Numerical Analysis on the Contribution of Urbanization to Wind Stilling: An Example over the Greater Beijing Metropolitan Area

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ABSTRACT
A decline of surface wind speed (wind stilling) has been observed in many regions of the world. The greater Beijing metropolitan area in China is taken as an example for analyzing the urbanization impact on wind stilling. This study set up five scenarios with different urbanization ratios and the same atmospheric forces and then simulated wind speed under each scenario using the next-generation Weather Research and Forecasting model. The results suggest that the correspondence between the regional average wind speed ratio of decrease $D_u$ and the ratio of urbanized area $d_{urban} (%)$ fits the relation $D_u = 3.09 \ln(d_{urban}) + 2.01$ in summer and $D_u = -5.16 \ln(d_{urban}) - 0.75$ in winter. During the period 1961–2008, the ratio of urbanized area over the greater Beijing metropolitan area increased from 1.3% to 11.9%, which is speculated as the cause of a $0.4 \text{ m s}^{-1}$ decline in regional average wind speed and the contributor to about 35% wind stilling.

1. Introduction

Surface wind speeds $u$ measured by terrestrial anemometers at 10-m height (all subsequent $u$ values refer to this height) have declined (termed “stilling”) over the past few decades in many regions of the world, such as China, South Korea, Italy, the west coast of Canada, the Netherlands, the Czech Republic, the United States, and Australia (Xu et al. 2006; McVicar et al. 2008; Jiang et al. 2010; Vautard et al. 2010; Ko et al. 2010; Fujibe 2011; Guo et al. 2011). Among the ever-increasing studies on $u$ trends, McVicar et al. (2012) reviewed 148 studies reporting terrestrial $u$ trends from across the globe (with uneven and incomplete spatial distribution and 54 different measurement periods). They found an average trend of $-0.014 \text{ m s}^{-1} \text{ yr}^{-1}$ in studies of more than 30 sites with observed data exceeding 30 years, which confirmed widespread stilling.

Wind stilling is a potential concern for wind power electricity production (McVicar et al. 2008; Jiang et al. 2010; Vautard et al. 2010), wind erosion, wind transport, and structural engineering (McVicar et al. 2008). It is also the main cause of globally widespread decreases of pan evaporation (Roderick et al. 2007; McVicar et al. 2012; Vautard et al. 2010; Yang and Yang 2012), which may lead to water resource or ecohydrological problems. In addition, the importance of $u$ trends for predicting interacting feedbacks between precipitation, temperature, and vapor pressure has recently been highlighted by the climate change community (McVicar et al. 2008). Therefore, investigating wind changes can improve our understanding of climate change and human activity, and their impacts on environmental, ecological, and socio-economic systems worldwide (Guo et al. 2011).

Many studies have tried to reveal precise causes of stilling. Rayner (2007) and McVicar et al. (2008) suggested that some changes in observed daily average wind speed may be caused by alterations in the local environment surrounding observing stations (e.g., growing trees or other obstacles progressively obstructing airflow). Xu et al. (2006) and Guo et al. (2011) attributed wind stilling over China to a north–south warming gradient in winter, and sunlight dimming from air pollution over central areas in summer. Jiang et al. (2010) asserted that the cause
was a decrease in contrasts of sea level pressure and near-surface temperature between the Asian continent and Pacific Ocean, under the background of global warming together with urbanization. Li et al. (2011), comparing daily wind speed at 12 stations (including urban and rural sites) over the greater Beijing metropolitan area during 1961–2008, suggested that the bulk of wind is strongly influenced by urbanization, accounting for around one-fifth of a regional mean declining trend (0.005 of 0.026 m s\(^{-1}\) yr\(^{-1}\)). On the contrary, Guo et al. (2011) observed a peculiar larger wind increase at urban stations than at rural stations with abrupt urbanization in China after 1990. This is similar to that observed in southeast Queensland and northeast New South Wales in Australia (McVicar et al. 2008). Vautard et al. (2010) summarized that wind stilling can be from 1) changes in mean circulation and/or a decrease of synoptic weather system intensity, both as consequences of climate change; 2) increasing surface roughness in the near field of each station and/or in boundary layer structure; and/or 3) instrumental or observational drifts. To further quantify the impact of surface roughness changes on wind stilling, Vautard et al. (2010) analyzed sensitivity of wind speed to the normalized difference vegetation index (NDVI) using the fifth-generation Pennsylvania State University–National Center for Atmospheric Research Mesoscale Model (MM5), concluding that 25%–60% of wind stilling could be caused by vegetation change. Besides, urbanization processes will lead to an increase in surface roughness. China has been experiencing rapid urbanization since the end of the 1970s, and the greater Beijing metropolitan area is the most typical example. After rapid urbanization over the last 30 years, Beijing is now one of the 10 largest megacities in the world, with a population exceeding 10 million (Miao et al. 2011). Another potential concern is that the surroundings of many World Meteorological Organization–standard stations in China have been rapidly urbanizing (Li et al. 2011). Therefore, it would be beneficial to make a case study to quantify possible influences of urbanization on wind speed.

