1	Projected Changes in Haze Pollution Potential in China: An							
2	<b>Ensemble of Regional Climate Model Simulations</b>							
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Abstract. Based on the dynamic downscaling by the regional climate model RegCM4 15 from three CMIP5 global models under the historical and the RCP4.5 simulations, this 16 17 article evaluated the performance of the RegCM4 downscaling simulations on the air environment carrying capacity (AEC) and weak ventilation days (WVD) in China, 18 which are applied to measure haze pollution potential. Their changes during the 19 middle and the end of the 21st century were also projected. The evaluations show that 20 the RegCM4 downscaling simulations can generally capture the observed features of 21 22 the AEC and WVD distributions over the period 1986-2005. The projections indicate 23 that the annual AEC tends to decrease and the annual WVD tends to increase almost over the whole country except central China, concurrent with greater change by the 24 late of the 21st century than by the middle of the 21st century. It suggests that annual 25 26 haze pollution potential would be enlarged under the RCP4.5 scenario as compared to the present. For seasonal change in the four main economic zones of China, it is 27 projected consistently that there would be a higher probability of haze pollution risk 28 29 over the Beijing-Tianjin-Hebei (BTH) region and the Yangtze River Delta (YRD) region in winter and over the Pearl River Delta (PRD) zone in spring and summer in 30 31 the context of the warming scenario. Over Northeast China (NEC), future climate change might reduce the AEC or increase the WVD throughout the whole year, which 32 favors the occurrence of haze pollution and thus the haze pollution risk would be 33 aggravated. Relative contribution of different components related to the AEC change 34 35 further indicates that changes of the boundary layer depth and the wind speed play the leading roles in the AEC change over the BTH and NEC regions. In addition to those 36

- two factors, the precipitation change also exerts important impacts on the AECchange over the YRD and PRD zones.
- 39 **Keywords** air environment carrying capacity, ventilation day, haze pollution potential,
- 40 regional climate model, evaluation and projection

## 42 **1 Introduction**

Haze, as a phenomenon of severe air pollution, exerts remarkably adverse 43 impacts on society and human health, thereby highly concerned by the public and 44 policy makers. Particularly in recent years, heavy haze events hit China frequently 45 (Wang et al., 2014; Zhang et al., 2014) and caused serious damages in many aspects. 46 For instance, they not only increased traffic accidents and delayed traffic (Wu et al., 47 2005; 2008), but also aggravated ill health problems including respiratory disease, 48 heart disease, cancer and premature death (Wang and Mauzerall, 2006; Xu et al., 49 50 2013). Thus, more and more attentions have been paid to the haze pollution in China. The increasing trend of the haze days in China during recent decades (Ding and 51 Liu, 2014; Song et al., 2014) is documented to be largely attributed to human 52 53 activities. Due to rapid economic development and urbanization, the pollutants emitted into the atmosphere have been increased, consequently resulting in an 54 intensification of haze pollution in China (Liu and Diamond, 2005; He et al., 2013; 55 Wang et al., 2013b; 2016). Climate change also plays an important role (Jacob and 56 Winner, 2009; Wang et al., 2016). Some studies have indicated that the reduction of 57 surface wind speed, surface relative humidity and precipitation in recent decades (Gao, 58 2008; Guo et al., 2011; Jiang et al., 2013; Song et al., 2014; Ding and Liu, 2014) 59 provide unfavourable conditions for the sedimentation and diffusion of air pollutants, 60 and thus increase the occurrence of haze pollution in China. Besides, the Arctic sea 61 62 ice declining under global warming contributes positively to the increase of haze days in eastern China (Wang et al., 2015; Wang and Chen, 2016). Other influential climate 63

factors for the increase of haze pollution in China, such as the weakening of the East Asian winter monsoon (Li et al. 2015; Yin et al., 2015) and the northward shifting of the East Asian jet (Chen and Wang, 2015), are also highlighted. In summary, the combined effects of increased pollutants and climate change are responsible for the haze pollution in China.

IPCC AR5 reported that continued emissions of greenhouse gases will cause 69 further changes in all components of the climate system (IPCC, 2013). From the point 70 71 view of the CMIP5 projected change in climate conditions, there are both positive and 72 negative contributors for the haze pollution in China. For example, the projected increase in precipitation (Xu and Xu, 2012; Tian et al., 2015; Wu et al., 2015b) is 73 expected to reduce haze pollution, whereas the decrease of the Arctic sea ice extent 74 75 (IPCC, 2013) and the weakening of the East Asian winter monsoon (Wang et al., 2013a) are inclined to increase haze pollution. So, how the haze pollution in China 76 will change under the future warming scenario is still an open issue. 77

