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RESEARCH ARTICLE

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Future haze events in Beijing, China: When climate warms by 1.5 and 2.0°C

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Abstract

China is the world's second-largest economy, and its capital Beijing has been suffering from severe haze pollution in recent years. However, how the winter haze events in Beijing vary under different global warming scenarios is still open for debate. In order to analyse long-term winter haze characteristics in Beijing in the future, we have simulated haze events using the haze weather index (HWI) for the warming periods of 1.5 and 2.0°C, based on 20 Coupled Model Intercomparison Project Phase 5 (CMIP5) models under two representative concentration pathways (RCP4.5 and RCP8.5). Our results indicate that 16 CMIP5 models have preferable performance in simulating the spatial pattern and occurrence frequency of winter haze events in Beijing. We highlight that in the 1.5 and 2.0°C global warming period (2020s–2050s), Beijing will face a significant increasing trend (6–9% growth rate) in the occurrence of winter haze events compared with the reference period (1986–2005). The frequency of winter haze events under the RCP4.5 increases less than under the RCP8.5 in the 1.5°C warming period but is closer to RCP8.5 in the 2.0°C warming period. The increase of winter haze events with respect to natural factors in Beijing could be attributed to stronger atmospheric inversions, weaker East Asian winter monsoons, and a shallowing East Asian trough induced by global warming. Our results will provide scientific instructions for environmental departments to better face meteorological hazards, such as air pollution episodes, thereby improving the early warning mechanism system for global warming.

KEYWORDS
1.5°C, 2.0°C, China, CMIP5, global warming, haze

1 | INTRODUCTION

Air pollution is a major environmental problem all over the world. Satellite-derived estimates suggest that 30% of the global population lives in regions above the World Health Organization (WHO) interim target one standard (35 μg·m^{-3}) for $PM_{2.5}$ in 2010–2012 (Brauer *et al.*, 2012; van Donkelaar *et al.*, 2015). According to the Global Burden of Diseases study, air pollution is the fifth-ranked global risk factor for human health, responsible for over 5.5 million premature deaths (Cohen *et al.*, 2017). Fine particulate matter is one major air pollutant that endangers human health, degrades visibility, and indirectly affects the global climate by participating in the clouding and raining process (Tamara *et al.*, 2014; Wang *et al.*, 2014a; Li *et al.*, 2016b; Broomandi *et al.*, 2017). From a global perspective, there are several areas with high $PM_{2.5}$ concentrations (e.g., for example, East Asia, India, Bangladesh, the Middle East, and North Africa) (van Donkelaar *et al.*, 2015; Marlier *et al.*, 2016). As one of the main megacities in Asia, Beijing and its adjacent economic areas have suffered serious airborne pollution, which have been further catalysed by frequent haze events since 2012 (Chen and Wang, 2015; Chen *et al.*, 2017). In January 2013, there was an extremely severe and persistent haze pollution over eastern China, affecting 30 cities and 800 million people over an area of 1.3 million km^2 and cancelling hundreds of flights (Huang *et al.*, 2014; Wang *et al.*, 2014b). Haze has become one of the most sever meteorological disaster, globally and regionally.

In general, haze is an atmospheric obscuration caused by fine particulate from various sources under specific meteorological conditions (Baklanov *et al.*, 2016). When the pollutant particles are directly discharged in the ground layer or converted in the atmosphere, and if the horizontal and vertical dispersion of pollutants is restrained, haze events occur. Low surface wind, high surface relative humidity, and a stable boundary layer can all restrain the dispersion of pollutants (Ding and Liu, 2013; Yin and Wang, 2017). Meteorological conditions not only determine the dispersion of the pollutants but also greatly control the formation of secondary aerosol precursors, including SO_2, NO_x, and VOC_s, which is an important part of haze formation in China (Huang *et al.*, 2014; Pei and Yan, 2018). The important role of meteorological factors on air pollution can be proven by the extremely severe haze pollution over eastern China in January 2013, analysis of this so-called "airpocalypse" period found that it could be attributed to the combined effect of various kinds of meteorological factors (Zhang *et al.*, 2013b; Wang *et al.*, 2014a).

The meteorological condition is just one of the important factors affecting haze events, the discharge of pollutants is the leading factor. However, when it comes to the positive or negative effects on haze events in the context of climate change, the response of relevant meteorological conditions should be focused on. These meteorological factors are changing under the impact of atmospheric circulation. Thus, it is crucial to understand the potential effects of relevant natural factors on haze, both for the purpose of environmental management and investigating the social consequences of global warming (Leung and Gustafson Jr, 2005; Jacob and Winner, 2009). Recently, the role of underlying climatic factors in association with haze events in regional weather conditions has been explored, and it is projected that these factors will influence the haze situation in the future (Niu *et al.*, 2010; Zhang *et al.*, 2015; Zou *et al.*, 2017). By analysing the Coupled Model Intercomparison Project Phase 5 (CMIP5) datasets, there are positive and negative contributors among different climate factors for the haze pollution in China (Han *et al.*, 2017). The decadal variability and climate change, including the weakened East Asian winter monsoon system and the associated decreased near-surface wind speeds (Niu *et al.*, 2010), the increase of relative humidity (Chen and Wang, 2015; Chen *et al.*, 2017), and the melting of Arctic ice (Wang *et al.*, 2015; Cai *et al.*, 2017), may provide favourable external conditions for future haze. On the contrary, the projected increase in precipitation is expected to relieve the haze pollution (Tian *et al.*, 2015; Li *et al.*, 2018b). Changes of atmospheric circulation driven by global warming are expected to alter the natural conditions that control haze formation and elimination (Li *et al.*, 2018b), but the magnitude and direction of this change are still unclear. However, how the haze situation in China will vary with the integrated change in climate is still open for debate.