This study takes Beijing as an example and simulates wind speed under different urbanization ratio scenarios and same atmospheric forces using a numerical model, and then analyzes the relationship between wind speed and urbanization ratio to reveal the contribution of urbanization to wind stilling.

2. Data and methods

The greater Beijing metropolitan area is located in north China, with a plain in the southeast and mountains in the northwest (Fig. 1), where there are 187 meteorological...
FIG. 2. Urban extent of five scenarios (each pixel represents an area of 3.6 × 3.6 km²): (a) NOurban, (b) urban86, (c) urban95, (d) urban05, and (e) urbanBJ. NOurban represents no urbanized area, and urbanBJ represents the urban extent that all the plain transforms into urbanized area. Urban86, urban95, and urban05 represent the urban extent in 1986, 1995, and 2005, respectively.
stations. Foyeding station is located in a hilly area, which is the highest station with altitude exceeding 1217 m above sea level. We collected daily wind speed from 1951 to the present from Beijing (Guoxiangtai) station. The land use datasets of 1986, 1995, and 2000 were downloaded from “Environmental & Ecological Science Data Center for West China, National Natural Science Foundation of China” (http://westdc.westgis.ac.cn), and the land use data of 2005 were collected from the Institute of Remote Sensing, Chinese Academy of Sciences.

To reflect the urbanization process of the metropolitan area, we obtained an urban extent map of Beijing in 1986, 1995, and 2005 from the land use data, as shown by red pixels in Figs. 2b–d. Based on the 2005 land use map in Fig. 2d, we designed five land use scenarios. The first land use scenario was designed by replacing the urbanized region of 2005 land use map (Fig. 2d) with cropland; thus we obtained the land use map shown in Fig. 2a, which hereinafter is called the NOurban scenario. In the same way, the other four land use scenarios were obtained by replacing the urbanized region of 2005 land use map with the urban extent of 1986 (Fig. 2b; urban86 scenario), urban extent of 1995 (Fig. 2c; urban95 scenario), urban extent of 2005 (Fig. 2d; urban05), and urban extent of the Beijing plain area (Fig. 2e; urbanBJ scenario), respectively. These five scenarios represent different extents of urbanization, from one extreme of no urbanization (NOurban scenario) to the other extreme in which all the Beijing plain is replaced by urban area (urbanBJ scenario). The simulated $u$ difference between these scenarios should reflect the impacts of urbanization on wind speed.

According to different urbanization scenarios, the 187 meteorological observation stations of Beijing were divided into five groups. The 29 stations located within the urban extent of 1986 (indicated by the solid red line in Fig. 1), called urban86 stations (symbolized by blue dots in the figure). Similarly, 18 stations outside the urban extent of 1986 but within that of 1995 were called urban95 stations. The six stations outside the urban extent of 1995 but within that of 2005 are called urban05 stations. The 60 remaining stations in the plain area are called rural stations, and 74 stations in the hilly area are called hill stations. Simulated wind speeds of these five station groups were averaged separately, to minimize occasional errors of single station analysis in calculating the impact of urbanization on wind speed.

