eliminated in this study done at daily scale.

In the first step, annual fluctuations in SSI and wind speed averaged for the 27 cities across China were compared for 1961–2011. The stepwise linear regression analysis was applied to verify the effect of wind speed on the variations in SSI.

In the second step, the 27 cities (27-C) were categorized into two groups—API\(_{85+}\) (14 cities with average API > 85) and API\(_{85}\)– (13 cities with average API \( \leq 85 \)). Annual SSI trends were compared between windy (average wind speed \( >2 \text{ m s}^{-1} \)) and windless (average wind speed \( \leq 2 \text{ m s}^{-1} \)) days during 1961–2011 respectively for the 27-C, API\(_{85+}\) and API\(_{85}\)– city groups. The two thresholds (85 API and 2 m s\(^{-1}\))
wind speed) were determined on the basis of mean API and wind speed in 2001–2011 for the 27 cities, respectively.

It is worth noting that to some extent, averaged API levels for the 2000s in the city groups depict air quality conditions for 1961–2011. This is because the background APIs for the cities across China were similar and low in the 1960s due to the then small economy. This was followed by a rapid economic growth and population expansion across the country, triggering significant anthropogenic aerosol emission and increased aerosol optical depth (AOD) in the following years/decades (Luo et al 2001, Qian et al 2006, Streets et al 2008). It could then be assumed that cities with higher API in the 2000s have relatively higher mean API in the last half century.

The trends in SSI for the 27 cities under windy and windless conditions were also compared at seasonal scale—spring (March to May), summer (June to August), autumn (September to November) and winter (December to February). To limit random effects on the analysis, only cities in each wind speed category with >10 clear-sky days in a year or >3 clear-sky days in a season were compared. This analysis isolated the effect of wind speed on long-term variations in SSI under different air pollution conditions.

The Durbin–Waston test (Durbin and Watson 1950, 1951, 1971) was used to check the presence of autocorrelation in the residuals, which has a statistical impact on decreasing the significance of a trend (Weatherhead et al 1998, Hinkelman et al 2009). To remove detected auto-correlations in the analyzed time series, the Cochrane–Orcutt procedure (Cochrane and Orcutt 1949) was applied. The statistics (trend slope and corresponding standard error, significance, determination coefficient $R^2$ and Durbin–Waston value) of the adjusted linear models fit to the time series are summarized in table 2.

In the third step, Pearson correlations between average annual SSI and wind speed for 1961–2011 were computed at seasonal and annual scales and compared with average daily API for 2001–2011 on station-by-station basis. This further explained the effect of air quality on the correlations between SSI and wind speed.

In the fourth step, average SSI was calculated for the different API ranges along with average API and SSI for the different wind speed ranges in the 27 cities in 2001–2011. A total of 16 182 samples were included in the analysis. This verified the direction and magnitude of the regulatory effect of wind-aerosol interaction on SSI. To account for regionally dependent changes in the API and wind speed samples, daily SSI data were weighted by multiplying the ratio of the mean for the 27 cities by that of the respective city groups.

In the fifth and final step, the Pearson correlation between daily SSI and wind speed as a function of API was examined to reveal the boundary at which aerosol amount is large enough to induce significant wind effect on SSI. To limit random effect, API levels were grouped to ensure that each calculated range included $\geq20$ samples, especially for API $\leq10$ and $\geq200$.

### Table 1. Air pollution index (API), corresponding air quality classification and PM$_{10}$, SO$_2$ and NO$_2$ pollutant concentrations.

| API     | Air quality classification | PM$_{10}$ | SO$_2$ | NO$_2$ |
|---------|----------------------------|-----------|--------|--------|
| 0–50    | I (excellent)              | 0–50      | 0–50   | 0–80   |
| 51–100  | II (good)                  | 51–150    | 51–150 | 81–120 |
| 101–150 | III(1) (slight pollution)  | 151–250   | 151–475| 121–190|
| 151–200 | III(2) (light pollution)   | 251–350   | 476–800| 191–280|
| 201–250 | IV(1) (moderate pollution) | 351–385   | 801–1200| 281–422.5|
| 251–300 | IV(2) (heavy pollution)    | 386–420   | 1201–1600| 423.5–565|
| 300+    | V (severe pollution)       | 421–600   | 1601–2620| 566–940|