A series of research projects have explored future haze events with an underlying idea to construct a comprehensive meteorological index for haze events (Horton *et al.*, 2014; Han *et al.*, 2017; Yin *et al.*, 2017). Air environment carrying capacity, which measures atmospheric capacity in transporting and dispersing pollutants into the atmosphere globally, provides a direct way to investigate the change in the haze pollution potential (Han *et al.*, 2017). Accumulation and diffusion of pollutants are closely related to the local atmospheric stability (Tai *et al.*, 2012). Furthermore, Horton *et al.* (2014) applied a modified version of the Atmospheric Stagnation Index (ASI) to realize the quantification of the global warming effect on atmospheric stagnation. In addition, Winter Haze Day using the surface visibility and relative humidity is proposed in Yin *et al.* (2017). Later, Cai *et al.* (2017) constructed a local haze weather index (HWI) using the temperature difference between upper and lower troposphere, lower meridional wind, and upper zonal wind. Only 28% of haze events were captured by a winter ASI, whereas 48% of the HWI > 0 days are haze days in Beijing, and the correlation between $PM_{2.5}$ and the HWI can be up to 0.66. A heavy pollution event is often the result of the comprehensive effect of various kinds of meteorological factors, which was further proven by research on weather conditions for severe haze events in January 2013 (Zhang *et al.*, 2013b). Therefore, consideration of different meteorological parameters will help us to sensitively explore the future haze situation.

In this study, we aim to estimate the potential frequency of winter haze events under the global warming scenarios of 1.5 and 2.0°C, mainly based on a reanalysis dataset and a CMIP5 dataset. Our results will provide scientific instruction for researchers in environmental departments to better face meteorological hazards, such as air pollution, thereby improving early warning mechanisms for global warming.

2 | DATASETS AND METHODOLOGY

2.1 | Datasets

2.1.1 | NCEP reanalysis data

Daily climate datasets from 1986 to 2005 including atmospheric temperature and wind vector were provided by the National Centers for Environmental Prediction (NCEP), available from the following website (https://www.esrl.noaa.gov/psd/data/gridded/reanalysis/). They are characterized with a resolution of $2.5^\circ \times 2.5^\circ$ (Kalnay *et al*., 1996).

2.1.2 | CMIP5 datasets

Twenty CMIP5 models with different spatial resolutions were applied in our study (Table 1), including daily outputs of historical and future climate experiments, under two representative concentration pathways (RCP4.5 and RCP8.5). RCP4.5 and RCP8.5 are named after the concentrations that approximate the intended level of radiative forcing values of 4.5 and 8.5 $W \cdot m^{-2}$, respectively, in the year 2100 relative to pre-industrial values. For the consistency of different datasets, we interpolated all of the 20 CMIP5 experiment outputs to the same resolution of $2.5^\circ \times 2.5^\circ$ as that of the NCEP reanalysis data. The detailed variables of the two datasets used in this study are provided in Table 2.

2.2 | Methodology

2.2.1 | Haze weather index

In this study, we focus on the frequency of haze events during boreal winter (December, January, and February), as this period typically experiences the most severe haze events in Beijing (Niu *et al*., 2010; Ding and Liu, 2013). Winter haze occurrence in Beijing is accompanied by a complex combination of meteorological factors. Here, we involve three meteorological elements when calculating HWI: temperature differences of the upper and lower troposphere, meridional winds in 850 hPa, and zonal winds in 500 hPa over Beijing (Cai *et al*., 2017). The three

TABLE 1 Basic information of 20 CMIP5 models

ID	Short name	Institution
1	ACCESS1.0	Australian Community Climate and Earth-System Simulator, Australia
2	ACCESS1.3	Australian Community Climate and Earth-System Simulator, Australia
3	BCC-CSM1.1	Beijing Climate Center, China Meteorological Administration, China
4	CanESM2	Canadian Centre for Climate Modelling and Analysis, Canada
5	CMCC-CM	Centro Euro-Mediterraneo per I Cambiamenti Climatici, Italy
6	CMCC-CMS	Centro Euro-Mediterraneo per I Cambiamenti Climatici, Italy
7	CNRM-CM5	Centre National de Recherches Météorologiques Coupled Global Climate Model, France
8	CSIRO-Mk3.6.0	Commonwealth Scientific and Industrial Research Organization, Australia
9	GFDL-CM3	Geophysical Fluid Dynamics Laboratory, USA
10	GFDL-ESM2M	Geophysical Fluid Dynamics Laboratory, USA
11	HadGEM2-CC	Met Office Hadley Centre, UK
12	INM-CM4	Institute for Numerical Mathematics, Russia
13	IPSL-CM5B-LR	Institute Pierre-Simon Laplace, France
14	MIROC5	Model for Interdisciplinary Research on Climate, Japan
15	MIROC-ESM	Model for Interdisciplinary Research on Climate, Japan
16	MIROC-ESM-CHEM	Model for Interdisciplinary Research on Climate, Japan
17	MPI-ESM-LR	Max Planck Institute for Meteorology (MPI-M), Germany
18	MPI-ESM-MR	Max Planck Institute for Meteorology (MPI-M), Germany
19	MRI-CGCM3	Meteorological Research Institute, Japan
20	NorESM1-M	Norwegian Climate Centre, Norway

