LETTER • OPEN ACCESS

An analysis of the urbanization contribution to observed terrestrial stilling in the Beijing–Tianjin–Hebei region of China

View the article online for updates and enhancements.

Environmental Research Letters

CrossMark

LETTER

An analysis of the urbanization contribution to observed terrestrial stilling in the Beijing–Tianjin–Hebei region of China

Jun Wang[1] , Jinming Feng[1], Zhongwei Yan[1,2], Yuan Qiu[1] and Lijuan Cao[3]

[1] Key Laboratory of Regional Climate-Environment for Temperate East Asia (RCE-TEA), Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029, People's Republic of China
[2] University of Chinese Academy of Sciences, Beijing 100049, People's Republic of China
[3] National Meteorological Information Center, China Meteorological Administration, Beijing 100081, People's Republic of China

E-mail: wangjun@tea.ac.cn

Abstract

Decreases in terrestrial near-surface wind speed (*NSWS*) were documented in many regions over the past decades. Various drivers have been proposed for this terrestrial stilling, such as weakening of ocean-land pressure gradients related to climate change and increased surface roughness linked to vegetation growth; but none have been robustly established as the cause. A plausible reason for this quandary is that the local impact of urbanization on *NSWS* has been overlooked. Here, we used homogenized *NSWS* records from *in situ* weather stations and a satellite-based dynamic urban–rural classification scheme to quantitatively assess the contribution of urbanization to observed terrestrial stilling during 1980–2016 over the Beijing–Tianjin–Hebei region of China. Results suggested that urbanization contributed approximately 8% to the observed decrease in the regional *NSWS* in urban areas, implying that urbanization played a minor role in terrestrial stilling, even in this rapidly developing region. The largest *NSWS* changes related to urbanization occurred in winter, followed by spring, autumn, and summer. Urbanization reduced the days with relatively strong winds but increased the days with light and gentle winds. We found that except for the Japanese 55 year reanalysis (JRA-55) dataset, none of the common reanalysis products reproduced the observed *NSWS* trends in urban or rural areas. However, this could be because of JRA-55's intrinsic negative bias in *NSWS* trends over land. Thus, regional terrestrial *NSWS* trends derived from reanalysis products deserve careful examination.

1. Introduction

Changes in wind have broad environmental and socio-economic implications, affecting the air quality in economically developed regions (Cai *et al* 2017, Pei and Yan 2018), the surface evaporation (Rayner 2007, McVicar *et al* 2012) and the wind energy resource (Pryor and Barthelmie 2010, Rasmussen *et al* 2011). As the climate warms, near surface wind speed (*NSWS*) over land, commonly referred to the 10 m wind speed, has declined over the past decades (Tuller 2004, Smits *et al* 2005, Mahowald *et al* 2007, McVicar *et al* 2008, Pryor *et al* 2009, Vautard *et al* 2010, Jiang *et al* 2010b, Wu *et al* 2018). Roderick *et al* (2007) firstly referred to this widespread phenomenon as 'terrestrial stilling'. By synthesizing previous studies reporting *NSWS* changes around the world, McVicar *et al* (2012) indicated that the average trend in *NSWS* was -0.14 m s^{-1} decade^{-1} in areas (e.g. North America, Europe, East Asia, Oceania) having more than 30 sites with the length of data more than 30 years.

Observed changes in *NSWS* in China were consistent with many other mid-latitude regions, featuring a decline over recent decades (Xu *et al* 2006, Jiang *et al* 2010b, Niu *et al* 2010, Fu *et al* 2011, Guo *et al* 2011, Chen *et al* 2013, Lin *et al* 2013). Previous studies have proposed various large-scale drivers and physical mechanisms to explain the causes of terrestrial stilling in China. Xu *et al* (2006) and Niu *et al* (2010) suggested that the *NSWS* in China, associated with the East Asian

monsoon, exhibited declines in either summer or winter, which was probably linked to regional radiative forcing induced by increases in greenhouse gas concentrations and air pollutants. Meanwhile, Fu *et al* (2011), Lin *et al* (2013) and Chen *et al* (2013) suggested that natural climate variability, such as the Pacific Decadal Oscillation and Arctic Oscillation, may be the primary driver for *NSWS* change in China. Recently, Zeng *et al* (2019) found a reversal in global terrestrial wind speed and attributed it to internal decadal atmosphere-ocean oscillations. Compared with the strong decline in *NSWS* observed at *in situ* weather stations, *NSWS* trends derived from reanalysis products and radiosonde records are much weaker (Vautard *et al* 2010, Chen *et al* 2013, Lin *et al* 2013). If anthropogenic forcings and natural climate variability are the main causes of *NSWS* change in China, then reanalysis and radiosonde data should produce similar *NSWS* changes to ground station observations. In addition, neither global nor regional climate models reproduce the historical *NSWS* changes over the past decades in China (Jiang *et al* 2010a, Bichet *et al* 2012), partly because these state-of-the-art models do not fully take into account the effects of changing surface characteristics in China (Chen *et al* 2012).

Several studies suggested that weakening *NSWS* over land can also be ascribed to an increase in surface roughness (Vautard *et al* 2010, Bichet *et al* 2012, Wu *et al* 2016, 2017, Zhang *et al* 2019b). Vautard *et al* (2010) suggested that surface roughness increases related to forest growth markedly reduced *NSWS* by 40%–60% in China during 1979–2008. Bichet *et al* (2012) also suggested that by only increasing surface roughness in climate models, the observed wind stilling in China could be reproduced. However, it should be noted that an increase in surface roughness may not be primarily or solely caused by vegetation. Using three atmospheric global climate models forced by historical sea surface temperature and sea ice records, Zeng *et al* (2018) found that the simulations with realistic vegetation changes could not reproduce the observed weakening of *NSWS* over land, including over China, implying that enhanced vegetation growth was not a primary driver for *NSWS* changes there. Recognizing the minor role of vegetation growth in the observed declines in *NSWS* in China, coupled with the knowledge that urbanization can also increase surface roughness, led us to assess the impact of urbanization on terrestrial stilling in rapidly urbanizing regions.

Urbanization modifies *NSWS* not only by changing surface aerodynamic characteristics, but also through enhancing urban heat island circulation (Bornstein and Johnson 1977). Given that a large proportion of *NSWS* observations are from meteorological stations located in urban areas, it is pertinent to consider whether the detected *NSWS* changes were affected by local urbanization. By applying the 'observation minus reanalysis' (OMR) method (Kalnay and Cai 2003), a recent study found that the underlying surface changes close to observing stations, mostly induced by urbanization, contributed mostly to the observed decline in *NSWS* over East China during 1992–2013 (Li *et al* 2018). The rationale of the OMR method is that reanalysis data are considered to include 'perfect' large-scale climate change signals but exclude local impacts of land use and cover changes (LUCC). Therefore, the difference between the observed and reanalysis climatic trends can be attributed to the effects of LUCC, such as urbanization. However, Jiang *et al* (2010b) estimated that the difference in the decline in *NSWS* between urban and rural stations in China was only -0.01 m s^{-1} decade^{-1}. It is noted that Jiang *et al* (2010b) classified urban and rural stations roughly using administrative divisions and hypothesized that urbanization impacts on *NSWS* for stations in provincial cities and other large cities were more profound than those in small cities and rural areas. However, the local impact of urbanization on *NSWS* may not be directly related to the extent of whole city, and may be very sensitive to changes in local neighboring environments (Peng *et al* 2018). In addition, rapid urbanization in China has led to very fast transitions from rural to urban environments around *in situ* weather stations. These issues can be addressed by adopting a dynamic urban–rural classification scheme, based on high-resolution satellite observations that accurately capture regional spatiotemporal patterns of urbanization within China.