### 3. Results and discussions

#### 3.1. Effect of slowing winds on China's dimming

Due to East Asian monsoon weakening and windbreak effects of high-rise buildings brought by rapid urbanization, suppressed winds are evident over China during the past few decades (Ren et al 2005, Xu et al 2006, Vautard et al 2010). From table 2, wind speed in the investigated cities decreases at an average rate of 0.15 m s$^{-1}$ decade$^{-1}$ for 1961–2011 under clear skies while SSI decreases by 4.8 W m$^{-2}$ decade$^{-1}$. This rate is relatively higher than the amount (2.3 W m$^{-2}$ decade$^{-1}$) estimated by Tang et al (2011) using quality-controlled data from 459 stations across China under all-sky conditions. China’s dimming is much stronger at city scale under clear-sky conditions (when aerosol is the dominant driving factor of SSI) than at regional scale under all-sky conditions. A similar conclusion was reached by Alpert et al (2005), Qian et al (2006, 2007) and Li et al (2012). As inferred from the linear regression in figure 1, wind suppression could reinforce solar dimming in China. Variations in SSI in the past half century are significant ($p<0.001$) and positively correlated ($R^2=0.454$) with wind speed.

Based on figure 1, wind speed decreases by 0.13 m s$^{-1}$ decade$^{-1}$ (or 0.27 m s$^{-1}$ decade$^{-1}$ after correction for autocorrelation) in China for the 1960s–1980s. Then starting from 1990, the rate slows down on an average of 0.08 m s$^{-1}$ decade$^{-1}$ (or 0.11 m s$^{-1}$ decade$^{-1}$ after correction for autocorrelation). SSI shares a similar transition with wind speed in decadal trend, consistent with the observation of Xu et al (2006). There is a noticeable decline (14.8 W m$^{-2}$ decade$^{-1}$) in SSI in the 1960s–1980s, following by a
Table 2. Summary statistics of linear models fit to the time series of annual and seasonal average surface solar irradiance (SSI, W m$^{-2}$) and wind speed (WS, m s$^{-1}$) under clear skies for 1961–2011 (figures 1, 2 and 4).

| Variable | WS | Slope     | $R^2$ | DW | Slope     | $R^2$ | DW | Slope     | $R^2$ | DW |
|----------|----|-----------|-------|----|-----------|-------|----|-----------|-------|----|
| SSI >2   | 0.628 ± 0.073 | 0.601 | 0.662 | -0.628 ± 0.089 | 0.503 | 0.578 | -0.622 ± 0.078 | 0.566 | 1.449  |
| SSI ≤2   | -0.814 ± 0.072 | 0.724 | 0.574 | -0.907 ± 0.096 | 0.646 | 0.478 | -0.702 ± 0.074 | 0.648 | 1.451  |
| SSI >2   | -0.507 ± 0.172 | 0.162 | 2.002 | -0.439 ± 0.203 | 0.088 | 2.021 | -0.595 ± 0.115 | 0.364 | 1.998  |
| SSI ≤2   | -0.707 ± 0.184 | 0.236 | 2.042 | -0.641 ± 0.225 | 0.145 | 1.966 | -0.655 ± 0.111 | 0.428 | 2.048  |

**Figure 2**

| Variable | Slope     | $R^2$ | DW | Slope     | $R^2$ | DW | Slope     | $R^2$ | DW |
|----------|-----------|-------|----|-----------|-------|----|-----------|-------|----|
| SSI >2   | -0.644 ± 0.119 | 0.373 | 1.639 | -0.674 ± 0.129 | 0.373 | 1.551 | -0.602 ± 0.067 | 0.620 | 1.048  |
| SSI >2   | -0.761 ± 0.125 | 0.431 | 1.450 | -0.700 ± 0.122 | 0.415 | 1.625 | -0.745 ± 0.067 | 0.716 | 0.987  |
| SSI >2   | -0.644 ± 0.119 | 0.373 | 1.639 | -0.681 ± 0.170 | 0.308 | 2.007 | -0.564 ± 0.112 | 0.316 | 1.948  |
| SSI ≤2   | -0.743 ± 0.164 | 0.274 | 1.914 | -0.700 ± 0.122 | 0.415 | 1.625 | -0.723 ± 0.119 | 0.409 | 1.961  |

**Figure 1**

| Variable | Slope     | $R^2$ | DW | Slope     | $R^2$ | DW |
|----------|-----------|-------|----|-----------|-------|----|
| SSI >2   | -0.666 ± 0.082 | 0.571 | 0.566 | -0.616 ± 0.089 | 0.503 | 0.578 |
| SSI ≤2   | -0.013 ± 0.001 | 0.734 | 0.689 | -0.481 ± 0.173 | 0.139 | 2.012 |

27-C, the total 27 investigated cities; API85+, cities with average API > 85; API85−, cities with average API ≤ 85.