| Table 1. Roughness heights for different land use types used in WRF (excerpts). |
|-------------------------------|-----------------|-----------------|
| Land use description          | Roughness height in summer (cm) | Roughness height in winter (cm) |
| Urban and built-up land       | 80              | 80              |
| Dryland/irrigated cropland    | 10–15           | 2–5             |
| Grassland/shrubland           | 5–12            | 1–10            |
| Broadleaf/mixed forest        | 50              | 20–50           |
| Water bodies                  | 0.01            | 0.01            |
To explore the impact of urbanization on wind speed in different season, we chose three clear summer days (20–22 June 2005) and three clear winter days (20–22 December 2005) as the simulation period. We then used a state-of-the-art mesoscale numerical weather prediction system, Weather Research and Forecasting Model (WRF; version 3.3, released 6 April 2011), to carry out the simulations. The WRF is a next-generation community...
numerical weather simulation and prediction system, designed to serve both operational forecasting and atmospheric research needs. It is suitable for a broad spectrum of applications, across scales from meters to thousands of kilometers (Skamarock et al. 2008). The simulation domain covered the entire Beijing area and part of surrounding provinces (Fig. 3), including the western and northern mountains and part of the Bohai Sea to the east.

Horizontal grid spacing was 3.6 km (number of grid cells $128 \times 89$), and the vertical grid contained 28 full sigma layers, from the surface to 50 hPa. We used the Yonsei University PBL scheme, which is a nonlocal-$K$ scheme with explicit entrainment layer and parabolic $K$ profile in an unstable mixed layer. Other physical parameterizations include the Milbrandt–Yau double-moment seven-class scheme, in which both the mass and the total number concentration of the hydrometeor categories (i.e., cloud, rain, ice, snow, graupel, and hail) are independently predicted (Milbrandt and Yau 2005), Dudhia shortwave radiation scheme, Rapid Radiative Transfer Model (RRTM) longwave radiation scheme, and Noah land surface model. No cumulus scheme was used because of the relatively small grid size (less than 5 km; Lin et al. 2007).

The Advanced Research WRF (ARW) was integrated for 72 h with time step 20 s for each land use scenario, from 0000 LST 20 June 2005 to 0000 LST 23 June 2005 in summer, and from 0000 LST 20 December 2005 to 0000 LST 23 December 2005 in winter. The $u$ at locations of the 187 stations was output every 2 h, and averaged daily to compare with observations. Initial and lateral boundary conditions were interpolated from National Centers for Environmental Prediction (NCEP) final analysis data [http://dss.ucar.edu/datasets/ds083.2/; this product is from the Global Data Assimilation System (GDAS)], with a spatial resolution of 1° and temporal resolution of 6 h. Roughness heights for different land use types used (default in WRF, version 3.3) for summer and winter days are given in Table 1 and were unchanged in all five land use scenarios.

3. Results

a. Model performance

Daily average 2-m temperatures and 10-m $u$ were simulated from 20 to 22 June 2005 and from 20 to 22 December 2005 at Beijing (Guangxiangtai) station, which are plotted in Figs. 4a and 4b along with the observed. Figure 4a shows that the simulated and measured 2-m temperatures of the six days are evenly distributed along the line $y = x$, which means the model can simulate the variation of 2-m temperature. The simulated 10-m $u$ in Fig. 4b also matches the observations, although not as well as the temperature in Fig. 4a. In addition, we designed another urban00 land use scenario using the urban extent of 2000 and simulated 2-m temperature and 10-m $u$ on the same days in 2000 as in 2005 (from 20 to 22 June and from 20 to 22 December). The results of simulated 2-m temperature and 10-m $u$ at the Beijing station are plotted in Figs. 4c and 4d along with the observed. They show that the model can simulate the 2-m temperature and 10-m $u$ in 2000 as that in 2005. Figures 4e and 4f show the simulated average 2-m temperature and 10-m $u$ with the observed for the four consecutive three days in 2000 and 2005. The simulated data have a consistent agreement with the observed, which indicates that the model can simulate the temporal change in 2-m temperature and 10-m wind speed.
b. Impacts of urbanization on wind speed