The aim of this study was to quantitatively assess the contribution of urbanization to regional terrestrial stilling in rapidly urbanizing regions. We used homogenized *NSWS* records from *in situ* meteorological stations within the Beijing–Tianjin–Hebei region of China and employed a dynamic urban–rural station classification scheme to examine urban–rural contrasts in trends in *NSWS* for 1980–2016. Specifically, we focused on the seasonality of impacts of urbanization on *NSWS* and compared frequency changes for different categories of winds. To determine the accuracy of reanalysis products in reproducing the historical *NSWS* changes, we quantified the uncertainty in long-term *NSWS* trends derived from different-generation reanalysis products. The rest of this paper is organized as follows. The data and method are described in section 2, and the results are presented in section 3, followed by the conclusions in section 4.

2. Methods

2.1. Observation and reanalysis datasets
Daily *NSWS* observations for 1980–2016 from 223 national stations in the Beijing–Tianjin–Hebei region (36°N–41°N; 114°E–119°E) were used in this study, compiled by the National Meteorological Information

Center of China Meteorological Administration. The raw *NSWS* time series were quality-controlled and homogenized using the *RH*-tests version 3 software package (Wang and Feng 2010). The *RH*-test algorithm contains two change-point detection approaches: a penalized maximum *t* test and a penalized maximum *F* test. The former test is good for detecting non-climatic changes (e.g. station relocation, changes in the observing system), when a reference series reflecting the regional *NSWS* change is available; while the latter test is suitable for sparse observing stations, when a reference series is lacking or distant (Wan *et al* 2010). Given the high station density in the region, we used a penalized maximum *t* test that accounts for the first-order autocorrelation to detect the inhomogeneities in individual station *NSWS* time series, which was further validated by detailed metadata information. Then, quantile-matching adjustment method that takes into account high-order inhomogeneities was applied to adjust the abrupt shifts related to non-climatic changes in *NSWS* time series. We treated a station as missing, if it had more than 1% missing values (i.e. $365 \times 37 \times 0.01 \approx 135$ d), and it was discarded from the following analyses. A total of 186 stations were selected. Their individual missing values were replaced by their corresponding climatological means for other available values of this specific calendar day across the entire study period.

To consider the uncertainties in the reanalysis products and their potential capacity to reproduce the regional mean *NSWS* change, we compared observed *NSWS* time series with those derived from a variety of different-generation reanalysis products. Table S1 presents the details of these reanalysis products. The first- and second-generation reanalysis products used in this study were from the National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) global reanalysis (NCEP-NCAR; Kalnay *et al* 1996), and the NCEP/Department of Energy (DOE) global reanalysis (NCPE-DOE; Kanamitsu *et al* 2002), respectively. The third-generation reanalysis datasets were from the European Reanalysis Interim reanalysis (ERA-Interim; Dee *et al* 2011), the Modern-Era Retrospective analysis for Research and Applications version 2 (MERRA2; Gelaro *et al* 2017), and the Japanese 55 year reanalysis (JRA-55; Kobayashi *et al* 2015). The newest generation reanalysis used was ERA-5. We also evaluated three versions of the Twentieth Century Reanalysis, generated by the US National Oceanic and Atmospheric Administration (NOAA; Compo *et al* 2011). To facilitate comparison, we used a bilinear interpolation algorithm to linearly interpolate the gridded reanalysis monthly mean *NSWS* time series to the geographical locations of *in situ* weather stations. The calculation procedure used for the regional mean *NSWS* time series based on reanalysis was the same as that based on observations.
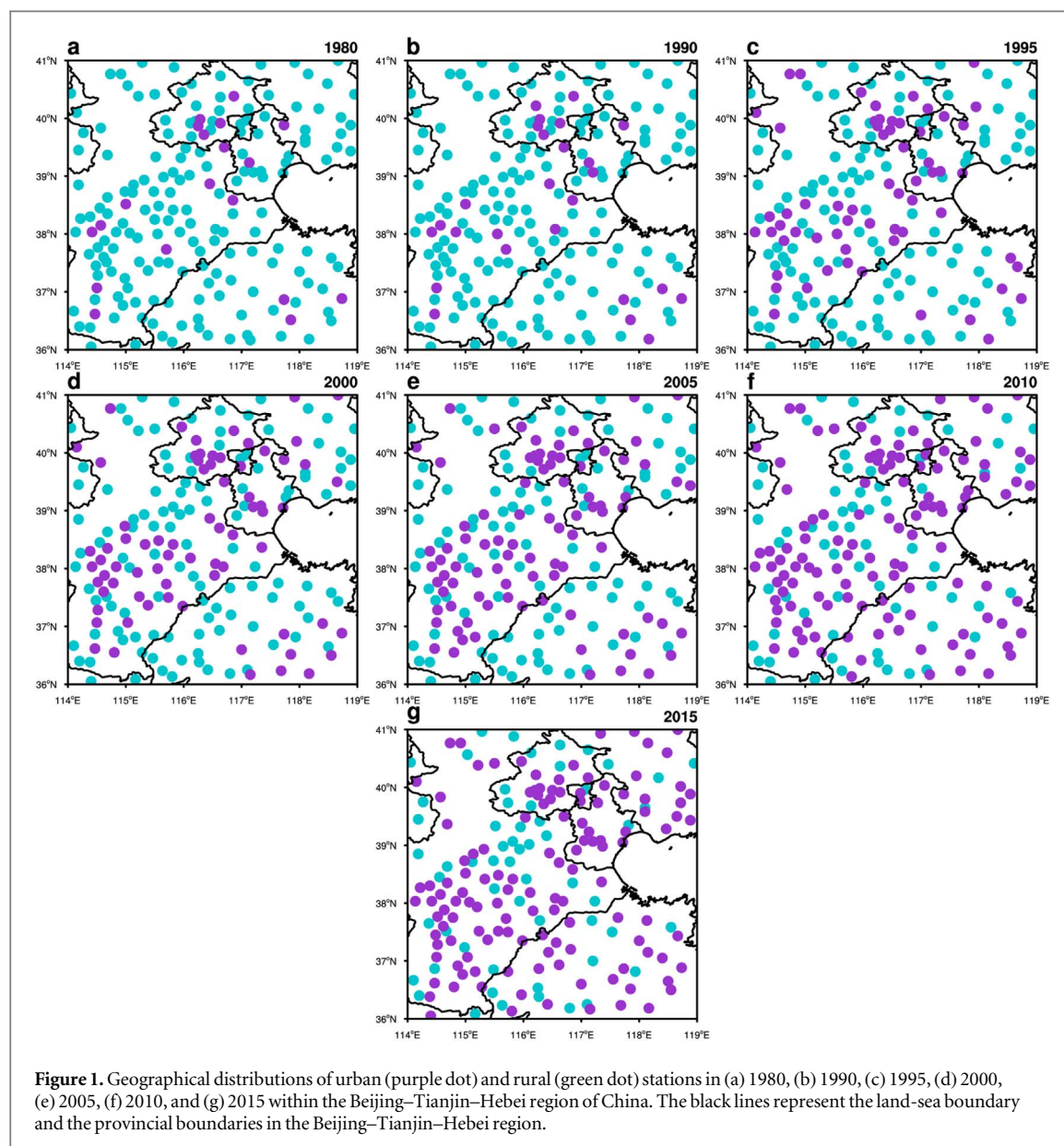
2.2. Dynamic urban–rural classification scheme