Spring, March to May; Summer, June to August; Autumn, September to November; Winter, December to February.

Significance level $p < 0.05$; $R^2$, coefficient of determination; DW, Durbin–Watson value. Based on Durbin–Watson criteria, there is no statistical evidence of autocorrelation if 1.59 ≤ DW ≤ 2.41 for this table. Bold values denote statistics of linear models adjusted by the Cochrane–Orcutt procedure to remove autocorrelation.
Figure 1. Annual time series of average daily surface solar irradiance (SSI, W m\(^{-2}\)) and wind speed (WS, m s\(^{-1}\)) over 27 cities across China under clear skies for 1961–2011. The equation establishes the linear regression relationship between SSI and WS for 1961–2011. Values after arrow symbols: trend slopes and corresponding standard errors. * Significant trend at the 95% confidence level.

A slight increase (4.0 W m\(^{-2}\) decade\(^{-1}\)) from the 1990s. Dimming is accompanied by a sharp increase in AOD, which peaks around the 1990s and decreases thereafter (Luo et al. 2001, Streets et al. 2008). Declining trends are also noted in the concentrations of both PM\(_{2.5}\) and PM\(_{10}\) in the 2000s (Yang 2009, Lei et al. 2011, Wang et al. 2012a, 2012b, 2013b). There is a scientific consensus that the most plausible explanation for China’s dimming is increasing anthropogenic aerosol loading (Che et al. 2005, Qian et al. 2006, 2007, Xia 2010), which could be enhanced by the observed stilling winds. Recent brightening in China’s cities has been proved to be due to decreasing API rather than climate change (Wang et al. 2013b). This phenomenon could benefit from the slowdown of wind speed decreasing rate in the 1990s–2000s.

It is worthy to note that the drops in SSI in 1982–1983 and in 1991 could be driven respectively by the impacts of El Chichon and Philippine Pinatubo volcanic eruptions, which emitted stratospheric aerosols unrelated to anthropogenic pollutants. After removing these years, SSI still shows a transition trend from dimming (–14.5 W m\(^{-2}\) decade\(^{-1}\) in the 1960s–1980s) to brightening (3.0 W m\(^{-2}\) decade\(^{-1}\) in the 1990s–2000s). This further confirms the impact of anthropogenic aerosols on SSI. By also removing the periods most heavily affected by volcanic eruptions, Riihimaki et al. (2009) verified that part of the increase in SSI in Oregon could be caused by the reduction in anthropogenic aerosols in 1980–2007.

3.2. Increasing influence of wind speed on SSI variations pushed by air pollution

To further clarify the regulatory effect of wind speed on SSI, annual fluctuations in SSI were compared for windy and windless conditions (figure 2). Generally, the annually averaged daily SSI for windy days is higher than that for windless days—further evidence of the positive effect of wind speed on SSI. From table 2, the rate of solar dimming in the 27 cities under windless days (7.1 W m\(^{-2}\) decade\(^{-1}\)) is 39% higher than that under windy days (5.1 W m\(^{-2}\) decade\(^{-1}\)). This suggests that solar dimming accelerates under windless conditions, which could enhance the concentration of pollutants/aerosols in the air thus further block the transmission of sunlight to Earth’s surface. Figure 2(a) shows a widening gap in annually averaged daily SSI between windy and windless conditions for the 1960s–1990s, indicating an increasing influence of wind speed on SSI variations. The strengthened wind effect on SSI could be due to China’s deepening haze pollution. The gap slightly narrows down in the 2000s, in line with observed declines in PM\(_{2.5}\) and PM\(_{10}\) concentrations.

Comparison of figures 2(b) with 2(c) shows that the gap in SSI between windy and windless conditions is much wider in API\(_{85+}\) than in API\(_{85−}\) city group. This suggests that the effect of wind speed on SSI strengthens with worsening air pollution. It is also shown in figure 3 that the correlation between SSI and wind speed is influenced by API. From figure 3(a), 24 out of the 27 cities have positive correlation between SSI and wind speed for 1961–2011. About 93% of API\(_{85+}\) cities and 85% of API\(_{85−}\) cities present positive correlation. This indicates that positive SSI-wind speed correlation is more likely for relatively more polluted conditions. Figure 2(c) depicts a gradually widening gap in SSI between windy and windless conditions for API\(_{85+}\) city group. This suggests that the gap in SSI almost closes up for API\(_{85−}\) city group. The gap slightly narrows down in the 2000s, in line with observed declines in PM\(_{2.5}\) and PM\(_{10}\) concentrations.