Table 2 shows the simulated regional average wind speed under different urbanization ratio scenarios. The urbanization ratio, which is defined as the areal percentage of urbanized region to that of the greater Beijing metropolitan area, ranges from 0% to 37.2%. Table 3 gives differences between two adjacent urbanization ratio scenarios. Tables 2 and 3 show a decline in the simulated regional average wind speed with urbanization ratio increasing. For example, the regional average wind speed on 20 June, from the NOurban scenario to urbanBJ scenario, declined from 2.12 to 1.89 m s\(^{-1}\), and the difference between adjacent NOurban and urban86 scenarios was -0.07 m s\(^{-1}\). Wind speed on the remaining five days showed similar results. However, on the three winter days of higher wind speed, wind declines from urbanization were greater than those on the three summer days. For example, on 20 December regional wind speed decreased from 6.56 m s\(^{-1}\) in the NOurban scenario to 6.05 m s\(^{-1}\) in the urban86 scenario. This was a decline of 0.51 m s\(^{-1}\), much larger than with the three summer days. If we assume the average of all six days represents the annual average situation, then from 1995 to 2005 the wind speed decrease from urbanization would be -0.05 [\((-0.02 - 0.08)/2\)] m s\(^{-1}\), or about -0.005 m s\(^{-1}\) yr\(^{-1}\). There would be another decrease of 0.24 [\((-0.09 - 0.39)/2\)] m s\(^{-1}\) in daily average wind speed, if the entire plain area of Beijing was converted to urbanized area. Calculated from the two extreme scenarios (NOurban and urbanBJ cases), that is, if the entire plain area in the metropolitan area was converted to an urbanized region, the total regional average wind decline from urbanization reaches 0.64 [\((-0.21 - 1.08)/2\)] m s\(^{-1}\).

We next constructed an empirical relationship of wind speed change with urbanized ratio over the metropolitan area. To do so, we calculated the ratio of each scenario’s urbanized area, and its corresponding decrease ratio of regional average wind speed, which was calculated as the average wind speed of the five land use scenarios, on both summer and winter days (Table 4). Figure 5 shows the average decrease ratio of wind speed \(\Delta u\) versus ratio of urbanized area \(\delta_{\text{urban}}\) (%). For summer days of weaker winds, the empirical relation was

\[
\Delta u = -3.09 \ln(\delta_{\text{urban}}) + 2.01, \quad (1)
\]

and for winter days of stronger winds, the relation was

\[
\Delta u = -5.16 \ln(\delta_{\text{urban}}) - 0.75. \quad (2)
\]

Equations (1) and (2) indicate that 20% urbanized area increase will lead to a decrease in regional average wind speed of about 7% in summer and about 16% in winter.

As shown in Table 1, the roughness height of urban and built-up land is larger than with the other land use types. Therefore, urbanization means an increase of surface roughness heights. As with the urbanized ratio, we calculated area-weighted roughness heights for each land use scenario over the metropolitan area and regional average wind speed change on the summer and winter days. These are respectively shown in Tables 5 and 6. As expected, average roughness heights increased with expansion of urbanized region, from the NOurban land use scenario (16.11 cm in summer and 7.88 cm in winter) to urbanBJ scenario (41.63 cm in summer and 36.45 cm in winter). Regional average wind speed decreased correspondingly (from 2.32 to 2.11 m s\(^{-1}\) in summer, and from 5.96 to 4.89 m s\(^{-1}\) in winter). The roughness height ratio \(Z\) of each land use scenario to the urban05 scenario \(Z_0\), and decrease of regional average 10-m wind speed \(\delta u\), are listed in Tables 5 and 6 and plotted in Fig. 6.

The fitted relation of wind speed change and roughness

![Figure 5](https://example.com/fig5.png)

**FIG. 5.** Average decrease ratio of regional wind speeds with ratio of urbanized area, on summer and winter days.
height ratio relative to the urban05 scenario for summer days was $\delta u = -0.21 \ln(Z/Z_0) + 0.09$, and for winter days $\delta u = -0.66 \ln(Z/Z_0) + 0.28$. Thus, doubling of roughness height led to a $u$ decrease by 0.14 m s$^{-1}$ in summer and 0.43 m s$^{-1}$ in winter.

c. Impacts of urbanization on wind speed observation

China has rapidly urbanized in recent decades, so that many meteorological stations originally in rural areas have been gradually surrounded by urban or built-up land. Table 7 shows average $u$ for different groups of stations, and Table 8 shows differences $\Delta u$ between two adjacent land use scenarios.

The simulated average $u$ for urban86, urban95, urban05, and rural stations all show a generally decreasing trend with urbanized ratio increasing (Tables 7 and 8). For example, the average $u$ for urban95 stations on the summer days was 2.26 m s$^{-1}$ in the NOurban case, but it fell to 2.13 m s$^{-1}$ (a 0.13 m s$^{-1}$ decrease) if cropland in the center area was converted to urban (urban86 case). This indicates that urbanization influences wind speeds in the surrounding rural region (according to the station classification, the urbanized region for the urban86 case did not cover urban95 stations). With urbanized region expansion to the urban95 case covering the urban95 stations, the average $u$ declines to 2.05 m s$^{-1}$ (a 0.08 m s$^{-1}$ decrease). Further expansion of the urbanized region to the urban05 case causes another 0.04 m s$^{-1}$ $u$ decrease ($=2.05-2.01$ m s$^{-1}$), which means that the urban outward expansion also causes $u$ decline in the inner region, but with relatively small magnitude. Analysis of the other group stations for both summer and winter days gave similar results.