We used satellite-based temporally varying LUCC observations for China to dynamically identify urban and rural stations; these were generated and provided by the Data Center for Resources and Environmental Sciences of Chinese Academy of Sciences (http://resdc.cn/). This dataset was produced, based on the Landsat Thematic Mapper/Enhanced Thematic Mapper satellite images, with high spatial resolutions of 100 m, for seven representative years: 1980, 1990, 1995, 2000, 2005, 2010 and 2015 (Liu *et al* 2014). Following the methods proposed by previous studies (Ren *et al* 2010, Ren and Zhou 2014, Liao *et al* 2018), we calculated the fraction of urban land cover (i.e. built-up areas in cities, counties and towns) for each year within a 2 km circular buffer region surrounding each station. When the urban land fraction of one station exceeded 33%, we treated it as an urban station. Several studies have used this procedure to select the reference stations in China (e.g. Ren and Zhou 2014, Liao *et al* 2018). Ren and Zhou (2014) suggested that this classification criterion could account for the different influences on station observations from local anthropogenic activities (e.g. urbanization). Temporally, we divided the whole analysis period into seven consecutive episodes: 1980–1989, 1990–1994, 1995–1999, 2000–2004, 2005–2009, 2010–2014 and 2015–2016. We used the urban land fraction in the starting year of each episode to determine the stations' categories (i.e. urban or rural) dynamically. Results of this dynamic urban–rural station classification are illustrated in figure 1.

2.3. Contribution of urbanization to the observed near-surface wind speed changes in urban areas

To eliminate the effect of the climatological mean on the construction of the regional mean *NSWS* time series, we calculated the daily *NSWS* anomalies relative to the climatological annual cycle (calculated based on the whole study period) for each station. To estimate the contribution of urbanization to the observed *NSWS* change in urban areas and eliminate statistical biases linked to the uneven distribution of stations, we divided the region into four $2.5° \times 2.5°$ grids. For each grid, we computed the average *NSWS* time series separately for urban and rural stations for each episode. Then, according to previous studies (e.g. Mann *et al* 1998, Cohen *et al* 2014), we constructed regional mean urban and rural *NSWS* time series for the Beijing–Tianjin–Hebei region by weighting each grid's time series by the cosine of its latitude. We considered their differences in the long-term (i.e. the period with all the years) *NSWS* trends as the impact of urbanization in urban areas. To reveal the seasonality of *NSWS* trends and estimate any related urbanization impacts, we calculated both seasonal mean urban and rural *NSWS* anomalies time series, based on conventional practice, for winter: December–February;

Figure 1. Geographical distributions of urban (purple dot) and rural (green dot) stations in (a) 1980, (b) 1990, (c) 1995, (d) 2000, (e) 2005, (f) 2010, and (g) 2015 within the Beijing–Tianjin–Hebei region of China. The black lines represent the land-sea boundary and the provincial boundaries in the Beijing–Tianjin–Hebei region.

spring: March–May; summer: June–August; and autumn: September–November. A detailed description of this procedure can be found in supplementary note 1, which is available online at stacks.iop.org/ERL/15/034062/mmedia.

2.4. Definition of different categories of windy days

In addition, we estimated the frequency trends for different categories of windy days and quantified their urbanization impacts. We defined light, gentle, moderate, and strong windy days, as days with wind speeds lower than their historical 25th percentile, higher than their historical 25th percentile but lower than their historical 50th percentile, higher than their historical 50th percentile but lower than their historical 75th percentile, and higher than their historical 75th percentile, respectively. We determined these daily-based percentiles for a specific calendar day by sorting historical (1980–2016) 15 d *NSWS* samples around this day (7 d before and after; reflecting data for

$15 \times 37 = 555$ d). We estimated trends in the regional mean annual frequencies of different categories of windy days for urban and rural stations separately and treated their differences as the impact of urbanization in urban areas.

2.5. Trend estimator and its significance test

We computed observed and reanalysis trends for the regional mean *NSWS* in urban and rural areas using the non-parametric Theil–Sen's robust linear trend estimator (Theil 1950, Sen 1968) and determined their corresponding 95% confidence intervals based on Hollander and Wolfe (1973). We conducted non-parametric Mann–Kendall tests of the null hypothesis of these trends of each station at the significance level of 0.05 (Mann 1945, Kendall 1975). We also tested the significance of a trend in each kind of regional mean time series and the time series of urban–rural differences at the significance levels of 0.01, 0.05 and 0.1 using the non-parametric Mann–Kendall tests.
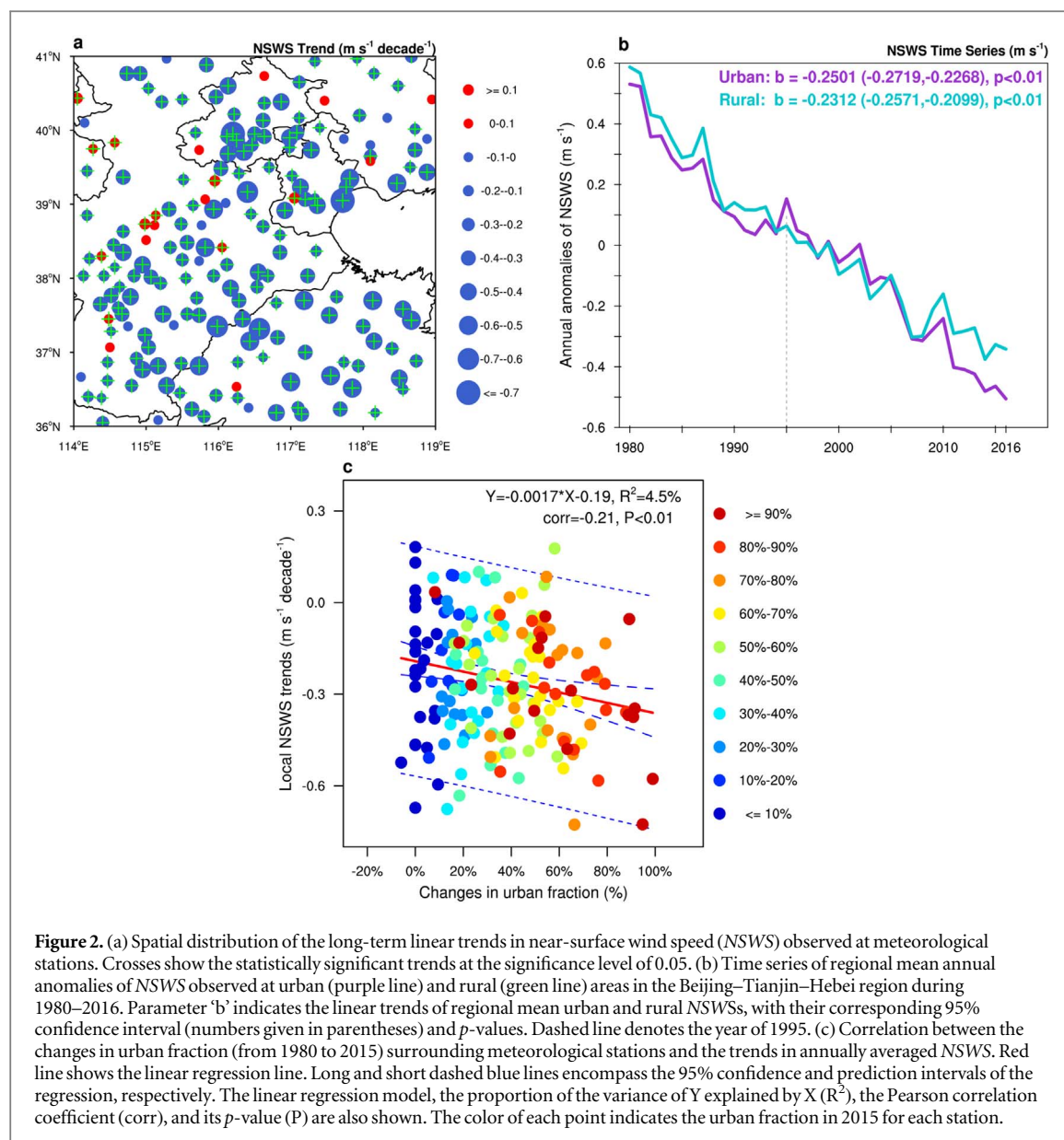
Figure 2. (a) Spatial distribution of the long-term linear trends in near-surface wind speed (*NSWS*) observed at meteorological stations. Crosses show the statistically significant trends at the significance level of 0.05. (b) Time series of regional mean annual anomalies of *NSWS* observed at urban (purple line) and rural (green line) areas in the Beijing–Tianjin–Hebei region during 1980–2016. Parameter 'b' indicates the linear trends of regional mean urban and rural *NSWS*s, with their corresponding 95% confidence interval (numbers given in parentheses) and *p*-values. Dashed line denotes the year of 1995. (c) Correlation between the changes in urban fraction (from 1980 to 2015) surrounding meteorological stations and the trends in annually averaged *NSWS*. Red line shows the linear regression line. Long and short dashed blue lines encompass the 95% confidence and prediction intervals of the regression, respectively. The linear regression model, the proportion of the variance of Y explained by X (R^2), the Pearson correlation coefficient (corr), and its *p*-value (P) are also shown. The color of each point indicates the urban fraction in 2015 for each station.

