Urbanization has stronger impacts than regional climate change on wind stilling: a lesson from South Korea

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Abstract

Wind stilling has been observed in many regions across the Northern Hemisphere; however, the related mechanisms are not well understood. Analyses of the wind speed variations in South Korea during 1993–2015 in this study reveal that the annual-mean surface wind speeds at rural stations have increased by up to 0.41 m s\(^{-1}\) decade\(^{-1}\), while those at urban stations have decreased by up to \(-0.63\) m s\(^{-1}\) decade\(^{-1}\). The local wind speed variations are found to be negatively correlated with the population density at the corresponding observation sites. Gustiness analyses show the increase in local surface roughness due to urbanization can explain the observed negative wind speed trends at urban stations as the urbanization effect overwhelms the positive wind speed trend due to climate change. The observed negative wind speed trend in urban areas are not found in the regional climate model simulations in the Coordinated Regional Climate Downscaling Experiment—East Asia (CORDEX-EA) as these models do not take into account the impact of urbanization on wind variations during the period. This study suggests that urbanization can play an important role in the recent wind stilling in rapidly developing regions such as South Korea. Our results suggest that future climate projections in CORDEX-EA may overestimate wind speeds in urban areas, and that future regional climate projections need to consider the effects of urbanization for a more accurate projection of wind speeds.

1. Introduction

Wind stilling has been reported as an important phenomenon in recent decades (Roderick et al. 2007, Vautard et al. 2010) as the observed land-surface wind speed has decreased in a number of regions (Bichet et al. 2012, Wu et al. 2018, Zeng et al. 2018). By analyzing the observations at 822 surface weather stations, Vautard et al. (2010) showed that the surface wind speed has been reduced by 5%–15% over almost all continents in the Northern Hemisphere (NH) mid-latitudes over 1979–2008. A recent study also showed a decrease in surface wind speeds and wind power potential in most of NH over the past four decades (Tian et al. 2019) exerting adverse impacts on wind-generated electricity (Sherman et al. 2017) and the dispersion of air pollutants (Li et al. 2019b), reducing evaporation (McVicar et al. 2012), and affecting soil erosion (Zhang et al. 2019). However, the mechanisms related to the observed wind stilling are not well understood (Wu et al. 2018, Zeng et al. 2018). Moreover, climate models have limited ability for simulating the long-term trend in surface wind speeds (Jiang et al. 2017, Tian et al. 2019), indicating the need for a clear understanding of the mechanisms of wind stilling.

From an atmospheric dynamic perspective, wind is affected by the pressure gradient force, Coriolis force, gravitational force, and the drag force (Wu et al. 2018). Guo et al. (2011) suggested that weakening of the lower-tropospheric pressure gradient force is the main cause for the reduced winds over China. In particular, Sherman et al. (2017) found that the wind decline in China is associated with the warming in the vicinity of the Siberian High. A study of the Tibetan Plateau also showed that the warming
of the Tibetan Plateau may reduce the latitudinal gradient of temperatures and surface pressure, which can be partly accounted for the observed local wind decline (You et al 2014). Some studies also showed the relationship between the changes in regional wind speeds and large-scale atmospheric circulation such as the El Nino Southern Oscillations (Nchaba et al 2017), the North Atlantic Oscillation (Azorin-Molina et al 2016, 2018), the Intertropical Convergence Zone, and the South Atlantic Anticyclone (Gilliland and Keim 2018). However, the changes in atmospheric circulation can explain only 10%–50% of the surface wind decline (Vautard et al 2010).

Wind stilling has been mainly observed over the land while the wind speed has increased over the ocean, in general (Young et al 2011, Zeng et al 2018). Thus, the related research has been focused on the role of the changes in surface drag. Sensitivity simulations suggest that an increase in surface roughness can contribute significantly to surface wind stilling (Vautard et al 2010, Bichet et al 2012). Changes in vegetation has been thought to contribute to this increase in roughness (Vautard et al 2010); however, a recent study showed that the increase in leaf area index can explain only a fraction of the observed surface wind speed decreases (Zeng et al 2018). With drastic land use changes, urbanization has more than doubled the aerodynamic roughness length and the zero-plane displacement height in Beijing over the period 1991–2011 (Liu et al 2018). Both observational and modeling studies show that urbanization can be significantly related to the reduced surface wind speed in Beijing (Li et al 2011, Hou et al 2013). The potential impact of urbanization on surface wind speed has also been identified in large cities in China (Wu et al 2016, 2017, Li et al 2018, 2019a, Peng et al 2018). The declining trends in surface wind speed show large regional variations in China with relatively smaller decreases in southern regions compared to northern regions (Shi et al 2015), indicating that background regional climate changes may partly counteract the urbanization effect. This aspect requires further studies.