Air environment carrying capacity (AEC), which is a combined metric to 78 measure atmospheric capacity in transporting and diluting pollutants into the 79 atmosphere, provides a direct way to investigate the change of the haze pollution 80 potential. When the AEC is low (high), it is unfavourable (favourable) for the 81 diffusion and cleaning of the pollutants, and thus the haze pollution is (not) prone to 82 occur. So far, the AEC has been applied in the operation of China Meteorological 83 84 Administration (CMA) to forecast haze pollution potential (Kang et al., 2016). On the other hand, CMIP5 global climate models (GCMs) show some limitations in 85

simulating regional climate due to their relatively coarse resolutions (Giorgi et al.,
2009). Regional climate models (RCMs) with higher resolutions are demonstrated to
outperform global models on the regional scale (Lee and Hong 2014; Wu et al. 2015a;
Gao et al. 2012, 2016b). Thus, this study is aimed to project changes of the haze
pollution potential in China from the AEC perspective, based on the downscaling
simulations of the regional climate model RegCM4 under the RCP4.5 scenario.

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93 **2 Model, data and method** 

# 94 2.1 Data, regional climate model and simulations

The regional climate model RegCM4 used in this study is developed by the ICTP 95 (Giorgi et al., 2012) and applied widely around the world. The model has the 96 97 horizontal resolution of 25 km and 18 vertical sigma layers with the top at 50 hPa. Based on the study of Gao et al. (2016a, b), we selected a suite of physical 98 parameterization schemes suitable for the simulation of China climate, including the 99 100 Emanuel convection scheme (Emanuel, 1991), the radiation package of the CCM3 model for atmospheric radiative transfer (Kiehl et al., 1998), the non-local formulation 101 of Holtslag (Holtslag et al., 1990) for planetary boundary layer, the SUBEX 102 parameterization for large-scale precipitation (Pal et al., 2000), and the CLM3.5 for 103 land surface process (Oleson et al., 2008). The land cover data were updated based on 104 the vegetation regionalization maps of China (Han et al., 2015). 105

106 The domain for the downscaling simulations is the region recommended by107 CORDEX-East Asia phase II (Giorgi et al., 2009), covering China continent and

adjacent regions. The RegCM4 simulations, called EC, HAD, and MPI for short, were 108 driven at 6-hourly intervals by the historical (1979-2005) and RCP4.5 (2006-2099) 109 simulations from three CMIP5 global models i.e., EC-EARTH, HadGEM2-ES, and 110 MPI-ESM-MR, respectively. In CMIP5, ~20 GCMs provide the six-hourly outputs of 111 wind speed, temperature, and humidity for dynamical downscaling. However, to drive 112 RCM modeling, the ratio of the resolution between GCMs and RCMs should not 113 exceed 6-8. So, only those GCMs with the resolution of 1~2 degree can be used to 114 drive RegCM4 simulations. Due to the availability of CMIP5 GCMs and considering 115 large volume of outputs for ~120-yr RegCM4 simulations, we just used these three 116 GCMs for this study. The average of the three simulations with equal weight is taken 117 as the ensemble mean. The historical simulation denotes the past climate, and the 118 119 RCP4.5 represents the medium-low radiative forcing scenario with the radiative forcing peaking at 4.5 Wm<sup>-2</sup> by 2100 (Taylor et al., 2012). Readers can visit 120 http://cmip-pcmdi.llnl.gov/cmip5 for the information about the three CMIP5 models 121 and the forcing. 122

To validate the performance of the RegCM4 downscaling simulations, the ERA-Interim reanalysis dataset (Uppala et al., 2008) with the horizontal resolution of  $0.75 \times 0.75$  was employed as observations, including 6-hourly boundary layer height, precipitation, geopotential height and wind speed.

127 **2.2 Analysis method** 

128 The AEC considers the processes of wet deposition and ventilation and is129 expressed in the form:

$$AEC = C_s \cdot (W_r \cdot R \cdot \sqrt{S} + \frac{\sqrt{\pi}}{2} \cdot U_{BL} \cdot H)$$
(1)

where  $C_s$  is the standard concentration of air pollutant (here, the value is 75 µ g m<sup>-3</sup>, 131 standard concentration for PM<sub>2.5</sub> in China),  $W_r$  is washout constant (6×10<sup>5</sup>), R is 132 precipitation, S is unit area and defined as 2500 km<sup>2</sup>,  $U_{BL}$  is mean wind speed 133 averaged within the boundary layer, H is boundary layer height (Xu and Zhu, 1989). 134 High (Low) AEC is disadvantageous (advantageous) for the occurrence of haze 135 pollution, indicating low (high) haze pollution potential. It should be pointed out that 136 the AEC measures atmospheric carrying capacity in transporting and diluting 137 pollutants. It does not reflect real emission characteristics. The  $C_s$  is the standard 138 concentration of air pollutant not the real concentration of the pollutant emitted into 139 the air. For different pollutants, different value can be fixed for  $C_s$ . Because what we 140 141 concerned in this study is the haze pollution potential, its value is set as the standard concentration for  $PM_{2.5}$  in China. 142