3. Results and discussion

3.1. Contribution of urbanization to the observed near-surface wind speed changes in urban areas

An analysis of the long-term linear trends of *NSWS* indicated a widespread wind stilling over the Beijing–Tianjin–Hebei region over the period 1980–2016 (figure 2(a)). The largest declines exceeding 0.7 m s^{-1} decade^{-1} occurred at two stations located within the cities of Beijing and Tianjin. An increase in *NSWS* was found at a few stations, but of much smaller magnitude. The regional average urban and rural *NSWS* time series were constructed and their corresponding long-term linear trends were estimated. As figure 2(b) shows, the regional mean annual anomalies of *NSWS* during 1980–2016 over the urban areas of the Beijing–Tianjin–Hebei region have decreased by 0.93 m s^{-1}. Urbanization should have contributed approximately 8% (0.07 m s^{-1}) to the observed decrease in the regional mean *NSWS* in urban areas. Thus, the

urbanization impact on the observed *NSWS* change was an order of magnitude less than the terrestrial stilling observed over the last four decades in urbanized areas of this region in China.

We also analyzed the decadal-scale trends in urban and rural *NSWS*s and compared their differences. We found large differences in the impacts of urbanization on *NSWS* change between earlier (1980–1995) and later (1996–2016) periods. The contribution of urbanization to the *NSWS* trend in urban areas was close to zero (0.01 m s^{-1} decade^{-1}) during the earlier period. However, urbanization-induced *NSWS* change in urban areas became profoundly negative (−0.11 m s^{-1} decade^{-1}) during the later period. This implies that urbanization influences on *NSWS* change during the later period are primarily responsible for the urbanization-related terrestrial stilling in the urban areas of Beijing–Tianjin–Hebei region. This result is consistent with historical urbanization trends in China over the last four decades, in which earlier and later periods witnessed relatively

slow and rapid urbanization processes, respectively (Wu *et al* 2015). As shown in figure S1(a), the later period also showed greater increases in stations' urban land cover ratios than during the earlier period. The consistent trend of observed *NSWS* in rural and urban areas during the earlier period could partly reflect increasing forest cover (including woodland, shrubland, sparse-forest and other forest lands) during this period in this region (figure S1(b)), which was linked to policy-driven afforestation, with a ban on deforestation and a return of cultivated lands to forests (Liu *et al* 2008). Related to rapid urban development, the ratio of forest land cover surrounding *in situ* weather stations decreased during the later period (figure S1(b)), reinforcing urbanization effects. Figure 2(c) shows the correlation between changes in urban land cover fraction surrounding meteorological stations from 1980 to 2015 and the observed trends in local *NSWS* over the whole study period. We found that there is only a weak correlation between the changes in urban fraction and the local *NSWS* trends with a small explained variance (only 4.5%), which further suggests that the impact of urbanization on the observed *NSWS* changes was minor over the last four decades in the Beijing–Tianjin–Hebei region of China.

3.2. Robustness tests

We conducted a series of sensitivity tests to validate the robustness of the estimated contribution of urbanization to the observed regional terrestrial stilling in urban areas (table S2). We first constructed the regional mean urban and rural *NSWS* time series using a static urban–rural classification scheme. We calculated the urban land-cover ratio within a 2 km circular buffer region surrounding each station for 2015, and considered any station having a fraction of urban land cover of more than 33% as urban during the entire study period. As shown in figure S2(a), the contribution of urbanization to the regional mean urban *NSWS* trend was estimated to be 20% (-0.20 versus -1.01 m s^{-1}). We noted that the magnitude of the urbanization contribution based on the static urban–rural classification was double that based on the dynamic one. As shown in figure S1(b), this difference could be related to forest growth during the earlier period around stations that became urbanized during the later period. Thus, the effect of forest growth on *NSWS* at earlier rural stations may be incorrectly ascribed to an effect of urbanization by a static classification scheme.

To test whether the estimated influence of urbanization was sensitive to urban fraction thresholds used in our classification, we recalculated the regional average *NSWS* time series for urban and rural areas by identifying urban stations as those having an urban land-cover ratio of greater than 20% within a 2 km buffer region. As figure S2(b) shows, we found that urbanization now contributed 11% to the regional mean *NSWS* trend observed in urban areas (-0.11

versus -0.94 m s^{-1}), which is closer to the initial estimate. In turn, we increased the urban fraction threshold to 40% and found that only 9% (-0.09 m s^{-1} versus -0.97 m s^{-1}) of the observed wind stilling in urban areas could be ascribed to urbanization in this case (figure S2(c)).

Next, we checked the sensitivity of the estimated urbanization effect on the *NSWS* trend to changes in the geographical scope of the circular buffer region around each station. We calculated the fraction of urban land-cover within a 1 km circular buffer region surrounding each station and considered any station with an urban fraction of more than 33% as urban. In this case, we found that urbanization only explained a decrease of 0.05 m s^{-1} in *NSWS* in urban areas, which was an order of magnitude much smaller than the observed change (-0.92 m s^{-1}; figure S2(d)). Then, we expanded the circular buffer region to a radius of 3-km and computed the urban fraction surrounding each station within this wider geographical scope. By increasing the screening standard around urban stations, we found that the contribution of urbanization to the observed wind stilling in urban areas was approximately 17%, which is slightly higher than the initial estimate (figure S2(e)).