Urbanization is a worldwide phenomenon (Grimm et al 2008), and South Korea has experienced significant urban expansion along with incredible economic growth over the last 60 years (Jeong et al 2019). A noteworthy decline in the surface wind speed was also identified over South Korea (Kim and Paik 2015), but the causes for this stilling remain unknown. Urbanization has been shown to affect temperatures and ecosystems in South Korea (Jeong et al 2019). Therefore, South Korea is an ideal location to investigate the role of urbanization on wind speed changes.

This study aims to understand the long-term surface wind speed change over South Korea and its potential causes, particularly focusing on the urbanization effect. We first examine the observed wind speed trends at weather stations across South Korea during the period 1993–2015. By categorizing the stations into the rural and the urban group, we separate the effects of the urbanization from the regional climate change effects. The population density is adopted as the parameter for measuring the level of urbanization impacts. We attempt to explain the urbanization effects on local wind speeds using the gust factors as a proxy for surface roughness. We also evaluate the performance of high-resolution climate change projections in the Coordinated Regional Climate Downscaling Experiment—East Asia (CORDEX-EA) on the surface wind speed over South Korea.

2. Data and methodology

We used the daily-mean wind speed and the daily-maximum gust wind speed data observed at the Korea Meteorological Administration (KMA) meteorological stations for analyzing the variations in the surface wind field (https://data.kma.go.kr). The number of KMA stations has gradually increased over the last century (Kim and Paik 2015). Because the gust wind speed data at most KMA stations has become available after 1992, we chose the 1993–2015 period for analysis in this study. The stations which provide continuous daily-mean wind speed and daily-maximum gust wind speed data with the missing values less than 0.1% during the study period are selected for analysis. After excluding the stations relocated during the period from the analysis for data homogeneity, data at 55 stations (figure 1(a)) are available for analyzing the annual- and seasonal-mean wind speed and their changes.

The population density from the Gridded Population of the World (GPW) version 4 (CIESIN 2016) which is considered a good proxy for urbanization, also used as an index to analyze the urbanization effects in Jeong et al (2019), was adopted as the parameter for representing the level of urbanization. We employed the population density of the year 2010 (figure 1(a)). The stations were grouped into two categories, rural (population density < 100 people km$^{-2}$), and urban (population density > 1000 people km$^{-2}$) stations, in order to analyze their annual and seasonal wind speed trends separately. We also used the number of housing units in South Korea during 1995–2015 as an indicator of the progress of urbanization. The housing data based on the Housing Census conducted every 5 years for 1995–2015 was obtained from the Korean Statistical Information Service (http://kosis.kr/). In addition, we also used the DMSP-OLS (Operational Linescan System of Defense Meteorological Satellite Program) nighttime light data (https://ngdc.noaa.gov/eog/), a yearly dataset available from 1992 to 2013 with a spatial resolution of 30 arc-seconds, as the proxy for urbanization. The data values range from 0 to 63. Here, we used the nighttime light values of the year 1993 and 2013.
For physical explanations of the observed wind speed change, we analyzed the gustiness (Wieringa 1973) data that can be used to estimate the local roughness length from routine wind speed observations at meteorological stations (Wever 2012). The gust factor defined as the ratio of the maximum gust wind speed in a time interval divided by the mean wind speed for that same interval, can be related to the local roughness length as below (Wever 2012):

\[
\langle G \rangle = \frac{U_{\text{max}}}{U_{\text{mean}}} = 1 + \frac{\alpha \kappa u c}{\ln \left( \frac{Z_{m}}{Z_{0}} \right)},
\]

