Changes of probabilities in different wind grades induced by land use and cover change in Eastern China Plain during 1980–2011

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Abstract

The differences of the near-surface wind speed (SWS) between the frictional wind model (FWM) and the observation are used to reflect the impacts of land use and cover change (LUCC) on SWS in Eastern China Plain (ECP). Results show that LUCC makes the range of SWS narrow, which had significantly weakening effect to stronger wind than weaker wind. In addition, the decrease of probabilities for observed gentle breeze (GB), moderate breeze (MB), and wind speed greater than or equal to 8 ms⁻¹ (WSGE8) are more significant in large cities than that in small cities.

Keywords: near-surface wind speed; frictional wind model; LUCC; probabilities; wind grade

1. Introduction

Long-term change of the observed near-surface wind speed (SWS) can be affected by both of land use and cover change (LUCC) and variation of atmospheric circulation strength, which has relation with anthropogenic activities and climate change, respectively. SWS declined has been reported in recent decades in different regions, such as North America (Greene et al., 2012), East Asia, and Central Asia and Europe (Vautard et al., 2010). A slowdown of SWS was also reported in China (Guo et al., 2011). Possible reasons causing SWS decrease include the weakening of large-scale circulations (Sušelj et al., 2010), the variability of the pressure gradient force (PGF) (Klink, 2007), and the weakening of the monsoon driving force (Xu et al., 2006).

However, some researches tend to deduce the cause of SWS decrease to the rise of surface roughness, which induced mainly by anthropogenic LUCC and natural factors, such as urbanization (Zhang et al., 2010) and vegetation recovery (Vautard et al., 2010). Li et al. (2008) showed the significant decrease of SWS was induced by urbanization and other types LUCC over China in recent 40 years. The SWS in urban areas was also found to be lower than suburban regions in some megacities of China (Li et al., 2011). In any case, LUCC can affect SWS changes, but it’s difficult to isolate the impacts of LUCC on SWS and quantify its effects on SWS. In our former research, the frictional wind model (FWM) was used to separate the effects of PGF and LUCC on the long-term changes of SWS, in which the balance among the PGF, the Coriolis force, and the surface drag force was supposed (Wu et al., 2016).

To isolate the influences of LUCC on SWS, the drag coefficient was derived using FWM with observed SWS and PGF calculated from observed air pressure from 1980 to 2011. Then, FWM was used to calculate the wind speed when the drag coefficient was held constant at its value of the year with less LUCC for each station, such as 1980, the beginning of the period used in the article, and this wind speed was called the model wind speed (MWS). Obviously, the MWS included the effect from temporal change of PGF and excluded the influence of drag coefficient change induced by LUCC, because the constant drag coefficient was used in the calculation of MWS. Finally, the difference between MWS and observed SWS at each station could quantify the influence of LUCC on SWS (Wu et al., 2016).

The changes of probabilities for SWS are another way to recognize the long-term variations of SWS besides the speed value itself. Meanwhile, the knowledge of probability distribution of SWS is essential for surface flux estimation, wind power estimation, and wind risk assessments (He et al., 2010). The increase of the drag coefficient and associated slowdown in SWS over ECP have been demonstrated by Wu et al. (2016), but the impacts of LUCC on changes in probabilities for different wind grades are remain unclear. In this article, temporal characteristics in probabilities of different wind grades induced by LUCC are investigated further based on our former FWM.

2. Data and Methods

ECP region is selected as research region. Daily mean wind speed data from 93 meteorological stations on the
ECP during 1980–2011 are used. The 93 stations are selected according to the following criteria: (1) the elevation of the station is below 200 m above sea level, (2) it is a national standard station, and (3) the missing data account for less than 1% of the total period studies. The observed SWS data was operated, provided, and quality tested by the China Meteorological Administration (CMA, 2003), and that which passed the homogeneity test and were therefore regarded as the credible dataset in China (Feng et al., 2004). Typhoon track data from the Joint Typhoon Warning Center for 1980–2011 were used to remove wind speed observation data influenced by typhoons at stations located within a circle with a radius of 2° in latitude and longitude centered on the middle of each typhoon. Population data is obtained from the National Bureau of Statistics of China, which is available only for the year 2005. We define the large radius of 2°

of LUCC. The enclosed area under the probability distribution of observed SWS is distinctly higher than SWS. Comparing MWS with observed SWS, it can be found that the fine regional characteristics were enclosed in observed SWS than MWS. Meanwhile, observed SWS shows a pronounced decreasing trend with the average linear trend of −0.19 m s−1 (10 year)−1, which can pass the significant t-test at 95% level, but MWS presents an increasing trend with an average of 0.11 m s−1 (10 year)−1 in ECP. The correlation coefficient between MWS and SWS is −0.35, which fail to pass significant t-test at 99% level. These results show that spatial distribution and long-term changes of observed SWS are inconsistent with that of MWS, because the influence of LUCC on MWS is excluded, while this influence is included in observed SWS.