Lastly, we explored the robustness of our results related to filling in missing values. We filled in missing values using a spatial biharmonic spline interpolation of the measurements from other stations. In this analysis, we found that only 8% of the observed *NSWS* trend could be attributed to the impact of urbanization (figure S2(f)). We also examined the temporal distribution of the missing values for each selected station and found that only three stations have the maximum length of continuous missing values more than or equal to one month (31 d). We removed these three stations in the analysis and found that the re-estimated impact of urbanization (without these stations) is close to that with these stations (-0.0214 versus -0.0189 m s^{-1} decade^{-1}; figure not shown). We also found the estimated impact of urbanization weighting by the cosine is almost the same as those with equal weights (-0.0189 versus -0.0206 m s^{-1} decade^{-1}; figure not shown), because the weights' difference between north and south grids is quite small (1.0174 versus 0.9826). Therefore, these robustness tests support the finding that the urbanization effect on the *NSWS* trend was an order of magnitude less than the terrestrial stilling observed in the urbanized areas of the Beijing–Tianjin–Hebei region over the past four decades.

3.3. The seasonality of urbanization impacts on the observed wind trends in urban areas

As for the annual mean *NSWS*, all four seasonal mean *NSWS*s over the Beijing–Tianjin–Hebei region also exhibited a decline during 1980–2016. The largest decreases in regional mean *NSWS* occurred in spring, followed by autumn, winter, and summer (figure 3). This result is consistent with the findings of Fu *et al* 2011 and
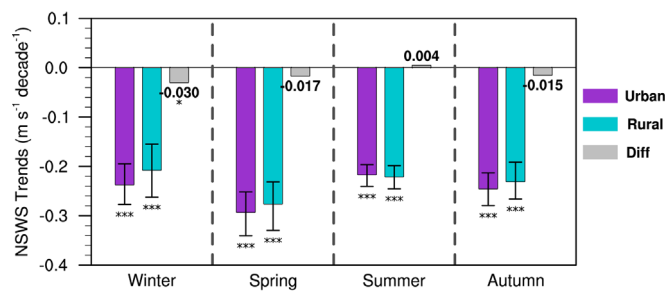
Figure 3. Linear trends in seasonal mean urban (purple bar) and rural (green bar) near-surface wind speed (*NSWS*) and their differences (Diff; gray bar) over the Beijing–Tianjin–Hebei region during 1980–2016. The vertical black bars indicate their corresponding 95% confidence intervals. The significances of trends are as follows: ***Significance at the 0.01 level; **Significance at the 0.05 level; *Significance at the 0.1 level. Blank indicates a trend is not significant.
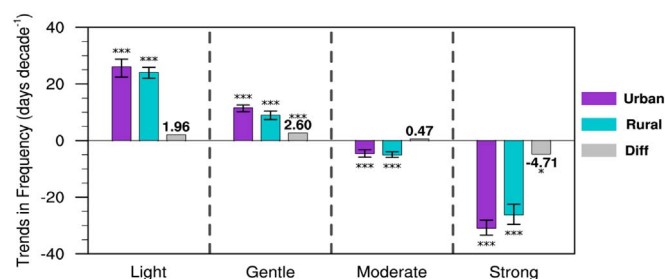
Figure 4. Linear trends in annual frequencies of different categories of winds (light, gentle, moderate and strong) observed in urban (purple bar) and rural (green bar) areas and their differences (Diff; gray bar) over the Beijing–Tianjin–Hebei region during 1980–2016. The vertical black bars indicate their corresponding 95% confidence intervals. The significances of trends are as follows: ***Significance at the 0.01 level; **Significance at the 0.05 level; *Significance at the 0.1 level. Blank indicates a trend is not significant.

Chen *et al* 2013, which also showed that spring witnessed the largest decreases in *NSWS* in China. Jiang *et al* (2010b) suggested that the *NSWS* decline in China was minimal in summer, and that winter experienced the most obvious terrestrial stilling, rather than spring. This may be associated with the difference in analysis periods. Jiang *et al* (2010b) focused on the period of 1956–2004, while this study concentrated on the last four decades. The recovery of the East Asian winter monsoon from the mid-2000s, as outlined by Wang and Chen (2014), may be responsible for the reduced decline in wintertime *NSWSs* over the past decade.

An analysis of urban–rural differences in *NSWS* trends for each season indicated that the largest urbanization-induced *NSWS* change occurred in winter, followed by spring, autumn and summer. Here, we propose two hypotheses for the seasonality of urbanization impacts on regional *NSWS* trends. Given that the influence of large-scale circulation and synoptic systems is much less dominant in summer than in winter, our first hypothesis is that urban breezes, induced by the urban heat island, play a more prominent role in summer in urban areas, negating the barrier effect of urban buildings on *NSWS* to some extent. Previous analysis based on numerical simulations also found a stronger response of *NSWS* to urbanization in winter than in summer (Hou *et al* 2013). Our second

hypothesis is that the effect of vegetation growth on *NSWS* in rural areas is more profound in summer than in winter, because boreal summer (winter) has the highest (lowest) vegetation productivity. A recent study has carried out a month-long simulation using the Weather Research and Forecast model and found that the westerly or northerly wind is decelerated by 0.3–1.5 m s^{-1} in the western and northwestern Beijing–Tianjin–Hebei region (mostly rural areas) due to the effects of afforestation (Long *et al* 2018). However, they did not assess the effects of afforestation for all the seasons. To explore the reasons for the seasonality of urbanization impacts on *NSWS* trends, high-resolution simulations incorporating information on urban developments and seasonal vegetation activities would be needed in further study.