where \( G \) is the gust factor, \( U_{\text{max}} \) is the maximum gust wind speed, \( U_{\text{mean}} \) is the mean wind speed, \( \alpha \) is the attenuation factor, and \( u \) is the normalized gust, \( c \) is a stability dependent factor, \( \kappa \) is the von Karman constant, \( Z_{m} \) is the measurement height above the ground, and \( Z_{0} \) is the local roughness length. The angled brackets denote the time-mean value. The gust factor can be used as a proxy of local surface roughness to explore the mechanism of the wind speed change and urbanization effect. In this study, we used the daily mean wind speed as the \( U_{\text{mean}} \) and daily maximum gust wind speed as the \( U_{\text{max}} \). Following Wever (2012), we applied a threshold of 2 m s\(^{-1}\) of daily mean wind speed for calculating the gust factors. The yearly gust factor was determined as the median of the daily gust factors of every year for the years that include at least 50 d with valid gust factors according to the above threshold value. Finally, only stations with the valid yearly gust factors for all the years of 1993–2015 were used for analysis. Thirty stations meet the selection criteria mentioned above. We analyzed the linear trend of the yearly gust factors and the relationships with wind speed change and urbanization for these 30 stations for physical explanations of the observed phenomena.

We also analyzed the wind speed changes from the regional climate model (RCM) simulations in the CORDEX-EA. CORDEX is a World Climate Research Program (WCRP) framework to evaluate RCM performance through a set of experiments aiming at producing regional climate projections (Giorgi et al 2009, Lake et al 2017). We used the simulations in the high resolution (0.22°; approximately 25 km) phase 2 experiment. The monthly-mean near-surface (usually, 10 m) wind speed values from the three available models (HadGEM3-RA, SNU-RCM, and WRF3.7.0) were used. Details of the models are provided in the website (http://cordex-ea.climate.go.kr/cordex/); the model data can be downloaded from the same site. Wind speed trends for 1993–2015 were calculated at the grids that include the corresponding meteorological stations.

3. Results

The observed surface wind speed trends across South Korea vary among stations (figure 1(a)). Thirty-seven stations (21 stations with \( p < 0.05 \) show increasing trends in the annual-mean wind speed during 1993–2015 with the largest value of 0.41 m s\(^{-1}\) decade\(^{-1}\), while 18 stations (11 stations with \( p < 0.05 \) show decreasing wind speed trends with the largest value of \(-0.63 \) m s\(^{-1}\) decade\(^{-1}\). Most stations with a significant decreasing trend are located in the regions where the population density exceeds 1000 people km\(^{-2}\) (figure 1(a)). Based on this finding, we analyzed the relationship between wind speed trends and population density as shown in figure 1(b). The analysis reveals significant negative correlation between the wind speed trend and population density, indicating that the observed decrease in the surface wind speed can be related to urbanization, especially for the stations at which the wind speed trend is statistically significant (\( p < 0.05 \), red dots in figure 1(b)). Elevation dependence of wind speed trends reported in previous studies for some regions (McVicar et al 2010, Guo et al 2017) is not found in South Korea (figure 1(c)).

To further evaluate the urbanization effects on the surface wind speed, the variation in the annual
wind speed at rural and urban stations are analyzed for the 23 year period 1993–2015 (figure 2(a)). The surface wind speed shows significant increasing and (0.08 m s\(^{-1}\) decade\(^{-1}\), p < 0.01) decreasing (−0.24 m s\(^{-1}\) decade\(^{-1}\), p < 0.001) trends for the rural (population density < 100 people km\(^{-2}\)) and urban (population density > 1000 people km\(^{-2}\)), respectively, in the period. The increase in buildings can enhance the surface roughness length as well as the zero-plane displacement height (Liu et al 2018), resulting in reduced surface wind speeds. Previous observational and modeling studies showed that urban developments and the associated increase in building heights can weaken surface wind speeds (Peng et al 2018). The number of housing units was nearly doubled in South Korea over the period 1995–2015, mostly in urban areas (dots in figure 2(a)). Such urban growth could have caused the observed weakening of winds at urban stations.