Probabilities of MWS and observed SWS were calculated using Equation (1) and fitted using Equation (2). The maximum of the probability density for observed SWS and MWS is 0.830 and 0.376, respectively, and the corresponding wind speed is 2.1 m s−1 and 2.0 m s−1, respectively. At the same time, the probability close to 2 m s−1 has been doubled by the influence of LUCC. The enclosed area under the probability days of i wind grade in i year. ni is the total observation days in i year. To fit the distribution of probability of wind speed, the kernel probability estimator is used, which is given in Equation (2) (Bowman and Azzalini, 1997).

\[
\text{PDF}(X) = \frac{1}{m} \sum_{i=1}^{m} w(X - X_i'; h)
\]

where, \(w\) is a probability density, which is symmetric with mean 0, and the variance of \(w\) is controlled by the parameter \(h\), which is called smoothing parameter. The detail information about \(w\) and \(h\) can be found in Bowman and Azzalini (1997). \(X = \{X_1, \ldots, X_m\}\) represents wind speed, \(X_i'\) denotes the center value of the interval in which \(X_i\) falls, and \(m\) denotes the integer part of \(S\), which is defined by Equation (3).

\[
S = \left( \max(X) - \min(X) \right) / 0.1; \quad (m = \text{int}(S))
\]

Additionally, Student’s t-test is used to determine the significance of the data, and the linear trend coefficient is computed using the least-squares method.

3. Results

3.1. Probability distribution of observed SWS and MWS

Distinct decrease of observed SWS in China has been demonstrated (Xu et al., 2006), and similar changes are also found in ECP. Figure 1 shows that observed SWS is bigger in inshore region than in inland region, which is also bigger in northern ECP than that in southern ECP with the highest value in Yangtze River Delta Region and the average of 2.3 m s−1 in whole ECP. On the other hand, the average of MWS reaches 2.8 m s−1, which is distinctly higher than SWS. Comparing MWS with observed SWS, it can be found that the fine regional difference is fewer in MWS than that in observed SWS, which means that more local characteristics were enclosed in observed SWS than MWS. Meanwhile, observed SWS shows a pronounced decreasing trend with the average linear trend of −0.19 m s−1 (10 year)−1, which can pass the significant t-test at 95% level, but MWS presents an increasing trend with an average of 0.11 m s−1 (10 year)−1 in ECP. The correlation coefficient between MWS and SWS is −0.35, which fail to pass significant t-test at 99% level. These results show that spatial distribution and long-term changes of observed SWS are inconsistent with that of MWS, because the influence of LUCC on MWS is excluded, while this influence is included in observed SWS.

Table 1. Six wind grades criteria.

| Grade | Name             | Wind speed (m s−1) |
|-------|------------------|--------------------|
| 1     | Calm             | 0–0.2              |
| 2     | Light air (LA)   | 0.3–1.5            |
| 3     | Light breeze (LB)| 1.6–3.3            |
| 4     | Gentle breeze (GB)| 3.4–5.4          |
| 5     | Moderate breeze (MB)| 5.5–7.9      |
| 6     | Wind speed greater than or equal to 8 m s−1 (WSGE8) | ≥8.0 |


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density function (PDF) curve of observed SWS and between the two half maximums, with the corresponding wind speed of 1.6 and 2.6 m s\(^{-1}\), respectively, reaches 67.1\% of the total area under the PDF curve (Figure 2(a)). While the wind speed corresponding to the two half maximums of the PDF curve of MWS is 1.2 and 3.5 m s\(^{-1}\) respectively, and the enclosed area between the two half maximums reaches 63.6\% of the total area under the curve (Figure 2(b)). It is obvious that LUCC made the PDF curve of observed SWS higher and narrower than that of MWS, at the same time wind speeds corresponding to the maximum of PDF curves are almost equal. Additionally, the probability of wind speed beyond 3.8 m s\(^{-1}\) is 1.8 and 20.6\% for observed SWS and MWS, respectively, and such distinct difference indicates that LUCC had significantly weakening effect to stronger wind than weaker wind, which implies observed SWS decrease was mainly induced by the decrease of strong wind episodes in ECP. Vautard et al. (2010) also addressed that LUCC decreased the strong wind more significantly than the weak wind over almost the northern hemisphere.