3.4. Urbanization impacts on the frequencies of different kinds of windy days in urban areas

Given that the occurrence of different categories of winds has a great impact on air quality and the installation of wind energy facilities (Shi *et al* 2019), we analyzed the changes in frequencies of different kinds of windy days and quantified their relationship to urbanization. As shown in figure 4, the frequencies of the days with light and gentle winds have increased over the Beijing–Tianjin–Hebei region during
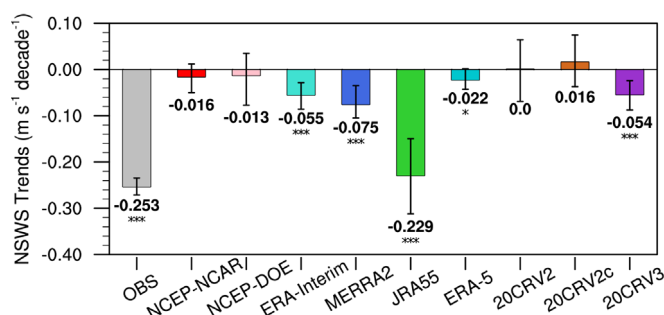
Figure 5. Linear trends in regional mean near-surface wind speed (*NSWS*) over the Beijing–Tianjin–Hebei region for 1980–2016, based on station observations (gray bar) and multiple reanalysis products (colored bars). The vertical black bars indicate their corresponding 95% confidence intervals. OBS, observations; NCEP-NCAR, National Centers for Environmental Prediction-National Center for Atmospheric Research global reanalysis; NCEP-DOE, NCEP/Department of Energy (DOE) global reanalysis; ERA-Interim, European Reanalysis Interim dataset; MERRA2, Modern-Era Retrospective analysis for Research and Applications version 2; and JRA55, Japanese 55 year reanalysis; ERA-5, newest ERA dataset; 20CRV2, 20CRV2c, 20CRV3, three versions of the Twentieth Century Reanalysis, generated by the US National Oceanic and Atmospheric Administration. The significances of trends are as follows: ***Significance at the 0.01 level; **Significance at the 0.05 level; *Significance at the 0.1 level. Blank indicates a trend is not significant.
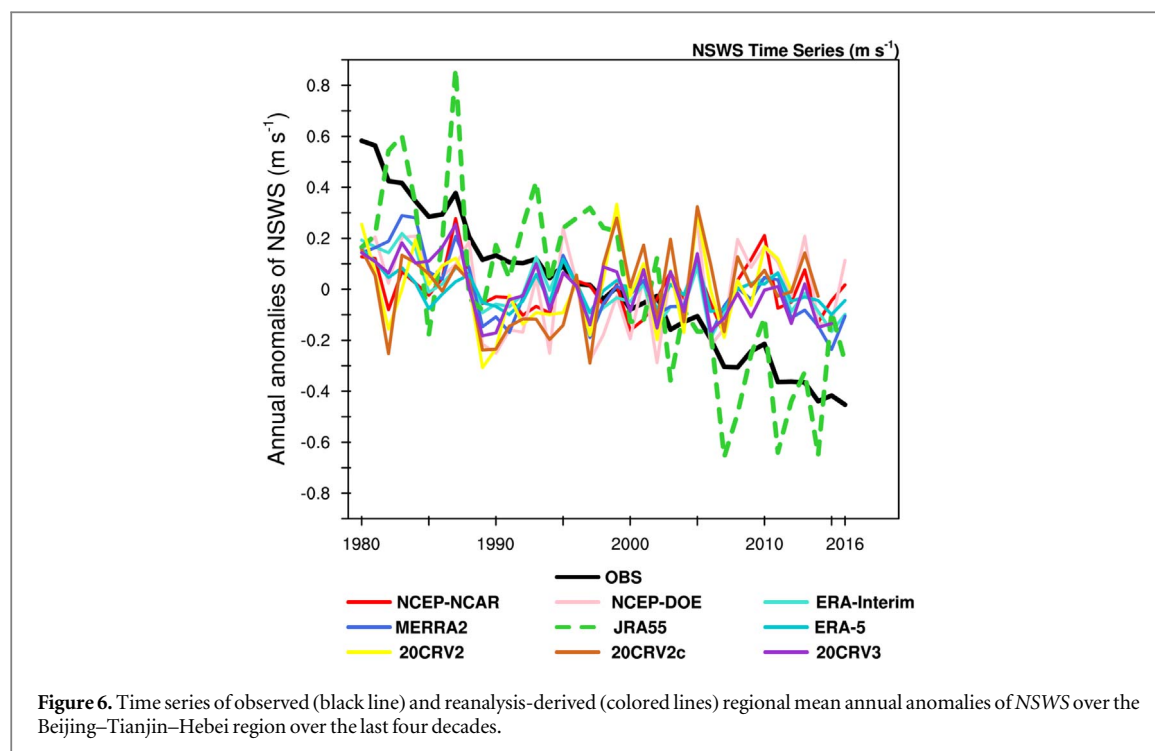
1980–2016, at the cost of a substantial decrease in the days with strong winds. This indicates that terrestrial stilling over the region was mainly linked to the huge reduction in strong windy days. By comparing the frequency trends for the four kinds of windy days between urban and rural areas, we found that urbanization increased the frequency of the days with light and gentle winds by about 2.0 and 2.6 d decade^{-1}, but reduced the days with strong winds by 4.7 d decade^{-1} in urban areas. We infer that during strong windy days, the change in *NSWS* is most likely controlled by large-scale synoptic factors. In these cases, local breezes induced by the urban heat island have a relatively low probability of accelerating air flows within urban areas. In contrast, for days with gentle or light winds, local circulation induced by the urban heat island would play a greater role in *NSWS* change, increasing the frequency of weaker windy days in urban areas.

3.5. Comparison of the observed and reanalysis wind trends

In addition to a comparison of urban and rural stations, some studies also used the OMR method to assess the urbanization impact on regional *NSWS* changes in China (Li *et al* 2018, 2019). Given that reanalysis products poorly represent many characteristics of historical *NSWS* changes in many regions (McVicar *et al* 2008, Pryor *et al* 2009, Chen *et al* 2013) as well as existing problems in the rationale of the OMR method (Trenberth 2004, Wang *et al* 2013, 2018), it is advisable to view the OMR-estimated urbanization contribution to the observed regional *NSWS* trend in urban areas with caution. To quantify uncertainties associated with reanalysis and assess the reliability of the OMR method in the estimation of the urbanization influence on urban *NSWS* change, we carried out a detailed comparison of observed *NSWS* trends with those derived from multiple reanalysis products.

Our results showed that except for JRA-55, none of the reanalysis products produced a similar *NSWS* trend to the station observations (figure 5). Comparatively, *NSWS* trends derived from third-generation reanalysis products (i.e. ERA-Interim, MERRA2, and JRA-55) appeared to be closer to the observations than first- and second-generation reanalysis products (i.e. NCEP-NCAR and NCEP-DOE). This difference is probably related to the continued improvements in the representation of critical physical processes in climate models, major advances in the data assimilation algorithms, and the greater number of observations used to produce third-generation reanalysis products (Dee *et al* 2011, Kobayashi *et al* 2015, Gelaro *et al* 2017). However, the regional mean *NSWS* trend derived from the newest generation reanalysis (ERA-5) was very small, despite its higher spatial resolution and more advanced assimilation system. Because the three versions of the Twentieth Century Reanalysis generated by NOAA assimilate only surface pressure observations and use monthly sea surface temperature and sea-ice distributions as boundary conditions within their climate models, coupled with an assimilation system comprising an ensemble Kalman Filter (Compo *et al* 2011), the *NSWS* trends derived from these reanalysis datasets were much weaker (20CRv3) and even positive (20CRv2, 20CRv2c). These results were valid for both urban and rural stations (figure S3).

As shown in figure 6, the JRA-55 reanalysis produced a similar *NSWS* trend to the observations, but exhibited much stronger interannual variability than the observed regional mean *NSWS*. This could be linked to the JRA-55's intrinsic deficiencies in deriving wind speeds over land. Torralba *et al* (2017) indicated that the height of the lowest atmospheric level within the JRA-55 climate model and assimilation system tends to be set too high over regions with high vegetation (trees), leading to underestimates of *NSWS* when interpolating wind speed from the lowest atmospheric level to 10 m altitude.

Figure 6. Time series of observed (black line) and reanalysis-derived (colored lines) regional mean annual anomalies of *NSWS* over the Beijing–Tianjin–Hebei region over the last four decades.

Comparisons of the observed and reanalysis *NSWS* trends suggested that the reanalysis-based estimates of *NSWS* trends involved much uncertainty, and that the climate models and assimilation systems used to generate these reanalysis data may have some deficiencies, such as the parameterization of surface layer processes. This implies that the OMR-estimated urbanization contribution to *NSWS* change was not only related to, but may have been irrelevant to, the impact of urbanization and other land-use changes on the *NSWS*. Thus, regional terrestrial *NSWS* trends derived from reanalysis and the OMR-estimated urbanization impacts deserve careful examination.

4. Conclusions

We used a dynamic urban–rural classification scheme to quantitatively assess the contribution of urbanization to the observed *NSWS* trend in urban areas of the Beijing–Tianjin–Hebei region in China for the period 1980–2016. We analyzed the urbanization impacts on seasonal mean *NSWSs* and the frequencies of different categories of windy days. Results suggested that urbanization influence only accounted for about 8% of the observed decrease in *NSWS* over the urban areas of this region. Clearly, the contribution of urbanization to regional terrestrial stilling was an order of magnitude smaller than the observed urban *NSWS* trend from *in situ* weather stations. This finding was validated by a variety of robustness tests. Hence, we concluded that urbanization played a minor role in terrestrial stilling, even in rapidly urbanizing regions. In addition, we found that the most profound urbanization effect on *NSWS* occurred in winter, followed by spring, autumn

and summer. Urbanization increased the frequencies of the days with light and gentle winds, at the expense of markedly decreasing strong windy days. Comparisons of the observed and reanalysis *NSWS* trends indicated that there were large uncertainties in the estimates of regional *NSWS* trends based on reanalysis data and that the OMR-based assessments of the effects of urbanization on *NSWS* may have been affected by the intrinsic deficiencies in reanalysis.