The previous study by Vautard et al (2010) suggests that the increase in vegetation during the growing season could also reduce surface wind speeds. However, this study reveals that the contrasts in the surface wind trend between the rural and the urban stations also occur in non-growing seasons (figure 2(b)). At urban stations, the wind speed shows significant (p < 0.001) declining trends for all four seasons with similar magnitudes (−0.26 ∼ −0.22 m s\(^{-1}\) decade\(^{-1}\), figure 2(b)), while the vegetation increase mainly occurs during the growing season (usually April to October for South Korea, Jeong et al 2019). If the vegetation increase was the main reason for the wind decline, the weakening of the surface wind should be much smaller in winter than in summer; however, the observed negative trend in the surface wind speed at the urban stations in winter (−0.25 m s\(^{-1}\) decade\(^{-1}\)) is nearly the same as that in summer (−0.26 m s\(^{-1}\) decade\(^{-1}\)). Hence, the wind speed reduction observed in South Korea is hardly attributable to vegetation changes.

Kim and Paik (2015) showed a decreasing trend of −0.13 m s\(^{-1}\) decade\(^{-1}\) over South Korea in an analysis of long-term (1954–2003) changes in wind speeds at 14 stations. Because most of these stations are located in urban areas, their results may be heavily affected by urbanization. Unlike their study and the results for urban stations presented above, the wind speed shows increasing trends at rural stations (figure 2). The increasing trend at the rural stations are of smaller magnitudes (0.04 ∼ 0.11 m s\(^{-1}\) decade\(^{-1}\)) than the decreasing trend at the urban stations and is not statistically significant (p > 0.05) for some seasons. The circulation change associated with the climate change could cause wind speed increases over some regions (Eichelberger et al 2008); enhanced land–sea thermal gradients under climate change can also lead to the wind speed increases (Karnauskas et al 2017), especially in coastal regions. The mechanisms behind the increased wind speed at the rural stations in South Korea need further studies. Nonetheless, the opposite surface wind speed trends between the urban and rural stations are consistent with the urbanization effect on wind stilling.

To further explore the physical processes related to the observed surface wind speed trend, we analyzed the relationship between the annual wind speed trend and the yearly gust factor trend (figure 3(a)). The gust factor can be related to the local roughness length, and can be obtained from routine wind observations at meteorological stations (Wever 2012). There is a significant (p < 0.001) negative relationship between the annual wind speed trend and the gust factor trend. The annual surface wind speed trend decreases as the gust factor trend increases. Considering the relationship between the gust factor and the local surface roughness (see Data and Methods), the increase in gust factor translates into the increase in the local surface roughness. Therefore, the observed surface wind decreases in South Korea can be explained by the increase in the local surface roughness. Both
urbanization and vegetation increases can increase the surface roughness (Wever 2012). As discussed above, vegetation increases mainly occur in the growing season, and thus cannot be related to the observed season-independent weakening of the surface wind. In addition, vegetation in the urban area likely decrease as urban development progresses. Rapid urbanization has occurred during the analysis period in South Korea as showed by the doubling of the number of housing units (figure 2(a)). We analyzed the urbanization effect on the observed gust factor changes using the population density as a proxy (figure 3(b)). A statistically significant ($p < 0.05$) positive relationship was found between the gust factor trend and the population density indicating that urbanization is likely the main cause for the local surface roughness increases in South Korea.

4. Discussions and conclusions

The influence of urbanization on the surface wind speed has been investigated in previous studies based on observations (Li et al 2011, 2018, Wu et al 2017, Liu et al 2018, Peng et al 2018) and model simulations (Hou et al 2013, Li et al 2019b). Contrasting the observed data at the urban stations against those at the rural (or suburban) stations, a typical method (Wu et al 2018) for identifying the effects of urbanization, reveals that the urban stations show larger decreases in the surface wind speed than the rural (or suburban) stations (Li et al 2011, 2018, Peng et al 2018). Some sites of low population density also show negative wind speed trends (figures 1(a) and (b)). Examinations of the details of these sites and employing nighttime light as an alternative proxy for
urbanization suggest that in some case the population density is not a suitable proxy for urbanization. For example, wind speed has decreased at a rate of $-0.33 \text{ m s}^{-1} \text{ decade}^{-1}$ at the Sokcho (38.2509 $^\circ$N, 128.5647 $^\circ$E) station with a population density of only 40.8 people km$^{-2}$, the number corresponding more to a rural station than an urban station. Despite the small population density of the site, the nighttime light has substantially increased from 1993 to 2013 (figure 4). The gust factor also shows an increasing trend (0.26 decade$^{-1}$) at this site. These indicate that this site has been substantially affected by urbanization despite its small population density. Although the population density can be a good proxy for urbanization in general, other proxies need to be considered for a more accurate determination of urbanizations.