According to the division into different groups of stations (details was given in section 2), the local decrease of $u$ can be generally calculated as the average $u$ difference of urban86 stations between the NOurban and urban86 cases, urban95 stations between NOurban and urban95 cases, urban05 stations between urban95 and urban05 cases, and rural stations between urban05 and urbanBJ cases. Average local $u$ decrease for summer days would be $-0.25$ m s$^{-1}$ for urban86 stations, $-0.08$ m s$^{-1}$ for urban95 stations, $-0.06$ m s$^{-1}$ for urban05 stations, and $-0.28$ m s$^{-1}$ for rural stations, as listed in Table 7. Average local $u$ decrease for winter days would be $-1.49$ m s$^{-1}$ for urban86 stations, $-0.31$ m s$^{-1}$ for urban95 stations, $-0.23$ m s$^{-1}$ for urban05 stations, and $-0.93$ m s$^{-1}$ for rural stations, as listed in Table 8. On average, the impact of urbanization on local $u$ observations would be $-0.17 [=(−0.25 − 0.08 − 0.06 − 0.28)/4] \text{ m s}^{-1}$ for summer days (about an 8% decrease over summer average wind speed), and $-0.74 [=(−1.49 − 0.31 − 0.23 − 0.93)/4] \text{ m s}^{-1}$ for winter days (about a 14% decrease over winter average wind speed). In other words, observed $u$ at stations surrounded by urban areas is 8%–14% less than that before urbanization. Impacts of urbanization on nonlocal sites would be $-0.05$ m s$^{-1}$ for summer days and 0.30 m s$^{-1}$ for winter days, 2%–6% less than that before surrounding urbanization. This indicates that the urbanization influence becomes weaker with distance, as expected.

d. Contribution of urbanization increase to wind stilling

The total area of the greater Beijing metropolitan area is about 16 807 km$^2$, and the area of urban and built-up land in the city in 1961 was about 215 km$^2$ (Lu et al. 2001) and that in 2008 was about 2000 km$^2$; that is, the urbanized ratio increased from 1.3% in 1961 to 11.9% in 2008. According to Eqs. (1) and (2), the change

![Fig. 6. Relation of wind speed change and relative roughness height to urban05 scenario, for summer and winter days.](image-url)
in wind speed was about 5.3% (−0.12 m s⁻¹) in summer, and about 12.9% (−0.7 m s⁻¹) in winter. On annual average, the u decrease because of urbanization was −0.41 [(=−0.12 − 0.7)/2] m s⁻¹. Regarding overall u decrease, Li et al. (2011) calculated the linear trend of observed wind speed at 0.026 in the metropolitan area during 1961–2008, that is, 1.22 m s⁻¹ for stronger winter winds. According to these two relations, about doubling the roughness height would decrease u by 0.14 m s⁻¹ in summer and 0.43 m s⁻¹ in winter, which is consistent with Vautard’s result, 0.26–0.33 m s⁻¹ (Vautard et al. 2010). Many Chinese rural meteorological stations have been gradually surrounded by urban area, which strongly impacts wind speed. Over the greater Beijing metropolitan area, this leads to an 8%–14% decrease in wind speed across the meteorological stations. Therefore, the effect of urbanization on observed wind speed at such stations should be corrected for, when detecting wind speed change or conducting related research.

In some previous studies, the influence of urbanization on wind speed was estimated by comparing wind speed observations between urban and rural stations (Li et al. 2011). This implies an assumption that if site A is within an urban expansion area but nearby site B is beyond the urban extent, the observed difference between the two sites represents the urban impact on wind speed. However, the observed u at site B is partially influenced by urbanization at site A. For example, in Greater Beijing, the local ratio of decrease of average wind speed from urbanization was 8%–14% for local sites (site A) and 2%–6% for surrounding rural sites (site B). Accordingly, it will induce an underestimation of 2%–6% to estimate the urbanization impact by comparing the observed wind speeds at site A and site B. Therefore, this uneven and spatially varying influence of urbanization on local and surrounding meteorological observations should be considered when choosing typical observation sites and using raw data. However, this ratio of decrease or spatial distribution may need further verification or correction when applied to other regions or periods.