The minor role of urbanization in *NSWS* changes is supported by the spatial incoherence between the rates of urban growth and wind stilling over China and other mid- to high-latitude regions in the Northern Hemisphere. For instance, the distribution of the observed *NSWS* trends in China (Zhang *et al* 2019a, 2019b) showed that terrestrial stilling was mainly concentrated in northern and northeastern China, while *NSWS* changes in the most rapidly urbanizing areas of eastern China (e.g. Beijing–Tianjin–Hebei, Yangtze River Delta, Pearl River Delta, and North China Plain) were relatively small. At the global scale, besides northern China, rapid declines in *NSWS* were also observed in eastern North America, northeastern Europe, Siberia and even over the Tibetan Plateau (You *et al* 2014, Zeng *et al* 2018, Zhang *et al* 2019b), where urbanization is very slow or negligible. A recent study indicated that decadal-scale variations of *NSWS* was dictated by internal decadal climate variabilities, rather than by the local impact of urbanization (Zeng *et al* 2019). This is consistent with our key finding that urbanization played a minor role in terrestrial stilling, even in this rapidly developing region.

There are at least two major limitations of this study. The first one relates to the issue of data accessibility. We only analyzed the *NSWS* trend in one representative metropolitan region of China. Thus, some

findings may be region dependent. Over some highly urbanized regions, such as the city of Beijing, approximately 20% of the regional mean decline in *NSWS* was found to be caused by urbanization (Li *et al* 2011). At a larger scale, like the Northern Hemisphere land, the influence of urbanization on *NSWS* remains to be explored. The second one relates to a need for validation. Because all the analyses performed in this study were based on station observations and reanalysis data, a series of sensitivity experiments using high-resolution regional climate models could be used to confirm the findings of this study.

Despite these limitations, this study rejected the hypothesis that urbanization was a dominant driver of regional terrestrial stilling in the urban areas of the Beijing–Tianjin–Hebei region. Given the minor role of vegetation growth in *NSWS* change (Zeng *et al* 2018), it appears that the observed decrease in *NSWS* over this region was probably driven by the natural internal variability of the climate system and/or large-scale anthropogenic climate changes. In the case of JRA-55 reanalysis, we found that a clear understanding of the interactions and couplings among the surface layer, planetary boundary layer and free atmosphere was a prerequisite to accurately reproduce historical and future *NSWS* changes. Hence, further efforts should be focused on conventional climate model development to address their deficiencies in representing critical processes.

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID iDs

Jun Wang ⬤ https://orcid.org/0000-0002-9429-6484

References

Bichet A, Wild M, Folini D and Schär C 2012 Causes for decadal variations of wind speed over land: sensitivity studies with a global climate model *Geophys. Res. Lett.* **39** L11701

Bornstein R D and Johnson D S 1977 Urban–rural wind velocity differences *Atmos. Environ.* **11** 597–604

Cai W, Li K, Liao H, Wang H and Wu L 2017 Weather conditions conducive to Beijing severe haze more frequent under climate change *Nat. Clim. Change* **7** 257–62

Chen L, Li D and Pryor S 2013 Wind speed trends over China: quantifying the magnitude and assessing causality *Int. J. Climatol.* **33** 2579–90

Chen L, Pryor S C and Li D 2012 Assessing the performance of Intergovernmental Panel on Climate Change AR5 climate models in simulating and projecting wind speeds over China *J. Geophys. Res. Atmos.* **117** D24102

Cohen J *et al* 2014 Recent Arctic amplification and extreme mid-latitude weather *Nat. Geosci.* **7** 627–37

Compo G P *et al* 2011 The twentieth century reanalysis project *Q. J. R. Meteor. Soc.* **137** 1–28

Dee D P *et al* 2011 The ERA-Interim reanalysis: configuration and performance of the data assimilation system *Q. J. R. Meteor. Soc.* **137** 553–97

Fu G, Yu J, Zhang Y, Hu S, Ouyang R and Liu W 2011 Temporal variation of wind speed in China for 1961–2007 *Theor. Appl. Climatol.* **104** 313–24

Gelaro R *et al* 2017 The modern-era retrospective analysis for research and applications, Version 2 (MERRA-2) *J. Clim.* **30** 5419–54

Guo H, Xu M and Hu Q 2011 Changes in near-surface wind speed in China: 1969–2005 *Int. J. Climatol.* **31** 349–58

Hollander M and Wolfe D 1973 *Nonparametric Statistical Methods* (New York: Wiley) ch 9 pp 207–8

Hou A, Ni G, Yang H and Lei Z 2013 Numerical analysis on the contribution of urbanization to wind stilling: an example over the Greater Beijing metropolitan area *J. Appl. Meteor. Climatol.* **52** 1105–15

Jiang Y, Luo Y, Zhao Z, Shi Y, Xu Y and Zhu J 2010a Projections of wind changes for 21stCentury in China by three regional climate models *Chin. Geogr. Sci.* **20** 226–35

Jiang Y, Luo Y, Zhao Z and Tao S 2010b Changes in wind speed over China during 1956–2004 *Theor. Appl. Climatol.* **99** 421–30

Kalnay E and Cai M 2003 Impact of urbanization and land-use change on climate *Nature* **423** 528–31

Kalnay E *et al* 1996 The NCEP/NCAR 40 year reanalysis project *Bull. Am. Meteor. Soc.* **77** 437–70

Kanamitsu M, Ebisuzaki W, Woollen J, Yang S-K, Hnilo J J, Fiorino M and Potter G L 2002 NCEP-DOE AMIP-II Reanalysis (R-2) *Bull. Am. Meteor. Soc.* **83** 1631–43

Kendall M G 1975 *Rank Correlation Methods* (London: Charles Griffin & Co.)

Kobayashi S *et al* 2015 The JRA-55 reanalysis: general specifications and basic characteristics *J. Meteor. Soc. Japan* **93** 5–48

Li Y, Chen Y and Li Z 2019 Effects of land use and cover change on surface wind speed in China *J. Arid Land* **11** 345–56

Li Z, Song L, Ma H, Xiao J, Wang K and Chen L 2018 Observed surface wind speed declining induced by urbanization in East China *Clim. Dyn.* **50** 735–49

Li Z, Yan Z, Tu K, Liu W and Wang Y 2011 Changes in wind speed and extremes in Beijing during 1960–2008 based on homogenized observations *Adv. Atmos. Sci.* **28** 408–20

Liao W *et al* 2018 Stronger contributions of urbanization to heat wave trends in wet climates *Geophys. Res. Lett.* **45** 310–11

Lin C, Yang K, Qin J and Hu Y 2013 Observation coherent trends of surface and upper-air wind speed over China since 1960 *J. Clim.* **26** 2891–903

Liu J, Li S, Ouyang Z, Tam C and Chen X 2008 Ecological and socioeconomic effects of China's policies for ecosystem services *Proc. Natl Acad. Sci. USA* **105** 9477–82