The term  $U_{BL} \cdot H$  is named ventilation coefficient (Krishnan and Kunhikrishnan, 143 144 2004). Large ventilation coefficient means that a deeper boundary layer can dilute 145 pollutants and strong winds can remove local pollutants, unfavourable for the haze occurrence, and vice versa. If each of the 6-hourly ventilation coefficients within one 146 day is less than 6000  $\text{m}^2 \text{s}^{-1}$ , this day is counted as one weak ventilation day (WVD) 147 (Leung and Gustafson, 2005). Longer WVD indicates more haze pollution incidents. 148 The threshold of 6000  $\text{m}^2 \text{s}^{-1}$  for the ventilation coefficient was widely used not only 149 in the U.S. (Hanson and McKee, 1983; Leung and Gustafson, 2005; Trail et al., 2013), 150 but also in other places such as India (Goyal and Rao, 2007; Manju et al., 2002), 151

Athens (Kassomenos et al., 1995), and Thailand (Pimonsree, 2008). A sensitivity analysis shows that that there is little change in the relationship between the WVD and the haze days if using different thresholds to calculate WVD.

According to Eq. (1), the AEC change results from changes in precipitation, wind speed, and boundary layer depth, which can be simplified as:

157 
$$\Delta AEC = \alpha \cdot \Delta R + \beta \cdot \Delta (U_{RI} \cdot H)$$
(2)

where  $\alpha = C_s \cdot W_r \cdot R$ ,  $\beta = C_s \cdot \frac{\sqrt{\pi}}{2}$ , and  $\Delta$  represents the difference between the future and present-day climate (RCP4.5 minus reference period).

160 The Eq. (2) could be further decomposed as follows:

161 
$$\Delta AEC = \alpha \cdot \Delta R + \{\beta \cdot \Delta U_{BL} \cdot H_{pd} + \beta \cdot (U_{BL})_{pd} \cdot \Delta H + \beta \cdot \Delta U_{BL} \cdot \Delta H + TR\}$$
(3)

The subscript "pd" denotes the present-day climate. The first to third terms in the right-hand side are associated with changes in precipitation, wind speed within the boundary layer, and boundary layer depth, respectively. The fourth term is a nonlinear term including the contribution of changes in both wind speed and boundary layer depth. Since we use 6-hourly data for the AEC calculation while monthly mean data for the diagnosis of the change, the last term TR (transient term, deviation from monthly mean) cannot be ignored, which is obtained as a residual.

The pattern-amplitude projection (PAP) method (Park et al., 2012) is applied to quantify the relative contributions of individual processes P<sub>i</sub> to the AEC change over certain region.

172 
$$P_{i} = \frac{\langle \Delta A E C_{i} \cdot \Delta A E C \rangle}{\langle \Delta A E C \cdot \Delta A E C \rangle}$$
(4)

173 in which  $\langle \rangle$  represents area mean,  $\Delta AEC_i$  represents components in the

174 right-hand side of Eq. (3).

As stated above, a low (high) AEC are favourable (unfavourable) for the 175 occurrence of the haze pollution. Longer (Shorter) WVD corresponds to more (less) 176 haze pollution incidents. To verify this conclusion, we calculated the quantized 177 relationship of the haze days with the AEC and the WVD during the period 178 1980-2016 in the observation. The data of the haze days, which are based on daily 179 visibility and relative humidity records from ~2400 observation stations in China, are 180 available from the CMA. The correlation analysis does show significantly negative 181 182 correlations between the haze days and the AEC, and significantly positive correlations between the haze days and the WVD over eastern China where the haze 183 mainly occurs. 184

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## **3 Performance of the downscaling simulations**

The performance of the RegCM4 downscaling simulations on the AEC spatial 187 pattern is firstly evaluated through the comparison with the observation. As shown in 188 Fig. 1a, the observed AEC is in general large in western China, with the maxima 189 located over Tibet. Low AEC is found mainly over central and eastern China, 190 northwestern Xinjiang, and parts of Northeast China. The simulated AEC 191 distributions from the ensemble (Fig. 1b) and its members (Fig. 1c-e) show general 192 resemblance to the observation. The spatial correlation coefficients between the 193 simulation and the observation are all higher than 0.75 (Table 1). On the national 194 average, the root mean square error (RMES) is small for the ensemble mean and each 195

member, which varies between 0.47 and 0.53 (Table 1). Nevertheless, there are also
some deficits in the simulations. For example, the AEC is underestimated over the
southern Xinjiang and overestimated over parts of North China. Our analysis indicates
that the simulation bias in boundary layer depth is the major factor for the simulated
AEC bias over most parts of China (figure not shown).