TABLE 2 All variables using in the research

Datasets/ variables	Time period	Surface	850 hPa	500 hPa	250 hPa
NCEP	(1986–2005)	Surface temperature	Air temperature, wind vector	Wind vector	Air temperature
CMIP5	(1986–2005) (2005–2100)	Surface temperature, surface level pressure	Air temperature, wind vector, geopotential height	Wind vector, geopotential height	Air temperature

meteorological elements are normalized to ΔT, V850, and U500:

The ΔT considers the anomaly of temperature difference between the upper and lower troposphere and is expressed in the following formula:

$$\Delta T = \frac{(T_{850} - T_{250}) - avg(T_{850his} - T_{250his})}{std(T_{850_{his}} - T_{250his})}. \quad (1)$$

In this formula, T_{850} denotes the area-averaged air temperature (32.5–45°N, 112.5–132.5°E) at 850 hPa and T_{250} is the area-averaged air temperature (37.5–45°N, 122.5–137.5°E) at 250 hPa; T_{850_his} and T_{250_his} are the same as T_{850} and T_{250}, but for the historical period (1986–2005); *avg* indicates a time average function and *std* is a time standard deviation function. When $\Delta T > 0$, it means that vertical temperature anomalies of warming in the lower layer and cooling in the upper layer, which can strengthen the atmospheric stability and restrain the vertical diffusion of pollutants.

The V850 considers the anomaly of meridional wind in the lower troposphere and is expressed in the following formula:

$$\text{V850} = \frac{v_{850} - avg(v_{850his})}{std(v_{850his})}. \quad (2)$$

In this formula, v_{850} indicates the area-averaged meridional wind speed (30–47.5°N, 115–130°E) at 850 hPa. For other parameters in Equation (2), please refer to Equation (1). When V850 > 0, in the lower troposphere (850 hPa, shown in Figure 1c), anomalous southerly winds in eastern China can lead to the pollutants to remain confined in the local environment under the background of northwest prevailing winds in winter.

The U500 considers the anomaly of zonal wind difference between north and south Beijing in the middle troposphere and is expressed as follows:

$$\text{U500} = \frac{(u_{500north} - u_{500south}) - avg(u_{500northhis} - u_{500southhis})}{std(u_{500northhis} - u_{500southhis})} \quad (3)$$

In this formula, u_{500_north} is the area-averaged zonal winds at 500 hPa in north Beijing (42.5–52.5°N, 110–137.5°E), and u_{500_south} is the area-averaged zonal winds at 500 hPa in south Beijing (27.5–37.5°N, 110–137.5°E). Similarly, for other instructions, please refer to Equation (1). When U500 > 0, an anomalous wind field of westerly wind strengthening in the north and weakening in the south of Beijing, bringing about an unfavourable situation for convection development and horizontal dispersion.

These three anomalies are all referenced to the historical daily climatology and normalized by the historical standard deviation to facilitate comparison between the historical and future climate. Finally, three standardized indexes are summed and then normalized to get the HWI.

$$\text{HWI} = \frac{(\Delta T + \text{V850} + \text{U500}) - avg(\Delta T + \text{V850} + \text{U500})}{std(\Delta T + \text{V850} + \text{U500})} \quad (4)$$

Positive HWI is advantageous for haze events and indicates high potential for their occurrence, whereas negative HWI is disadvantageous for haze events and indicates an unlikeliness for their occurrence. It should be pointed out that a HWI > 0 shows weather conditions conducive to pollutants accumulating in the local environment. As for HWI > 1, it indicates a higher severe haze pollution potential, but it fails to capture as many days as possible with haze occurrence potential. For convenience, we describe a HWI > 0 day as a "haze event" and a HWI > 1 day as a "severe event" in our study.

2.2.2 | Definition of 1.5 and 2.0°C scenarios

In 2015, the 21st Conference of the Parties to the Paris Accords agreed to take steps toward limiting the global mean annual surface air temperature increase to well below 2.0°C above pre-industrial levels and to pursue efforts toward a target of 1.5°C (Schleussner *et al.*, 2016). As part of an ambitious global plan, more integrated analysis on the effects of limiting global warming to 1.5 and 2.0°C is required (Lang and Sui, 2012; Li *et al.*, 2018b; Shi *et al.*, 2018).

In order to be consistent with the 20-year reference period (1986–2005), a moving average method is used to calculate the 20-year-averaged global mean surface annual temperature under the RCP4.5 and RCP8.5 (Schleussner *et al.*, 2016; Shi *et al.*, 2018). We further determine the warming periods