### 3.2. Temporal changes of probabilities in six wind grades

Temporal changes of probabilities of observed SWS in six wind grades are shown in Figure 3(a). The probabilities of observed LA and LB increase in recent
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Figure 3. Temporal changes of probabilities in six wind grades ((a), (b) represents probabilities of observed SWS, and MWS respectively, and (c) denotes probability difference between observed SWS and MWS. $R^2$ is correlation coefficient and the threshold of 99% confidence level is 0.21).

30 years with the linear trend of $1.1\% \text{ (10 year)}^{-1}$ and $3.0\% \text{ (10 year)}^{-1}$, respectively, and the probabilities of observed calm, GB, MB, and WSGE8 show decrease trends with linear trend of $-0.57\% \text{ (10 year)}^{-1}$, $-2.2\% \text{ (10 year)}^{-1}$, $-0.9\% \text{ (10 year)}^{-1}$, and $-0.4\% \text{ (10 year)}^{-1}$, respectively. All of these linear trends are significant at 99% confidence level. Figure 3(b) indicates the probabilities of calm, LA, and LB of MWS that show weak decreases at rates of $-0.09\% \text{ (10 year)}^{-1}$, $-1.2\% \text{ (10 year)}^{-1}$, and $-0.45\% \text{ (10 year)}^{-1}$, respectively, which are indistinctive at 99% confidence level. The probabilities of GB, MB, WSGE8 of MWS have increasing trends, in which MB and WSGE8 passed significant t-test at 99% level. These characteristics are inconsistent with that of observed SWS, which means that the wind speed excluding the influence of LUCC has indistinctive linear trends in weak wind grades, and has evident increase in strong wind grades. The temporal changes of the probability differences in the same wind grades between observed SWS and MWS (PDs) are shown in Figure 3(c), which was induced by LUCC purely, because the impact of LUCC on probability variations of MWS was excluded, and this influence was included in probability variations of observed SWS. The PDs of LA and LB show striking increases with linear rates of $2.4\% \text{ (10 year)}^{-1}$ and $3.4\% \text{ (10 year)}^{-1}$ respectively, which is bigger than the increase trends of LA and LB in observed SWS, respectively. On the contrary, the PDs of GB, MB, WSGE8 show decreasing trends of $-2.8\% \text{ (10 year)}^{-1}$,
In this article, the differences between FWM wind speed and observed SWS are used to reflect the impacts of LUCC on SWS. The changes of probabilities of six wind grades are investigated, in which the influences of LUCC on these probabilities are revealed, and the main results are as follows:

1. The observed SWS corresponding to the maximum probability is close to 2.0 m s$^{-1}$, and the probability close to 2.0 m s$^{-1}$ was increased more than twice from 0.376 to 0.830 by the influence of LUCC purely. Meanwhile, LUCC made the PDF curve of observed SWS much higher and narrower than that of MWS. The probability of wind speed beyond 3.8 m s$^{-1}$ is 1.8 and 20.6% for observed SWS and MWS, respectively, and such distinct difference shows that LUCC has significantly weakening effect to stronger wind than weaker wind, which means that observed SWS decrease was mainly induced by the decrease of strong wind episodes in ECP.

2. The most distinct characteristic for the changes of wind speed probabilities induced by LUCC included two aspects: one was the decreases of GB, MB, and WSGE8 and the increases of LA and LB significantly; the other one was the decrease of the probability of calm. The decrease trends of probabilities of GB, MB, and WSGE8 in large cities were more pronounced than that in small cities. Additionally, when excluding the influences of LUCC, the probabilities of weak wind speed grades should show insignificant linear trends, and the probabilities of MB and WSGE8 should have an evident increase rate of 0.69 % (10 year)$^{-1}$ and 0.40% (10 year)$^{-1}$, respectively.

This article mainly analysis the spatio-temporal characteristics of wind speed probabilities in six grades. However, some limitations and drawbacks should be mentioned. The turbulent vertical mixing and blocking effect of buildings are ignored in the FWM, so the physical mechanism of changes in probabilities for different wind grades should be further studied from the view of considering both dynamical and thermodynamic effects. LUCC in ECP region includes urbanization, farmland irrigation, returning farmland to forest, and other types, so it is necessary to quantify the influences of different type LUCC on SWS, but the effects of different LUCC type are hard to be distinguished in diagnostic analysis, and therefore this issue should be simulated by regional climate models in the near future.
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