<table>
<thead>
<tr>
<th>Case</th>
<th>Urban86 stations</th>
<th>Urban95 stations</th>
<th>Urban05 stations</th>
<th>Rural stations</th>
<th>Hill stations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>u</td>
<td>Δu</td>
<td>u</td>
<td>Δu</td>
<td>u</td>
</tr>
<tr>
<td>NUrban</td>
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<td>—</td>
<td>2.26</td>
<td>—</td>
<td>2.21</td>
</tr>
<tr>
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<td>2.13</td>
<td>−0.13</td>
<td>2.18</td>
</tr>
<tr>
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<td>−0.06</td>
<td>2.05</td>
<td>−0.08</td>
<td>2.14</td>
</tr>
<tr>
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<td>2.01</td>
<td>−0.03</td>
<td>2.08</td>
</tr>
<tr>
<td>UrbanBJ</td>
<td>1.91</td>
<td>0.01</td>
<td>1.95</td>
<td>−0.07</td>
<td>1.89</td>
</tr>
</tbody>
</table>

Table 8. As in Table 7, but for winter days.
There are two approaches for detecting the contribution of urbanization to wind stilling. The first is from the observations: 1) first choosing two time series of data at a central area of urbanization and at a rural area and obtain the decrease trend and then 2) comparing these two changes to estimate the affection of urbanization on the surface wind changes. The second is from the simulations: 1) choosing two different periods with different urbanization and atmospheric forces, denoted U1, U2 representing the urbanization and A1, A2 representing the atmospheric forces in the two periods; 2) setting four scenarios, namely U1A1 (the urbanization condition in the first period and the atmospheric forces in the first period), U1A2, U2A1, and U2A2; 3) simulating the wind speed under different scenarios; and 4) comparing them to separate the impacts of urbanization and atmospheric forces, that is, the differences between U1A1 and U2A1 (or U1A2 and U2A2) and between U1A1 and U1A2 (or U2A1 and U2A2) indicating the impacts of urbanization and atmospheric forces, respectively. Li et al. (2011) adopted the first method, while we chose the second method in this study. However, we only got the atmospheric forces in one period (A2), and therefore only the difference between U1A2 and U2A2 was simulated and the impact of atmospheric forces could not be analyzed; more data and further study are expected.

The roughness height of urbanized area was taken from WRF, which is its default value rather than the true value for the Beijing area. Although a gross estimate of roughness increase from urbanization could not be found (Vautard et al. 2010), it is known that the roughness in an urban area is greater than cropland. However, a more realistic value should be investigated. Furthermore, we selected only six typical summer and winter days to represent annual average condition. More days in other seasons or other regions should be studied, although urbanization impacts on winds should be qualitatively similar for given atmospheric boundary conditions.

5. Conclusions

In this study, we simulated wind speed under different urbanized ratio and same atmospheric forces using the next-generation Weather Research and Forecasting model, and then examined the relationship of wind speed change with urbanized area, to reveal the impact of urbanization on wind stilling. In the greater Beijing metropolitan area, the regional average wind speed ratio of decrease $\Delta u$ with the ratio of urbanized area $\delta_{\text{urban}}$ (%) fits the relation $\Delta u = -3.09\ln(\delta_{\text{urban}}) + 2.01$ in summer, and $\Delta u = -5.16\ln(\delta_{\text{urban}}) - 0.75$ in winter. It suggests a 20% increase in urbanized area would cause a 7%–16% decrease of wind speed. During the period 1961–2008, the urbanized ratio increases from 1.3% to 11.9% and leads to 0.4 m s$^{-1}$ decline in regional average wind speed, which is speculated to contribute about 35% of wind stilling.

The roughness height for urbanized area adopted in our simulation is the default value in WRF. Moreover, only six days in summer and winter were chosen for simulation. Therefore, to more accurately evaluate the impact of urbanization on wind stilling, the roughness height of urbanized areas demands further study, and additional days in different seasons and different regions should be considered. Beyond wind speed, other state variables like temperature and moisture are also influenced by urbanization. Further study of these variables will improve our understanding of the impact of human activity on environmental, ecohydrological, and socio-economic systems.

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