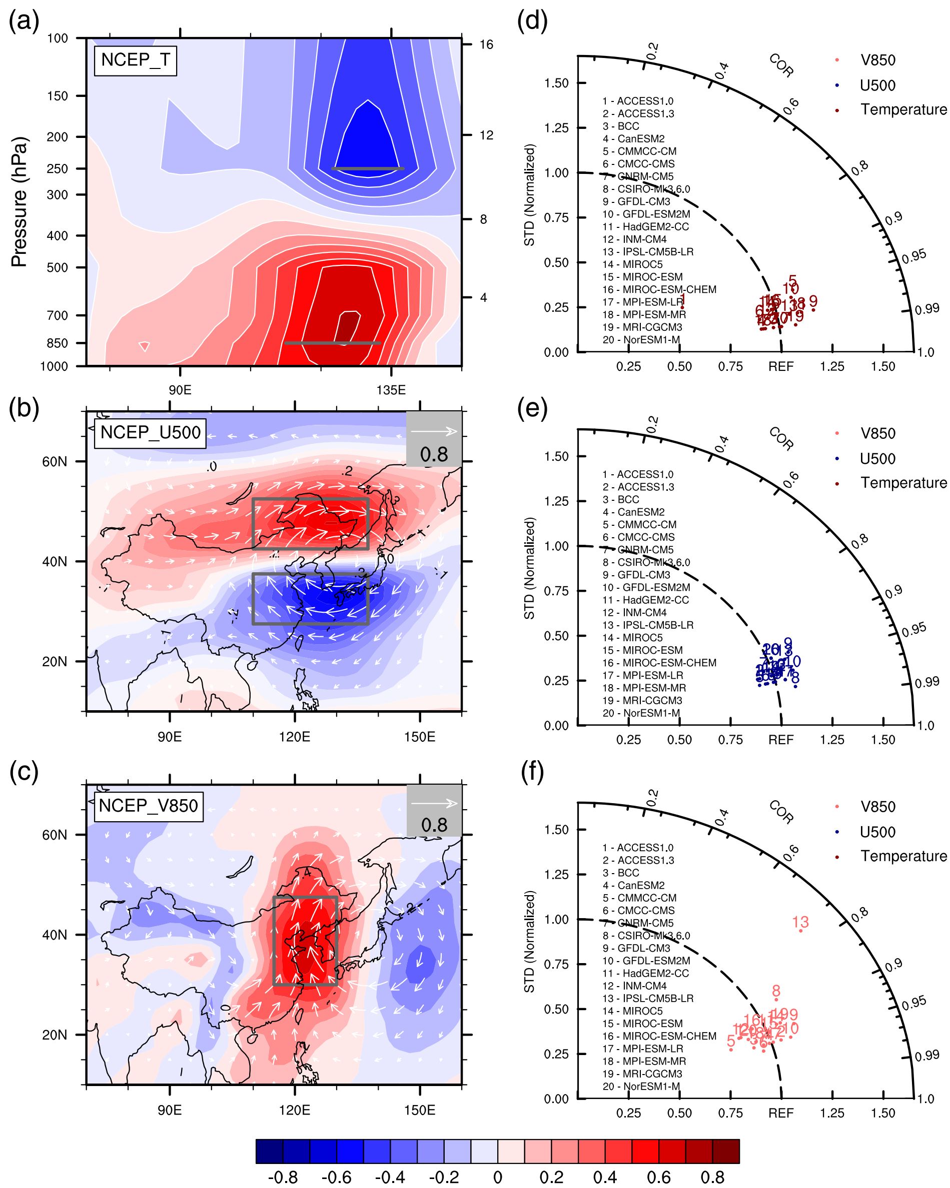

FIGURE 1 Performance of CMIP5 models in simulating meteorological anomalies (HWI > 0) during 1986–2005 period. Based on NCEP datasets: (a) 40°N vertical section distribution anomaly of atmospheric temperature with HWI > 0; (b) 500 hPa wind anomaly with HWI > 0, shading indicates zonal flow; (c) 850 hPa wind anomaly with HWI > 0, shading indicates meridional flow; (d)–(f) the correlation coefficients (the arc) and standard deviation (the *x*-axis) between each of the CMIP5 models and the NCEP datasets of the three meteorological anomalies using Taylor diagrams

with 1.5 and 2.0°C higher than the pre-industrial value (1850–1900). Accounting for the model discrepancy on the start time of the historical experiment, the warming levels are derived relative to the reference period (1986–2005) instead of the pre-industrial period (1850–1900) (Schleussner *et al.*, 2016). The reference period is 0.6°C warmer than the pre-industrial level (IPCC, 2013), which translates the global warming targets of 1.5 and 2°C as warmings of 0.9 and 1.4°C relative to the reference period level, respectively.

3 | RESULTS

3.1 | Haze events simulation and model selection

We evaluate performances of the 20 CMIP5 models in simulating the haze events (HWI > 0) using Taylor diagrams (Figure 1). This method provides a concise statistical summary in a single diagram on how well two patterns match each other based on their correlation and the normalized standard deviation (Taylor, 2001). The anomalies of HWI > 0 mean the meteorological conditions favourable to the occurrence of hazy pollution. Vertical temperature anomalies of warming in the lower layer and cooling in the upper layer shown in Figure 1a, can strengthen the atmospheric stability. The middle troposphere (500 hPa, shown in Figure 1b) displays an anomalous wind field of westerly wind strengthening in the north and weakening in the south of Beijing. In the lower troposphere (850 hPa, shown in Figure 1c), anomalous southerly winds in eastern China can lead to the pollutants to remain confined in Beijing area under the background of northwest prevailing winds in winter.

Figure 1d–f displays the correlation coefficient and normalized standard deviation between NCEP datasets and the CMIP5 models in the meteorological anomalies when HWI > 0, using Taylor diagrams. Apparently, simultaneous meteorological patterns are shown by the NCEP datasets and the 20 CMIP5 models. The normalized standard deviations of CMIP5 models are distributed between 0.75 and 1.25, except for the model ACCESS1.0 and IPSL-CM5B-LR. The correlation coefficients from the other 18 models are higher and can reach 0.95 at a 99% confidence level, while only ACCESS1.0 and IPSL-CM5B-LR own relatively low correlations. Thus, we remove ACCESS1.0 and IPSL-CM5B-LR from the 20 CMIP5 models for the purpose of decreasing error bias and keeping better consistency among the models.