We further present the observed and simulated distribution of the seasonal AEC 201 in China during 1986-2005. For the observation, the winter AEC is the lowest among 202 the four seasons in a broad region of China (Fig. 2a). In spring, the AEC increases 203 204 significantly and the regions with high AEC expand obviously. The central eastern China is dominated by the low capacity (Fig. 2c). Compared with the case in spring, 205 the summer AEC increases over central China while decreases slightly over Tibet and 206 207 Northeast China (Fig. 2e). The AEC distribution in autumn is similar to that in winter but with larger capacity over the regions except Tibet (Fig. 2g). The seasonal 208 variation of the AEC in the ensemble simulation agrees with that in the observation 209 although there are some discrepancies (Fig. 2b, 2d, 2f and 2h). The spatial correlation 210 coefficient between the simulation and the observation ranges from 0.60 to 0.79 and 211 the RMES is in the range of 0.47 to 0.75 for the national average in four seasons 212 (Table 2). 213

The WVD distribution during 1986-2005 in the observation and the ensemble simulation is displayed in Fig. 3a and Fig.3b, respectively. It is noticed that the simulated pattern and the observed pattern are approximate to each other. Namely, the number of weak ventilation days per year is relatively small over Tibet while relatively large over central and eastern China, Northeast China, southern North
China and Xinjiang. The spatial correlation between them is 0.75. However, we also
note that the WVD is overestimated by the ensemble simulation.

The wet deposition is observed to be large over southern China and the south edge of the Tibetan Plateau while small over northwestern China (Fig. 3c). According to Eq. (1), the wet deposition pattern exactly corresponds to the distribution of precipitation. The observed features can also be captured by the ensemble simulation (Fig. 3d). The spatial correlation coefficient between the simulation and the observation is up to 0.85.

In brief, the downscaling simulations of the RegCM4 can reasonably reproduce the observed characteristics of the distribution of the AEC, WVC and wet deposition in China. It provides justification to use them for the future projection.

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#### 231 **4 Projected changes**

232 Fig. 4 exhibits the ensemble projected changes in AEC, WVC and wet deposition during the middle of the 21st century (2046-2065) and the end of the 21st century 233 (2080-2099) relative to the reference period 1986-2005. The periods 2046-2065 and 234 2080-2099 are commonly used to represent near-term and long-term in the CMIP5 235 projection, respectively (IPCC, 2013). A general decrease in AEC and an overall 236 increase in WVC are projected over almost the whole country except central China in 237 the context of the RCP4.5 scenario. The change in magnitude is larger by the end of 238 the 21st century than by the middle of the 21st century. The maximum decrease in 239

AEC appears at the edge of the Qinghai-Tibet Plateau and the Loess Plateau, with the 240 percentage change being 4% for the middle of the 21st century and 5% for the end of 241 242 the 21st century. The relatively large decreases are located in Southwest China, northern North China, Northeast China and Inner Mongolia (Fig. 4a and Fig.4b). The 243 increase in WVD is projected to be particularly pronounced in western and northern 244 China (Fig. 4c and Fig. 4d). The three ensemble samples agree well on the sign of the 245 changes, indicative of a good consistency in the projection. In contrast, there would be 246 an increasing tendency for the AEC and a decreasing tendency for the WVD over 247 248 central China where the climatological capacity is low in the reference period 1986-2005. However, the sign of the projected change is inconsistent among the three 249 ensemble samples. Compared with the ensemble projection, the EC and HAD show 250 251 relatively large discrepancy for the sign of the projected change in AEC and WVD, respectively (Figures not shown). 252

For the change in wet deposition, a general increase is projected across China, also with greater change in 2080-2099 than in 2046-2065 (Fig. 4e and Fig. 4f). In addition, we can find inconsistent signs of the projected change over southern China during 2046-2065 (Fig. 4e) and over some parts of Northeast China during 2080-2099 (Fig. 4f). The inconsistent during 2046-2065 (2080-2099) is mainly due to the difference of the HAD (MPI) projection from the other two ensemble members (Figures not shown).

Following, we turn to examine the seasonal and annual changes of the AEC and WVD over the four main economic zones of China (Fig. 1f) which suffer severely

Northeast China (NEC), Yangtze River Delta economic zone (YRD), and Pearl River 263 Delta economic zone (PRD) in more detail. 264 1) Beijing-Tianjin-Hebei region 265 As shown in Fig. 5a, the ensemble projection indicates a decrease of the AEC in 266 all four seasons during the middle of the 21st century. The percentage change relative 267 to 1986-2005 is the lowest in spring and the largest in winter. The changes in summer 268 and autumn are between -2% and -3%. The three ensemble members agree on the sign 269 270 of the changes in all seasons except spring but with different spread. For the summer season, the spread is the smallest. While in other seasons, it is close to or larger than 271 the ensemble projected change. During the end of the 21st century, the decrease of the 272 273 AEC is further enhanced, with the largest enhancement occurring in winter. Moreover, the spread in general becomes much larger. For annual change, both the ensemble and 274

from the haze pollution at present, i.e., Beijing-Tianjin-Hebei region (BTH),

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its members project that the AEC would reduce during the middle and the end of the21st century with the larger amplitude in the latter period.