It is also noted that simple comparisons of the observed data at the urban and the rural stations may underestimate the impacts of urbanization, as rural stations also may have been partially affected by urbanization as they grow in populations and infrastructure (Li et al 2018). The observed rate of decline in the surface wind speed at the urban stations across South Korea estimated in this study is comparable to that in Hong Kong ($-0.6$ and $-0.16 \text{ m s}^{-1} \text{ decade}^{-1}$ for 1968–1995 and 1996–2017, respectively; see Peng et al 2018), Beijing ($-0.29 \text{ m s}^{-1} \text{ decade}^{-1}$ averaged at 15 surface levels during 1991–2011; see Liu et al 2018), and eastern China ($-0.16 \text{ m s}^{-1} \text{ decade}^{-1}$ during 1991–2015; see Li et al 2018). It is noteworthy that the wind speed trends at the urban stations are opposite to those at the rural stations. This suggests that the weakening of winds by urbanization has dominated the strengthening effects of the climate change in determining the recent surface wind speed trends in South Korea. This may affect projections of future surface winds and associated fluxes over land surfaces. Climate simulations in the Coupled Model Intercomparison Project Phase 3 and 5 (CMIP3 and CMIP5) generally underestimate the rate of decline in surface wind speed by an order of magnitude (Jiang et al 2017).

Analyses of the recently released CORDEX-EA phase 2 model data show that the magnitude of the simulated surface wind speed trends in South Korea is much smaller than the observed values (figure 5). Especially, the simulations show no relationship between the surface wind speed trends and urbanization (figure 5) in contrast to the observations. These results suggest that the models participated in the CORDEX-EA phase 2 experiments are not capable of replicating the observed effects of urbanization in the surface wind speed. This indicates that the historical simulations and future projections in the CORDEX-EA may overestimate the wind speed in the urban area, a great concern in applying the CORDEX data to assess the impacts of climate change on wind-sensitive sectors (Lake et al 2017). Thus, our results highlight the need to improve parameterizations for more accurate representations of the effects of urbanization as well as the effects of other land use and land cover types.

Our results show that urbanization weakens the surface wind speed. This has important implications for urban developments and our lives. Firstly, it exacerbates the problem of urban air pollution.

Figure 5. Relationships between observed and modelled wind speed trends with population density of 2010. Brown dots indicate the trends of observation at meteorological stations, and open circles indicate the trends from the model simulations of CORDEX-EA.
et al (2019b). Climate projections suggest that future weather conditions will be more conducive to forming severe haze (Cai et al 2017); reduced wind speed due to urbanization will worsen air quality in urban regions. Thus, it is critical to understand clearly the urbanization effects on winds and their feedback to the urban environment. Secondly, because reduced evaporative cooling in cities is among the dominant drivers of the urban heat island (UHI) phenomenon (Zhao et al 2014, Li et al 2019a), the reduction in wind speed by urbanization and associated reduction in evaporation will further enhance UHI (McVicar et al 2012). In conclusion, our results emphasize the importance of considering the wind-related urbanization effects in addition to the traditional hotspot—temperature, for better understanding and predicting of the environment change in urban areas.

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Data availability statements

The meteorological data is available from the Korea Meteorological Administration (https://data.kma.go.kr). The population density data is available from the Gridded Population of the World (GPW) version 4 dataset (http://dx.doi.org/10.7927/H4NP22DQ). The housing data is available from the Korean Statistical Information Service (http://kosis.kr/). The DMSP-OLS (Operational Linescan System of Defense Meteorological Satellite Program) nighttime light data is available from the website (https://ngdc.noaa.gov/eog/). The CORDEX-EA data is available from their website (http://cordex-ea.climate.go.kr/cordex/).

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