The remaining 18 models are further evaluated in simulating the occurrence frequency of HWI > 0 in Figure 2, as the second reference for model selection. It is clear that the models differ substantially in the frequency of favourable weather conditions from 1986 to 2005, when HWI > 0. The frequency exhibits a wide range, from 866 to 947 days for HWI > 0 and 288 to 326 days for HWI > 1. By comparing with the NCEP datasets, we excluded the models named GFDL-CM3 and MPI-ESM-LR with the worst performance in simulating frequency of HWI > 0 and HWI > 1. As stated above, 16 CMIP5 models survived after two rounds of selection and proved to have a better ability in simulating weather conditions favourable to haze events.

3.2 | Climate change and haze events in the 1.5 and 2.0°C warming scenarios

Figure 3 shows changes in global mean surface temperature under RCP4.5 and RCP8.5 from 1986 to 2080. A good agreement in global mean surface temperature is shown between NCEP datasets and the ensemble mean from the selected 16 models, for the reference period 1986–2005. It illustrates that the projected difference of the global mean surface annual temperature under RCP4.5 and RCP8.5 is little before the 2020s, but gradually increases after the 2020s in Figure 3. The 1.5°C warming targets would occur during the periods of 2019–2039 under RCP4.5, and during the 2015–2035 under RCP8.5. The 2.0°C threshold of global warming would be reached in 2041–2061 and 2028–2048 under the RCP4.5 and RCP8.5, respectively. Compared with RCP4.5, a higher carbon emission pathway (RCP8.5) could yield a faster warming rate that crossing the 1.5 and 2.0°C thresholds earlier.

As shown above, the projection of the multi-models ensemble mean has reliable capability in simulating haze events for future warming scenarios. For the next step, we calculate the HWI for the warming periods to make a detailed statistical analysis of haze events (HWI > 0) and severe haze events (HWI > 1) (Figure 4). The statistical results of the multi-models ensemble mean for HWI > 0 and HWI > 1 in the reference period are consistent with these in the NCEP datasets, with a deviation rate of less than 5%. The frequency of HWI > 0 in the reference period is lower compared to the NCEP datasets (916 days vs. 931 days), while that of HWI > 1 is higher than the NCEP datasets (301 days vs. 288 days).

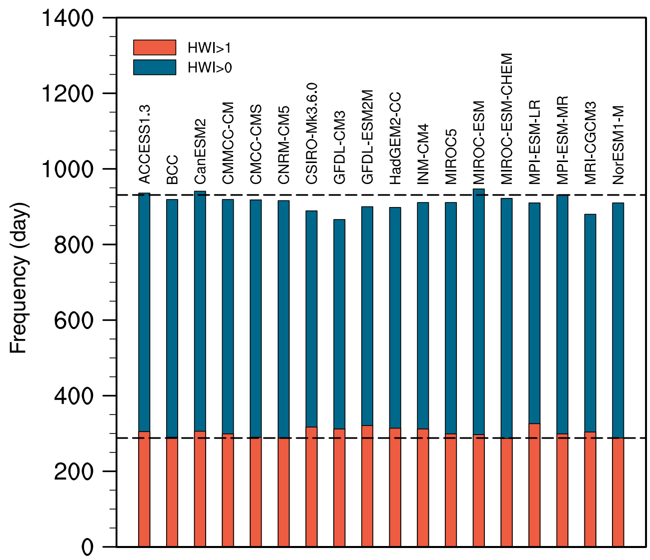

FIGURE 2 Days of weather conditions favourable to haze events in Beijing during boreal winter from 1986 to 2005. The blue column indicates days of HWI > 0; the orange column indicates days of HWI > 1. The black dashed lines show the reference days of HWI > 0 (931 days) and HWI > 1 (288 days) derived from NCEP

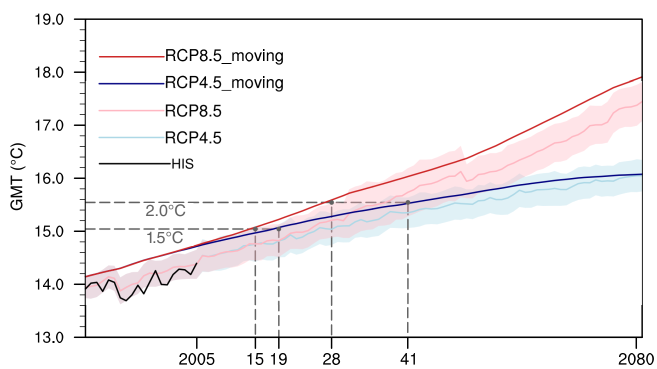

FIGURE 3 Changes in global mean surface temperature under RCP4.5 and RCP8.5 from 1986 to 2081. Light blue (light red) solid line: the 16-models-mean outputs under RCP4.5 (RCP8.5). Blue (red) solid line: The 20-year slipping averaged 16-models-mean outputs under RCP4.5 (RCP8.5). Translucent shading indicates the dispersion of one deviation from multi-model results. Horizontal reference lines in orange indicate the global warming cases of 1.5 and 2.0°C