A widening gap in annually averaged daily SSI between windy and windless conditions is also noted for all the seasons (figure 4). The gap in SSI is widest in winter—the season with the highest API level (API=90). From figure 3(e), SSI in winter is positively correlated with wind speed in almost all the cities during 1961–2011. There is only one exception in the API\(_{85−}\) city group, where a negative correlation exists between SSI and wind speed. In contrast, the gap is hardly noticeable in summer (figure 4(b))—the season with the lowest API level (API=68). Figure 3(c)
shows that 26% of the investigated cities have negative correlation between SSI and wind speed in summer, all of which cities are in the API85–city group. The gaps in SSI are relatively moderate in spring (API = 81) and autumn (API = 79). A significant positive correlation is noted between SSI and wind speed in 52% and 67% of the country in spring (figure 3(b)) and autumn (figure 3(d)), respectively. The widths of the gaps in SSI between windy and windless conditions generally match with average API levels. Furthermore, only winter shows a narrowing gap in SSI starting from the 2000s. This suggests that the utilization of renewable energy for heating might be the main contributor to air quality improvement in China (Lin et al 2010, Shaw et al 2010, Shi et al 2010).

The hypothesis that wind may reduce the effect of aerosols on SSI when aerosol load is high still stands after correction for autocorrelations in the time series. From table 2, differences in trend slopes of SSI between windy and windless conditions are insignificant for API85–cities/other seasons with higher aerosol load. In summer, the 95% confidence interval of the SSI trend slope for wind speed >2 m s−1 category (−5.1 W m−2 decade−1 ∼ −8.5 W m−2 decade−1) extends beyond that for wind speed ≤2 m s−1 category (−5.8 W m−2 decade−1 ∼ −8.2 W m−2 decade−1). By contrast, in winter, the confidence interval of the dimming rate for windless conditions (5.9 W m−2 decade−1 ∼ 7.6 W m−2 decade−1) is almost completely higher than that for windy conditions (4.3 W m−2 decade−1 ∼ 6.0 W m−2 decade−1). This further proves that the regulatory effect of wind speed on SSI mainly performs in polluted circumstances. In API85+ cities, the confidence intervals of SSI trend slopes computed for wind speed >2 m s−1 and ≤2 m s−1 categories also overlap; indicating 85 API is not the exact threshold for wind effect on SSI to be important.

Assuming that wind indirectly influences SSI through dispersion of pollutants/aerosols, the magnitude of this effect could depend on and in turn adequately reflect air quality. The
more polluted the air at any place and time, the stronger the regulatory effect of wind speed on SSI. In other words, the degree to which wind–aerosol interaction amplifies or dampens solar dimming is a function of the prevailing pollution condition. The gap in SSI between windy and windless clear-sky days could therefore serve as a critical indicator for air quality. It could be used to estimate air quality in regions (county scale) and periods (before 2000) without direct air quality monitoring to compensate for the spatial and temporal limitation of API measurement in China. Wind speed and SSI data have wider spatial distribution and longer temporal trends than API data in China.

3.3. Correlations of SSI, wind speed and API

The basic regulation dynamics of SSI by the interactions between wind and aerosol are depicted in figure 5. On the left of figure 5, SSI progressively decreases with increasing API, suggesting the well established attenuation effect of air pollution on radiation. Under non-polluted conditions (API ≤ 100, table 1), average daily SSI is 213 W m$^{-2}$. When the atmosphere starts getting polluted (100 < API ≤ 200), average daily SSI is 195 W m$^{-2}$, dropping by 8%. Then when air pollution worsens (API > 200), SSI is maintained around the lowest value of 177 W m$^{-2}$, dropping by 17% from that of non-polluted condition. Averagely, when API increases by one level (note that API difference between two successive levels is 50), SSI decreases by 6 W m$^{-2}$.

