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News & Views

The first 5-year Clean Air Action did increase the blue days in winter over Beijing-Tianjin-Hebei

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China has made great efforts to mitigate its long-standing environmental problem in recent years. In China, during the first 5-year Clean Air Action (2013–2017), remarkable reductions in primary pollutants such as SO_2 and fine particle matter ($PM_{2.5}$) have been achieved, especially in Beijing-Tianjin-Hebei (BTH) region [1,2]. After an explosive increase in concern for the Beijing Blue Events in 2015, the direct changes of blue days in China have received widespread attention [3,4]. However, less air pollution does not directly correspond to more blue skies. For example, days with high cloud cover or precipitation do not belong to blue days even though there is less air pollution. In addition, inconsistencies between dropping PM, unchanged low visibility events, and a remarkable increase of aerosol optical depth can be found even during the COVID-19 lockdown period [5–7]. Beyond that, unfavorable meteorological conditions counteract the effects of reduced emissions, resulting in frequent haze in the BTH region [8,9]. Therefore, emission reductions do not lead directly to more blue days.

Along with living standard enhancement, there is an advanced understanding that the blue day should be a day with blue sky and great air quality. Then a novel index named the Chinese Blue Days Index (CBDI) has been put forward to reveal the long-term spatiotemporal change of Chinese blue days [10]. However, the CBDI represents a national average level, which is inappropriate for BTH. In addition, earlier works that have focused on daily observational data are unable to rule out the effects of meteorology and air pollution.

In this study, to quantitatively distinguish the impact of aerosol on blue days from the meteorology, the effectiveness of the first 5-year Clean Air Action was assessed with using the Weather Research and Forecasting Model coupled with chemistry (WRF-Chem). Two sensitivity experiments were designed to investigate the effects of emission control strategies since 2013. The baseline experiment was the control simulation, which was conducted using anthropogenic emissions from 2017 and fully coupling aerosols and meteorology. The sensitivity experiment had the same configurations apart from anthropogenic emissions in 2012. Our experiments were conducted for two typical winters as the blue days in winter were the greatest concern. The first one is the last winter of the first 5-years Clean Air Action (i.e., Nov., Dec. 2017, and Jan. 2018), and the second one is the first winter after the first 5-years Clean Air Action (i.e., Nov. and Dec. 2018). Due to a lack of meteorological observations for model evaluation, our experiments did not include Jan. 2019. To focus on the BTH region, a triple nesting scheme was adopted (Fig. S1 online). Model configuration can be found in Table S1 (online). Detailed descriptions of the materials, methods, and model set are summarized in Supplementary materials.

The BTH blue days (BBDs) were firstly defined with three criteria following methods of Wang et al. [10]: no precipitation (Non-Prep), low cloud cover (LCC) $\leq$ 30%, and visibility $\leq$ 15 km at 14:00 BJT. The model performances were evaluated with *in situ* observations in BTH. The simulated temporal variations in visibility, LCC, and Non-Prep matched well with the observed ones, with correlation coefficient values higher than 0.88, 0.76, and 0.84 respectively (Fig. S2a–c online). Consequently, the simulated BBDs agreed well with the observed ones, with a correlation coefficient beyond 0.85 and a high accuracy beyond 80.23% (Fig. S2d online). These results indicated a good model performance. The spatial distributions of the simulated visibility, LCC, Non-Prep, and BBD showed patterns similar with the observed ones (Fig. S3 online). These results indicated the rationality of evaluating BBDs changes under different emission scenarios.

A widespread decline in anthropogenic emissions during 2013–2017 has been documented in many studies [1,11,12], while few have focused on the variations in winter. Based on the Multi-resolution Emission Inventory for China (MEIC v1.3; http://meicmodel.org) [13], the average emissions of primary aerosol species and trace gases during winter 2012 and 2017 in BTH are shown in Table S2 (online). Compared with 2012, the remarkable effectiveness of Clean Air Action can be detected for SO_2 and PM coarse

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(coarse mode of particle matter, calculated by the difference between PM_{10} and $PM_{2.5}$), whose amplitudes were reduced by more than 50% in winter for BTH. In contrast, minor declines were detected for NO_x and NH_3, which were below −26% and −15% respectively. These results were consistent with earlier studies [11,12,14]. Nonetheless, the emissions of volatile organic compounds (VOCs) still increased beyond 12.66% and 16.84% in Beijing and Tianjin and displayed a weak reduction below −6.58% in Hebei. These indicated that more attentions should be paid to the VOCs, NO_x, and NH_3 emission controls in the future.