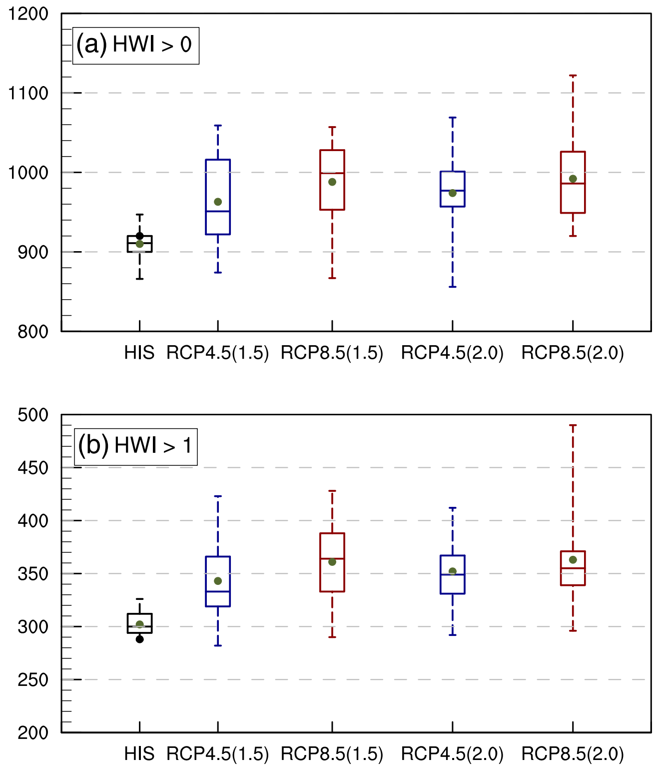

FIGURE 4 Frequency difference of HWI > 0 (>1) (days) in warming periods relative to the reference period: (a) counts the days of HWI > 0 in the historical periods and in the 1.5 and 2.0°C scenarios; (b) corresponds to (a), but for HWI > 1. The box whisker plots show the minimum, 25th, 50th, 75th, and maximum intervals of the CMIP5 experimental results. The green dots represent the results of the 16-models-mean. The black dot donates the referenced results using the NCEP reanalysis dataset

Compared with the reference period, Beijing will experience more frequent haze days under the warming period. Under RCP4.5, the frequency of HWI > 0 increases 53 days at a rate of 5.7% in the 1.5°C warming period and 80 days at a rate of 8.7% in the 2.0°C warming period. Under RCP8.5, it increases 78 days at a rate of 8.5% in the 1.5°C warming scenario and 82 days at a rate of 8.9% in the 2.0°C warming scenario. In the additional 0.5°C warming scenario, there are only 4 days increasing in frequency with HWI > 0 (Figure 4a), which is negligible.

As for the severe haze events when HWI > 1 (Figure 4b) under RCP4.5, the rate of frequency increasing can be up to 13.9% (42 days) and 19.9% (60 days) in the 1.5 and 2.0°C warming periods, correspondingly, twice as much as for the haze events HWI > 0. Similarly, the increasing frequency of HWI > 1 under RCP8.5 is 60 days (19.9%) during the 1.5°C warming period and 62 days (20.6%) during the 2.0°C warming period. Only 2 days with HWI > 1 under RCP8.5 increased in the additional 0.5°C warming period. It is worth noting that the frequency of haze events under RCP8.5 is higher than RCP4.5 in the 1.5°C warming period, but less than RCP4.5 in the additional 0.5°C period, both for HWI > 0 and HWI > 1.

3.3 | Effects of possible mechanisms on haze events changes

Our study shows a significant enhanced trend in haze days and severe haze days. The increasing frequency of haze event in the terms of meteorological factors is consistent with the mean state changes affecting the Beijing region. Figure 5 displays the changes of sea surface pressure and wind vector fields in the lower troposphere between the historical period and the warming periods under RCP4.5 and RCP8.5. A strengthened positive phase of Arctic Oscillation is displayed, which means a low in the Arctic area and two highs in the regions of the Pacific and Atlantic, respectively. Under this circumstance, cold air is confined within the high latitudes; a warmer land and a colder ocean lead to a weakening land-sea thermal discrepancy, resulting in weakening East Asian winter monsoons (Niu *et al.*, 2010; Yin and Wang, 2017). In addition, East Asia is covered by widespread anomalous southerly winds, which also verifies the above analysis. The weaker north-east wind from the high latitude fails to blow the pollutants over Beijing away, hampering the horizontal diffusion of particulate matter. More stable atmospheric stratification, caused by surface warming, may inhibit the vertical diffusion of pollutants. The difference between Figure 5a,b explains why more HWI > 0 (>1) days are shown under RCP8.5 in the 1.5°C warming periods. As for the 2.0°C warming periods, the similar intensity of Arctic Oscillation displayed in Figure 5c,d is one possible factor for no obvious HWI > 0 (>1) differences between the two scenarios. This is supported by a circulation field in the middle layer of the troposphere.

Figure 6 shows an anomaly of the cyclonic circulation over the East Asia. In addition, a strong and obvious high anomaly controls mainland China, especially East Asia, implying the weakness of the East Asian trough during the future warming periods. The shallowing East Asian trough brings less cold and dry air to the Beijing area, thus favours the formation and maintenance of haze events (Chen and Wang, 2015; Chen *et al.*, 2017).

4 | DISCUSSION

In this study, we applied a meteorological based index for the purpose of evaluating the haze events in Beijing under the 1.5 and 2.0°C global warming scenarios. The HWI considers three meteorological factors affecting the accumulation and diffusion of pollutants and is specifically designed for capturing Beijing haze events (Cai *et al*., 2017). All relevant variables can be simulated and provided based on the outputs of CMIP5 models. By contrast, application of other indexes is limited considering the data availability. For example, air environment carrying capacity involves variables, like boundary layer height, that are not provided in CMIP5 simulations (Horton *et al*., 2014; Kang *et al*., 2016; Han *et al*., 2017). The index of winter haze days based on visibility and relative humidity from ground observations is usually adopted by investigating the relationship between winter haze and climate factors in other studies as well (Li *et al*., 2016a; Zhang *et al*., 2016; Pei and Yan, 2018). However, those indexes are not appropriate when it comes to future winter haze under the background of global warming. HWI is a reliable and computable index for predicting the haze events considering weather conditions.