As for the WVD (Fig. 5b), an increasing tendency is projected by the ensemble for annual and seasonal mean during the middle of the 21st century. The change is the smallest in summer and the largest in winter. The ensemble members show good agreement on the positive change in winter, autumn, and annual mean. During the late of the 21st century, the increase in WVD is further enlarged in winter and autumn while it is reduced in spring and summer. There is no appreciable change for annual mean as compared to that in the middle of the 21st century. Only for the winter season and annual mean, all the individual simulations consistently show the same projectionas the ensemble.

286 2) Northeast China

The annual and seasonal AEC is projected by the ensemble to decrease during the middle of the 21st century, and the percentage changes are comparable among four seasons and annual mean (Fig. 6a). The ensemble members also project negative tendency consistently except in spring. Compared with the middle of the 21st century, the case for the end of the 21st century is similar but with larger decrease. Besides, all the three ensemble members show good consistence for the projection.

The WVD is projected by the ensemble and its members to increase during the middle and the end of the 21st century for annual mean and all four seasons (Fig. 6b). Similarly, the projected change is larger during the end of the 21st century than during the middle of the 21st century, with the largest increase appearing in spring.

297 3) Yangtze River Delta economic zone

The ensemble projection indicates that the AEC would decrease for annual mean 298 and all the seasons except autumn (Fig. 7a). The percentage change is the smallest in 299 spring (with the decrease of less than 1%) and the greatest in winter (with the 300 decrease of more than 3%). The counterparts for summer and autumn are about -2% 301 and 1%, respectively. However, large spread exists among the projections of the three 302 ensemble members. Only for winter and annual mean, they project the same sign of 303 304 the change. At the end of the 21st century in the ensemble projection, the decrease in AEC is enhanced to 6% in winter. Consistent change is projected by the ensemble 305

members. In contrast, the decrease in summer and the increase in autumn are
weakened as compared to the middle of the 21st century. A slight increase of the AEC
is found in spring. For annual mean AEC, the decrease is somewhat larger by the end
of the 21st century than by the middle of the 21st century.

The WVD for annual mean, winter and spring is projected by the ensemble to 310 increase, with larger change during the end of the 21st century than during the middle 311 of the 21st century (Fig. 7b). The greatest change occurs in winter. For summer, the 312 ensemble projects that the WVD almost remains unchanged during the middle of the 313 314 21st century while increases at the end of the 21st century. For autumn, the ensemble projects that the WVD decreases slightly during the middle of the 21st century while 315 increases slightly by the end of the 21st century. The ensemble members show good 316 317 consistency of the projections for winter and annual mean during both periods.

## 318 4) Pearl River Delta economic zone

As projected by the ensemble (Fig. 8a), the annual, spring and summer AEC 319 320 would decrease. Such a decrease is relatively larger during the middle of the 21st century than during the end of the 21st century and the greatest decrease occurs in 321 spring. For winter, the AEC is projected to increase and be comparable during the 322 middle and the end of the 21st century. For autumn, the projected AEC decreases by 323 about 1% over the period 2046-2065 and increase by about 0.5% over the period 324 2080-2099. However, the projections from the three members are not consistent for 325 326 all four seasons.

The ensemble projects an increase in WVD for annual mean and four seasons, 327 with the greatest increase in summer during the middle of the 21st century (Fig. 8b). 328 329 The individual members consistently show the positive change for spring, summer, and annual mean. Compared with the middle of the 21st century, the increase of the 330 WVD is reduced in summer while enhanced for annual mean and the remaining 331 seasons during the late of the 21st century. The autumn is the season with the 332 maximum change. The individual members show the same projections as the 333 ensemble on the sign of change still for spring, summer, and annual mean. 334

335 The consistence of the three ensemble members on the direction of the projected change which can be used to visualize the uncertainty in the projection is further 336 summarized in Table 3. In general, although there are some uncertainties on the 337 338 regional changes, the three members consistently project a decrease of the AEC or an increase of WVD for annual mean over the four economic zones, especially over the 339 Beijing-Tianjin-Hebei region and Northeast China. It signifies that future climate 340 341 change will contribute positively to the haze pollution in these regions. For seasonal change, decrease in AEC or increase in WVD, is projected consistently to appear in 342 all four seasons over Northeast China. It suggests that there would be an increase of 343 haze pollution potential throughout the whole year. Besides, the consistent projections 344 indicate a higher potential risk of haze pollution over the Beijing-Tianjin-Hebei 345 region and the Yangtze River Delta region in winter and over the Pearl River Delta 346 347 zone in spring and summer.