Accordingly, a noticeable cut-emission effect on blue days is manifested in Fig. 1a. There was a comprehensive increase in BBDs in BTH and surrounding areas compared with that using emission in 2012, which was closely related to the cut-aerosol distribution (Fig. S4a–f online). In comparison, southeastern Beijing (over 45%), southern Tianjin (over 65%), and Hebei (over 65%) showed the highest increasing rate, with a maximum exceeding 53 d at an increasing rate of 157.14%. We also noticed a mismatch between the most apparent emission reduction in Beijing and the most obvious BBDs increase in southern Hebei (Fig. S5a online). This may be caused by the variations of VOCs and the corresponding climate-aerosol feedback effect, which needs further study.

Furthermore, the major contributor to the increase of BBDs was detected. With fixed meteorology, the simulation suggested that reduction of emissions would lead to significantly higher visibility (Fig. 1b, passing the 95% confidence level). In addition, the most notable increase of visibility (over 46%) ran slightly from the northeast to southwest, which was consistent with the BBDs variations. Overall, the correlation coefficient between visibility and BBDs was beyond 0.93. It should be mentioned that winter is the "dry" season for BTH with low LCC and little precipitation, therefore the difference of LCC and Non_Prep between two MEIC emissions can not pass the 95% confidence level (Fig. S6 online) [15]. This demonstrated the dominant role of visibility and the minor effects of LCC and precipitation on BBD increase. Meanwhile, it emphasized the significance of emission control in increasing BBDs in recent years.

The variations in regional hourly average BBDs and visibility under different emissions in BTH are plotted in Fig. 1c. Clearly, emission controls contribute to greater visibility, with a mean increment of 2.57 km. Meanwhile, it helped to weaken visibility decline during serious pollution episodes (in blue bars in Fig. 1c). Additionally, it was emphasized that emission reduction brings into a better-than-better effect, meaning that control measures