The present results of increased frequency of haze events in Beijing in winter under the global warming background are consistent with recent relevant studies (Cai *et al*., 2017; Han *et al*., 2017; Pei and Yan, 2018; Chen *et al*., 2019). However, for the first time, our research provides quantitative assessment of haze frequency in Beijing at different warming scenarios of 1.5 and 2.0°C under RCP4.5 and RCP8.5. The average frequency of winter haze events varies from 45 days in the reference period to 48 days during the 1.5°C warming periods and 50 days during 2.0°C warming periods under RCP4.5. Under RCP8.5, the winter average frequency in the 1.5°C warming level increases to 50 days, while in the 2.0°C warming level, it will not rise anymore. Many studies on the effects of the 2.0°C warming highlight that there are substantial differences between 1.5 and 2.0°C

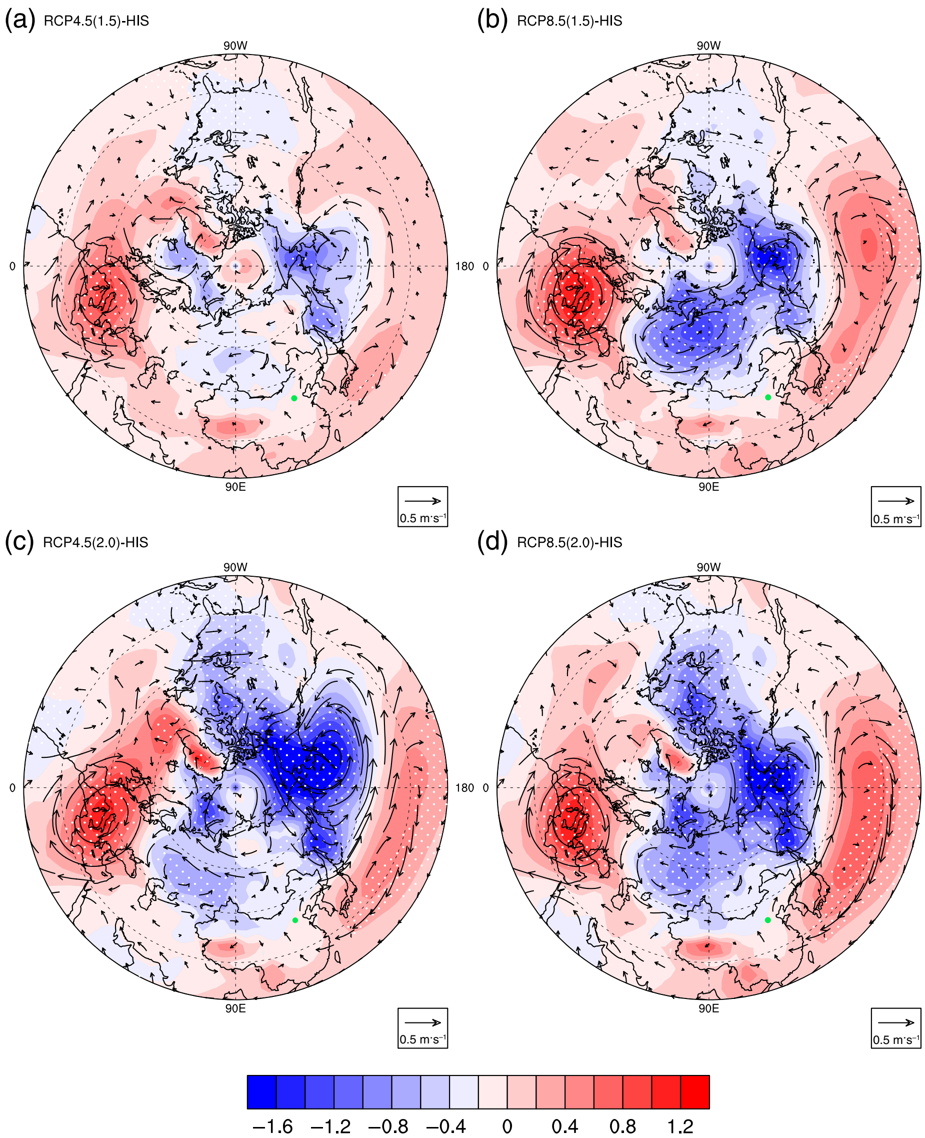

FIGURE 5 The simulated 16-models-mean anomalies of sea level pressure and 850 hPa winds vectors in boreal winter. Mean changes of 1.5°C warming periods and 2.0°C warming periods relative to the reference periods under RCP4.5 and RCP8.5 are shown in (a) and (b), (c) and (d), respectively. HIS represents the period of 1986–2005, RCP4.5(1.5) and RCP8.5(1.5) represent the periods of 2019–2038 and 2015–2034, RCP4.5(2.0) and RCP8.5(2.0) represent 2041–2060 and 2028–2047. White dots represent the area where the sea level pressure changes are significant at the 95% confidence level based on a student *t*-test

warming targets in terms of temperature extremes and precipitation extremes (Wang *et al.*, 2017; Shi *et al.*, 2018). Different from previous studies, surprisingly, we found that the 2.0°C warming will not lead to significant increases in the frequency of haze events relative to the 1.5°C warming, especially in RCP8.5.