Liu J *et al* 2014 Spatiotemporal characteristics, patterns, and causes of land-use changes in China since the late 1980s *J. Geogr. Sci.* **24** 195–210

Long X *et al* 2018 Does afforestation deteriorate haze pollution in Beijing–Tianjin–Hebei (BTH), China? *Atmos. Chem. Phys.* **18** 10869–79

Mahowald N M, Ballantine J A, Feddema J and Ramankutty N 2007 Global trends in visibility: implications for dust sources *Atmos. Chem. Phys.* **7** 3309–39

Mann H B 1945 Nonparametric tests against trend *Econometrica* **13** 245–59

Mann M E, Bradley R S and Hughes M K 1998 Global-scale temperature patterns and climate forcing over the past six centuries *Nature* **392** 779–87

McVicar T R, Van Niel T G, Li L T, Roderick M L, Rayner D P, Ricciardulli L and Donohue R 2008 Wind speed climatology and trends for Australia, 1975–2006: capturing the stilling phenomenon and comparison with near-surface reanalysis output *Geophys. Res. Lett.* **35** L20403

McVicar T R *et al* 2012 Global review and synthesis of trends in observed terrestrial near-surface wind speeds: implications for evaporation *J. Hydrol.* **416** 182–205

Niu F, Li Z, Li C, Lee K and Wang M 2010 Increase of wintertime fog in China: potential impacts of weakening of the Eastern Asian monsoon circulation and increasing aerosol loading *J. Geophys. Res.* **115** D00K20

Pei L and Yan Z 2018 Diminishing clear winter skies in Beijing towards a possible future *Environ. Res. Lett.* **13** 124029

Peng L, Liu J, Wang Y, Chan P, Lee T, Peng F, Wong M and Li Y 2018 Wind weakening in a dense high-rise city due to over nearly five decades of urbanization *Build. Environ.* **138** 207–20

Pryor S C and Barthelmie R J 2010 Climate change impacts on wind energy: a review *Renew. Sustain. Energy Rev.* **14** 430–7

Pryor S C, Barthelmie R J, Young D T, Takle E S, Arritt R W, Flory D, Gutowski W J, Nunes A and Roads J 2009 Wind speed trends over the contiguous United States *J. Geophys. Res.* **114** D14105

Rayner D 2007 Wind run changes: the dominant factor affecting pan evaporation trends in Australia *J. Clim.* **20** 3379–94

Rasmussen D J, Holloway T and Nemet G F 2011 Opportunities and challenges in assessing climate change impacts on wind energy—a critical comparision of wind speed projections in California *Environ. Res. Lett.* **6** 1–9

Ren G, Zhang A, Chu Z, Zhou J, Ren Y and Zhou Y 2010 Principles and procedures for selecting reference surface air temperature stations in China (in Chinese) *Meteor. Sci. Technol.* **38** 78–85

Ren G and Zhou Y 2014 Urbanization effect on trends of extreme temperature indices of national stations over mainland China, 1961–2008 *J. Clim.* **27** 2340–60

Roderick M L, Rotstayn L D, Farquhar G D and Hobbins M T 2007 On the attribution of changing pan evaporation *Geophys. Res. Lett.* **34** 251–70

Sen P K 1968 Estimates of the regression coefficient based on Kendall's Tau *J. Am. Stat. Assoc.* **63** 1379–89

Shi P, Zhang G, Kong F, Chen D, Azorin-Molina C and Guijarro J A 2019 Variability of wind haze over the Beijing–Tianjin–Hebei region tied to wind speed in the lower troposphere and particulate sources *Atmos. Res.* **215** 1–11

Smits A, Klein-Tank A M G and Können G P 2005 Trends in storminess over the Netherlands, 1962–2002 *Int. J. Climatol.* **25** 1331–44

Theil H 1950 A rank-invariant method of linear and polynomial regression analysis: III *Proc. K. Ned. Akad. Wein.* **53** 1397–412

Torralba V, Doblas-Reyes F J and Gonzalez-Reviriego N 2017 Uncertainty in recent near-surface wind speed trends: a global reanalysis intercomparison *Environ. Res. Lett.* **12** 114019

Trenberth K E 2004 Climate (communication arising): impact of land-use change on climate *Nature* **427** 213

Tuller S 2004 Measured wind speed trends on the west coast of Canada *Int. J. Climatol.* **24** 1359–74

Vautard R, Cattiaux J, Yiou P, Thépaut J and Ciais P 2010 Northern Hemisphere atmospheric stilling partly attributed to an increase in surface roughness *Nat. Geosci.* **3** 756–61

Wan H, Wang X and Swail V R 2010 Homogenization and trend analysis of Canadian near surface wind speeds *J. Clim.* **23** 1209–25

Wang J, Yan Z and Feng J 2018 Exaggerated effect of urbanization in the diurnal temperature range via 'observation minus reanalysis' and the physical causes *J. Geophys. Res. Atmos.* **123** 7223–37

Wang J, Yan Z, Jones P D and Xia J 2013 On 'observation minus reanalysis' method: a view from multidecadal variability *J. Geophys. Res. Atmos.* **118** 7450–8

Wang L and Chen W 2014 The East Asian winter monsoon: re-amplification in the mid-2000s *Chin. Sci. Bull.* **59** 430–6

Wang X L and Feng Y 2010 *RHtestsV3 User Manual* Climate Research Division, Atmospheric Science and Technology Directorate, Science and Technology Branch, Environment Canada, Toronto

Wu J, Zha J L and Zhao D M 2016 Estimating the impact of the changes in land use and cover on the surface wind speed over the East China Plain during the period 1980–2011 *Clim. Dyn.* **46** 847–63

Wu J, Zha J and Zhao D 2017 Evaluating the effects of land use and cover change on the decrease of surface wind speed over China in recent 30 years using a statistical downscaling method *Clim. Dyn.* **48** 131–49

Wu J, Zha J, Zhao D and Yang Q 2018 Changes in terrestrial near-surface wind speed and their possible causes: an overview *Clim. Dyn.* **51** 2039–78

Wu W, Zhao S, Zhu C and Jiang J 2015 A comparative study of urban expansion in Beijing, Tianjin and Shijiazhuang over the past three decades *Landscape Urban Plan.* **134** 93–106

Xu M, Chang C, Fu C, Qi Y, Robock A, Robinson D and Zhang H 2006 Steady decline of east Asian monsoon winds, 1969–2000: evidence from direct ground measurement of wind speed *J. Geophys. Res.* **111** D24111

You Q, Fraedrich K, Min J, Kang S, Zhu X, Pepin N and Zhang L 2014 Observed surface wind speed in the Tibetan Plateau since 1980 and its physical causes *Int. J. Climatol.* **34** 1873–82

Zeng Z, Piao S, Li L Z, Ciais P, Li Y, Cai X, Yang L, Liu M and Wood E F 2018 Global terrestrial stilling: does Earth's greening play a role *Environ. Res. Lett.* **13** 124013

Zeng Z *et al* 2019 A reversal in global terrestrial stilling and its implications for wind energy production *Nat. Clim. Change* **9** 979–85

Zhang R, Zhang S, Luo J, Han Y and Zhang J 2019a Analysis of near-surface wind speed change in China during 1958–2015 *Theor. Appl. Climatol.* **137** 2785–801

Zhang Z, Wang K, Chen D, Li J and Dickinson R 2019b Increase in surface friction dominates the observed surface wind speed decline during 1973–2014 in the Northern Hemisphere lands *J. Clim.* **32** 7421–35