The temporal evolution of the annual and seasonal AEC and WVD over the four 348 main economic zones are also plotted (Figs. 5-8 c-g), and the corresponding trend 349 values projected by the ensemble for the period of 2016-2099 are summarized in 350 Table 4. Theil-Sen trend analysis (Theil, 1950; Sen, 1968) was used to estimate the 351 trends and the non-parametric Mann-Kendall test (Mann, 1945; Kendall, 1975) was 352 used for significant test. Generally, the secular variations of the AEC and the WVD 353 show some diversity across different seasons over the regions except NEC where a 354 decrease in AEC and an increase in VWD is projected uniformly. Nevertheless, for 355 356 the trends significant above the 95% level, it is interesting to notice that the decrease in AEC is mostly accompanied with the increase in WVD, for instance for winter over 357 TBH, for annual mean and all the seasons over NEC, for annual mean, winter and 358 359 summer over YRD, and for annual mean and autumn over PRD.

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#### **361 5** Contributions of different factors to the change of AEC

Based on Eqs. (2) and (3), we further investigate the contribution of different factors to the projected change in AEC. For brevity, we only show the results for the period 2046-2065 in the following, because the case for the period 2080-2099 is similar.

Figs. 9a and 9b exhibit relative contributions to the annual AEC change over the course of 2046-2065 from changes in precipitation and ventilation, respectively. Overall, the ventilation change plays a dominant role in and contributes positively to the change of the AEC over most parts of China, particularly in western and northern China (Fig. 9b). In contrast, the relative contribution of the precipitation change is in
general negative over western and northern China while positive over southern China
(Fig. 9a).

According to Eq. (3), the effect of ventilation change can be decomposed into four terms, i.e., wind speed change, boundary layer depth change, nonlinear term, and transient term. Among these contributors for annual ventilation change, the effects of boundary layer depth (Fig.9d) and wind speed (Fig.9c) are relatively large and the former is greater than the latter over most parts of eastern China. The transient term also exert effects for instance over some parts of western and southern China (Fig.9f), while the effects of the nonlinear term are tiny across China (Fig. 9e).

Fig. 10 further presents relative contributions of aforementioned factors to 380 381 annual and seasonal AEC change over the four economic zones as projected by the ensemble and its members. As shown in Figs. 10a and 10b, changes in wind speed 382 and boundary layer depth have the greatest contributions to the AEC change over the 383 384 THB and NEC regions for annual mean and all the seasons except summer. The contribution from the precipitation is in general relatively small. Besides, the effects 385 of the transient term are larger than that of the precipitation, and the effects of the 386 nonlinear term can be negligible. These results indicate that changes in wind speed 387 and boundary layer depth are the leading contributors responsible for the AEC change 388 over the two regions. In contrast, over the YRD (Fig.10c) and PRD (Fig.10d) zones, 389 change in precipitation also plays an important role. The contribution from the 390

391 precipitation change is comparable to and even larger than that from changes in wind392 speed and boundary layer depth for all the seasons except winter.

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### **6 Conclusion**

In this study, we conducted downscaling simulations by use of the RegCM4 driven by three CMIP5 models' results under the historical simulation and the RCP4.5 scenario. On this basis, we evaluated the fidelity of the RegCM4 simulations on the AEC and WVD which are indictors for haze pollution potential, and then projected their change during the middle and the end of this century for China and four main economic zones. The major findings are summarized below:

1) The evaluation indicates that the RegCM4 downscaling simulations in general 401 402 show good performance in modeling the climatological distribution of the annual and seasonal AEC, despite some discrepancies in certain regions. The spatial correlations 403 between the simulation and the observation for annual mean and four seasons are 404 405 higher above 0.6. The simulations also well capture the observed WVD pattern with relatively small WVD over Tibet and relatively large WVD over central and eastern 406 407 China, Northeast China, southern North China and Xinjiang, although the WVD is overestimated systematically. 408

2) The annual AEC and WVD are respectively projected by the ensemble to
decrease and increase almost in the entire region except central China, accompanied
with larger amplitude by the end of the 21st century than by the middle of the 21st
century. The decreases in AEC are relatively large over Tibet, Southwest China,

northern North China, Northeast China and Inner Mongolia. The increase in WVD is
particularly pronounced in northern China. The individual members present consistent
projections of changes as the ensemble. In contrast, the ensemble projects an increase
in AEC and a decrease in WVD over central China. However, the sign of the
projected change is inconsistent among the ensemble samples.