The right part of figure 5 shows negative correspondences between SSI and API for different wind speed ranges, suggesting that wind indirectly influences SSI through interaction with aerosols. Wind noticeably disperses air pollutants and thereby increases SSI under wind speed <2.5 m s$^{-1}$ conditions. On average, every 0.5 m s$^{-1}$ increase in wind speed decreases API by 5.7 points (6.0%) and correspondingly increases SSI by 3.5 W m$^{-2}$ (1.7%). The sensitivity of API and SSI to changes in wind speed reduces when winds exceed the 2.5 m s$^{-1}$ cut-off point. From this point, every additional 0.5 m s$^{-1}$ increase in wind speed on average decreases API by only 1.6 points (2.0%) and increases SSI by 1.3 W m$^{-2}$ (0.6%). In the 2.5–3.5 m s$^{-1}$ wind speed range, API and SSI are respectively maintained around the lowest (77 points) and highest (213 W m$^{-2}$) levels. When winds are stronger than 3.5 m s$^{-1}$, every 0.5 m s$^{-1}$ increase in wind speed decreases API by 1.1 point (1.5%) and decreases SSI by 1.2 W m$^{-2}$ (0.6%). This is especially true for dusty regions as in Northwest and North China where every 0.5 m s$^{-1}$ increase in wind speed increases API by 1.5 point (1.8%) and decreases SSI by 1.8 W m$^{-2}$ (0.8%). It could then be inferred that winds greater than 3.5 m s$^{-1}$ enhance aerosol concentration in the atmosphere probably by inducing dust-storms which in turn attenuate SSI. This effect is further verified by the finding of Mahowald et al (2007) that winds rather than precipitation drive much of the variability of dustiness in China, suggested by high correlations between winds and VIS5 (visibility less than 5 km) or EXT (surface extinction).
The regulatory effect of wind speed on SSI is influenced by the wind–aerosol interaction. The minimal discrepancy in the magnitude of wind-driven change in API and SSI could be due to disturbances from other potential factors such as water vapor and regional circulation patterns. Water vapor is a strong absorber of solar radiation that a 10% increase in water vapor attenuates SSI by up to 0.5% (Wild 2009). Regional circulation patterns through sea-level pressure differences additionally influence changes in SSI, especially during strong high pressure systems causing predominantly clear-sky conditions (Chiacchio and Vitolo 2012).

Figure 6 reveals how SSI-wind speed correlation is influenced by API. When API $\leq 50$ (excellent air quality,
table 1), the correlations between SSI and wind speed are negative, probably due to insignificant wind dispersion of aerosols. The absolute values of the coefficients are less than 0.2 under non-polluted conditions (API \(\leq 100\), table 1), suggesting weak SSI-wind speed correlations. When API exceeds the 125 boundary, wind effect on SSI starts to be important (coefficient > 0.3). And when air pollution reaches moderate status (API > 200), SSI is strongly (coefficient > 0.5) and significantly \((p < 0.05)\) correlated with wind speed. Although the coefficients of SSI-wind speed correlations are not very high in statistical terms, they are acceptable for indirect natural effects. This evidence is consistent with that in figures 2-4, which shows that more polluted conditions/periods have more significant wind regulatory effect on SSI. Furthermore, the evidence in figure 6 lays the basis for further studies on separating the effects of aerosol and wind speed on SSI, as the effect of wind on SSI is apparently negligible under API \(\leq 100\) conditions but then strengthens with increasing API beyond the 100 cut-off point.

4. Conclusions

An interesting finding of this study is that despite wind weakening, worsening air pollution in China is pushing wind speed into a non-negligible regulator of solar radiation. This is indicated by the widening gap in annually averaged daily SSI between windy and windless clear-sky days over 27 cities across China for the last half century. The increasing influence of wind speed on SSI is especially noticeable in cities and seasons with relatively high air pollution. In contrast, hardly any gap exists in SSI for the API85–city group and summer season (the season with the lowest API level). The gap in SSI is closely related to air quality and could therefore serve as a good indicator for air quality.

The proposed plausible mechanism by which wind speed regulates SSI is through interaction with aerosols. Wind speeds of 2.5 m s\(^{-1}\) and 3.5 m s\(^{-1}\) are two cut-off points. Under winds <2.5 m s\(^{-1}\) conditions, SSI is positively sensitive to changing wind speeds due to the strong dispersion effect of winds on air pollutants. Then when winds exceed the 2.5 m s\(^{-1}\) cut-off point, the enhancement effect of wind on SSI weakens due to impotent attenuation effect of winds on API. With winds stronger than 3.5 m s\(^{-1}\), the reaction of SSI to changes in wind speed becomes negative as a result of enhanced aerosol (especially dust particles) concentration. The magnitude and direction of the driving force of wind speed on API and SSI vary with changing winds.

Winds play an important role in evaluating the contribution of air pollution to solar dimming. The regulatory effect of wind speed on SSI becomes significant and important when API exceeds the boundary of 125. Under strong and perennial pollution conditions, SSI could even be more sensitive to wind speed than to API. Despite wind speed, wind direction is also a potential influencing factor of SSI. Strengthening winds could increase aerosol dispersion in source regions and aerosol concentration in downwind regions. This calls for further studies in relation to wind direction, wind–aerosol interaction and SSI regulation.
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