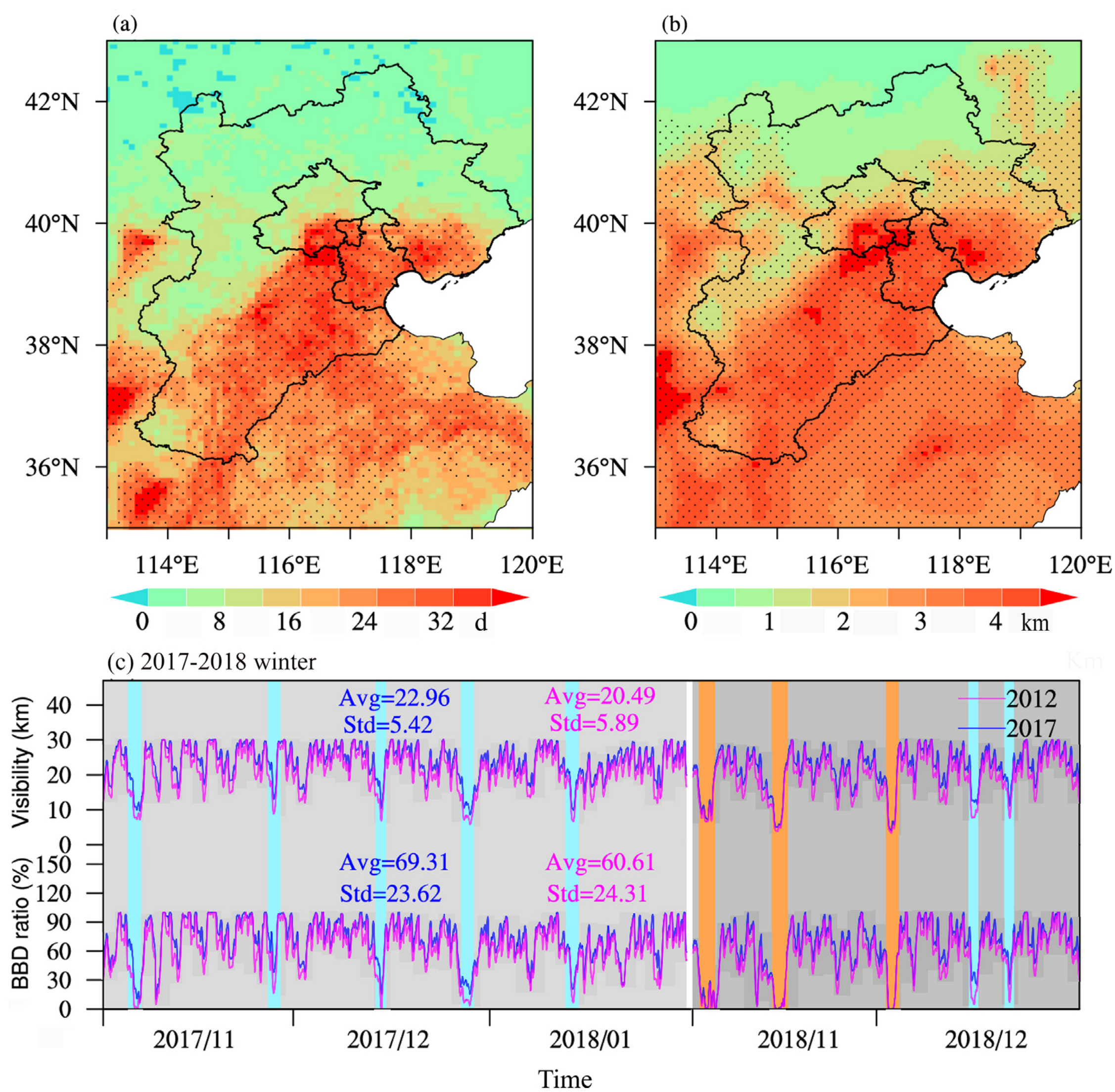

Fig. 1. Spatial distributions of differences of simulated total blue days (Sum_BBD, unit: d) (a), and average visibility (unit: km) (b) under different MEIC (2017 and 2012) during winter 2017 and winter 2018 over BTH. The black dots mean the changes pass the 95% confidence level by *t*-test. (c) The time series of the regional hourly average BBDs occurrence rates (BBD ration) over BTH. The blue bars represent the serious pollution episodes have been improved by emission control measures, and the orange bars mean the opposite.

improved visibility during relatively higher-visibility days efficiently, such as Nov. 16–21, 2017, and Dec. 30–31, 2017. By reducing the amplitude of oscillation at an hourly scale, lower standard deviations can be detected for visibility. Following the variations of visibility, the emission controls seemed to be effective to improve most of the extreme pollution events and favored a bluer-than-bluer mechanism during relatively bluer days on the regional scale in the same period. We also noticed that the extreme pollution episodes in Nov. 2018 and early Dec. 2018 seemed to refute strict emission measures (in orange bars in Fig. 1c). This suggests that the unfavorable influence of meteorology may have played a more important role for regional non-blue days in BTH on that days.

On average, the regional average BBDs occurrence rates over the 16 sites rose from 54% to 65%, which was consistent with the regional mean results (from 60% to 69%). Regionally, those control measures remarkably increased the Beijing blue days from 22.32 days/month (d/m) in 2012 to 25.73 d/m in 2018, from 12.4 to 17.67 d/m in Tianjin, and 18.91 to 22.01 d/m in Hebei, respectively. Overall, a regional mean BBDs increase beyond 2.79 d/m was revealed. It was also notable that the emission-cut measures lead to a weaker correlation coefficient between visibility and BBDs in BTH. The correlation coefficients decrease from 0.97/0.93/0.93 to 0.94/0.92/0.91 in Beijing/Tianjin/Hebei, respectively. This meant that the dominant role of visibility on BBDs may have been diminished with its improvement, which needs further study.

The impacts of Clean Air Action since 2013 on the blue days in winter over BTH were explored in this study. Emission reduction led to significantly higher visibility and widespread increase of BBDs in BTH by an average of 2.79 d/m and a maximum exceeding 53 d. Although the unique emission controls may favor more extensive blue days and reduce extreme pollution episodes in China, more efforts should be implemented to increase more blue days effectively in the future, which would provide a reference to future policymaking from a new perspective. Further study should be conducted to qualify the positive feedback mechanism of emission-cut and blue days and the effects of the newest Blue Sky Protection Campaign Plan should be evaluated.

Conflict of interest

The authors declare that they have no conflict of interest.

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Appendix A. Supplementary materials

Supplementary materials to this article can be found online at https://doi.org/10.1016/j.scib.2022.01.009.

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