3) The consistency analysis suggests that there would be a high probability of the 418 increase in air pollution risk over the BTH and YRD regions in winter and over the 419 PRD zone in spring and summer in a warmer world. Over NEC, climate change might 420 421 reduce the AEC or increase the WVD throughout the whole year, favorable for the occurrence of haze pollution and also indicative of an aggravation of haze pollution 422 risk. Furthermore, the contribution analysis indicates that changes in boundary layer 423 424 depth and wind speed play the leading roles in the AEC change over the BTH and NEC regions. In addition to the aforementioned two factors, the precipitation change 425 is also an important factor influencing the ACE change over the YRD and PRD zones. 426 427 In this study, we mainly showed the downscaled results driven by three global models. Note that the planetary boundary layer depth is not a standard CMIP5 output 428 variable, and the coarse vertical resolution of the global models prevents us from 429 estimating the planetary boundary layer depth. These make it hard to estimate whether 430 the consistencies and inconsistencies of the projection is caused by the global models 431 or to some extent affected by the dynamical downscaling of the regional model. 432 433 Besides, it should be emphasized again that our study focused on the atmospheric carrying capacity which is associated with the wet deposition and the ventilation. It is 434

just one of the contributors for the haze change. Other factors such as emission, wind
direction, relative humidity are also vital for the incident of haze. To get a full picture
for future change of the haze, their effects need to be studied by models with
chemistry/aerosol module coupled in the future work.

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- 596 **Captions:**
- 597 Table 1. Statistic results for the simulation skills in annual mean AEC for the period598 of 1986-2005.
- **Table 2.** Statistic results for the ensemble simulation skills in seasonal AEC for theperiod of 1986-2005.
- Table 3. The consistence of the three ensemble members on the direction of the projected change over the four economic zones of China. Consistent projection on the decrease in AEC is markerd by  $\sqrt{}$  and that on the increase in WVD is marked by  $\frac{1}{\sqrt{}}$ .
- Table 4. Trends of AEC and WVD (%/10a) over the four economic zones of China,
  based on 9-year running mean time series of the percentage change during
  2016-2099. Asterisks indicate the trends are statistically significant above the 95%
  confidence level.
- Figure 1. Spatial distribution of annual AEC (unit:10<sup>4</sup>t/a/km) during 1986-2005: (a)
  observation, (b) ensemble, (c) EC, (d) HAD, (e) MPI. (f) Four main economic
  zones of China, Beijing-Tianjin-Hebei region (BTH), Northeast China (NEC),
  Yangtze River Delta economic zone (YRD), and Pearl River Delta economic
  zone (PRD).

Figure 2. Spatial distribution of seasonal AEC (unit: 10<sup>4</sup>t/a/km) during 1986-2005:
(a-b) winter, (c-d) spring, (e-f) summer, (g-h) autumn. Left panel is for the
observation and the right panel is for the ensemble simulation.

617	Figure 3. Spatial distribution of (a-b) the number of weak ventilation days per year
618	and (c-d) wet deposition (unit: 10 <sup>4</sup> t/a/km) during 1986-2005: (a, c) observation,
619	(b, d) ensemble simulation.

Figure 4. Ensemble projected percentage changes (relative to 1986-2005) in (a-b)
AEC and (c-d) WVD during (a, c) 2046-2065 and (b, d) 2080-2099. Hatched

regions indicate all ensemble members agree on the sign of change.

- **Figure 5.** Range of projected percentage changes (relative to 1986-2005) in (a) AEC
- and (b) WVD during 2046-2065 and 2080-2099, and 9a running mean time series
- of percentage changes in (c) annual, (d) winter (DJF), (e) spring (MAM), (f)
- summer (JJA), (g) autumn (SON) for the Beijing-Tianjin-Hebei region. In Figure
- 627 (a-b), the bars represent the ensemble projection and the marks represent the
- 628 individual projection of the three members; the left (right) bar in each group is for
- 629 2046-2065 (2080-2099). In Figure (c-g), the solid (dashed) lines represent
- 630 changes in AEC (WVD).
- **Figure 6.** Same as Figure 5, but for Northeast China.
- **Figure 7.** Same as Figure 5, but for Yangtze River Delta economic zone.
- **Figure 8.** Same as Figure 5, but for Pearl River Delta economic zone.
- **Figure 9.** Relative contributions (unit: %) of individual components to annual AEC
- change in the middle of the 21st century based on the ensemble results. (a)
- 636 precipitation, (b) ventilation, (c) wind speed averaged with the boundary layer, (d)
- 637 boundary layer depth, (e) nolinear term, (f) transient term.

638	Figure 10. Relative contributions (unit: %) of individual components to annual AEC
639	change in the middle of the 21st century averaged over four main economic
640	zones of China: (a) BTH, (b) NEC, (c) YRD, (d) PRD. The bars represent the
641	ensemble projection and the marks represent the individual projection of the three
642	members. Bars from left to right in each group are in turn for annual, DJF, MAM,
643	JJA, and SON.

of 1986-2005.					
Simulations	Simulations Pattern correlation (CC)				
EC	0.76	0.47			
HAD	0.79	0.53			
MPI	0.76	0.47			
Ensemble	0.77	0.48			

 
 Table 1.
 Statistic results for the simulation skills in annual mean AEC for the period
 

period of 1986-2005.					
Season	Pattern correlation coefficient (CC)	Root mean square error (RMES)			
Winter	0.79	0.75			
Spring	0.75	0.67			
Summer	0.60	0.57			
Autumn	0.78	0.47			

 
 Table 2.
 Statistic results for the ensemble simulation skills in seasonal AEC for the
 

650	Table 3. The consistence of the three ensemble members on the direction of the
651	projected change over the four economic zones of China. Consistent projection on the
652	decrease in AEC is marked by $\checkmark$ and that on the increase in WVD is marked by

☆.

Economic zone	Period	ANN	DJF	MAM	JJA	SON
рти	2046-2065	$\sqrt{c}$	$\sqrt{\frac{1}{2}}$		$\checkmark$	$\sqrt{\frac{1}{22}}$
DIII	2080-2099	$\sqrt{\frac{1}{2}}$	X			
NEC	2046-2065	$\sqrt{\frac{1}{2}}$	$\sqrt{\frac{1}{2}}$	X	$\sqrt{\frac{1}{2}}$	$\sqrt{\frac{1}{2}}$
NEC	2080-2099	$\sqrt{\frac{1}{22}}$	$\sqrt{\frac{1}{2}}$	$\sqrt{\frac{1}{2}}$	$\sqrt{\frac{1}{2}}$	$\sqrt{\frac{1}{22}}$
VDD	2046-2065	$\sqrt{\frac{1}{2}}$	$\sqrt{\frac{1}{2}}$			
IKD	2080-2099	$\Delta$	$\sqrt{\frac{1}{2}}$			
	2046-2065	$\Delta$		$\Delta$	$\Delta$	
ΓΚD	2080-2099			$\Delta$	$\Delta$	

655	Table 4. Trends of AEC and WVD (%/10a) over the four economic zones of China,
656	based on 9-year running mean time series of the percentage change during 2016-2099.
657	Asterisks indicate the trends are statistically significant above the 95% confidence

658 level.

Economic zone	Variable	ANN	DJF	MAM	JJA	SON
DTH	AEC	-0.41*	-0.96*	0.02	-0.19*	-0.80*
ын	WVD	0.33	2.30*	-1.53*	-0.51*	0.55
NEC	AEC	-0.46*	-0.76*	-0.26*	-0.41*	-0.61*
NEC	WVD	1.49*	2.60*	1.30*	0.73*	0.97*
VDD	AEC	-0.27*	-1.17*	0.32*	-0.45*	-0.02
IKD	WVD	0.51*	0.88*	-0.26	0.71*	-0.15
	AEC	-0.14*	-0.03	-0.22*	-0.12	-0.29*
PKD	WVD	1.17*	-0.01	-0.30	2.17*	1.50*



River Delta economic zone (YRD), and Pearl River Delta economic zone (PRD).



(a-b) winter, (c-d) spring, (e-f) summer, (g-h) autumn. Left panel is for theobservation and the right panel is for the ensemble simulation.



**Figure 3.** Spatial distribution of (a-b) the number of weak ventilation days per year and (c-d) wet deposition (unit:  $10^4$ t/a/km) during 1986-2005: (a, c) observation, (b, d) ensemble simulation.



**Figure 4.** Ensemble projected percentage changes (relative to 1986-2005) in (a-b) AEC, (c-d) WVD, and (e-f) wet deposition during 2046-2065 (left panel) and 2080-2099 (right panel). Hatched regions indicate all ensemble members agree on the sign of change.



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Figure 5. Range of projected percentage changes (relative to 1986-2005) in (a) AEC 682 and (b) WVD during 2046-2065 and 2080-2099, and 9a running mean time series of 683 percentage changes in (c) annual, (d) winter (DJF), (e) spring (MAM), (f) summer 684 (JJA), (g) autumn (SON) for the Beijing-Tianjin-Hebei region. In Figure (a-b), the 685 bars represent the ensemble projection and the marks represent the individual 686 projection of the three members; the left (right) bar in each group is for 2046-2065 687 (2080-2099). In Figure (c-g), the solid (dashed) lines represent changes in AEC 688 (WVD). 689





Figure 6. Same as Figure 5, but for Northeast China.





Figure 7. Same as Figure 5, but for Yangtze River Delta economic zone.



Figure 8. Same as Figure 5, but for Pearl River Delta economic zone.



Figure 9. Relative contributions (unit: %) of individual components to annual AEC
change in the middle of the 21st century based on the ensemble results. (a)
precipitation, (b) ventilation, (c) wind speed averaged with the boundary layer, (d)
boundary layer depth, (e) nolinear term, (f) transient term.

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**Figure 10.** Relative contributions (unit: %) of individual components to annual AEC change in the middle of the 21st century averaged over four main economic zones of China: (a) BTH, (b) NEC, (c) YRD, (d) PRD. The bars represent the ensemble

projection and the marks represent the individual projection of the three members.
Bars from left to right in each group are in turn for annual, DJF, MAM, JJA, and
SON.