The increasing winter haze events in Beijing can be attributed to climate change induced by greenhouse gas warming. There are many climatic factors influential to the haze events in Beijing; for example, Arctic Sea ice, Eurasian snow, Siberian high pressure, East Asian jet streams, and stratosphere warming over the mid-high latitude (Wang *et al.*, 2015; Zhang *et al.*, 2016; Zou *et al.*, 2017). This research picks out only the most probable direct circulation anomalies controlling the haze occurrence in Beijing winter, including East Asian winter monsoons, Arctic Oscillation, and the East Asian trough (Niu *et al.*, 2010; Zhang *et al.*, 2016; Yin and Wang, 2017; Li *et al.*, 2018a; Pei and Yan, 2018). A weakened East Asian winter monsoons will recede the northerlies over the central and eastern China, which is unfavourable for the outward transport of pollutants from central and eastern China, leading to more haze occurrence (Li *et al.*, 2016a; 2016b). The Arctic Oscillation was shown to greatly influence the East Asian winter monsoon (Niu *et al.*, 2010). Extraordinary, the positive phase of Arctic Oscillation pattern is changing with the scenarios, which can well explain that the difference between RCP4.5 and RCP8.5 in frequency under the warming case of 1.5°C is larger than that under the warming case of 2.0°C. The shallowing East Asian trough is responsible for haze events because its associated decreased circulation brings less cold and dry air to the Beijing area, and favours the formation and maintenance of haze events (Chen and Wang, 2015; Chen *et al.*, 2017). The subsystems of East Asian winter monsoons and the East Asian trough at different levels are dynamically coupled together (Xu *et al.*, 2016).

Climate not only affects the diffusion of pollutants, but also the formation of secondary pollutants. Model perturbation studies find that sulphate concentration increases with temperature due to the faster SO_2 oxidation, while nitrate and organic semi-volatile components convert from the particle phase to the gas phase under the temperature increase (Kleeman, 2007; Jacob and Winner, 2009). The chemical effect of global warming is not considered in our research because some of the likely trends act in opposite directions (Kleeman, 2007).

However, research on future haze situations needs to consider not only the changes in natural factors induced by global warming, but also the changes in anthropogenic aerosol emissions, which is not discussed in our research. The main human-induced pollutant sources in winter over Beijing area are fossil fuel combustion,

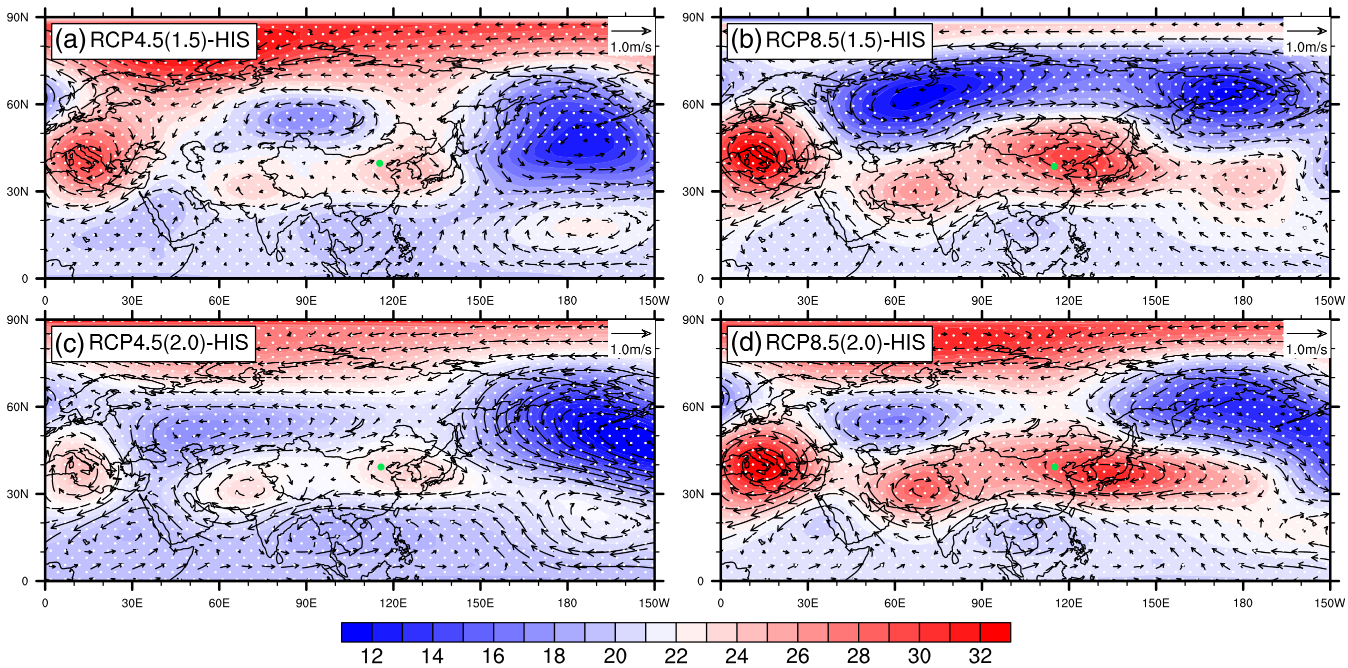

FIGURE 6 The simulated 16-models-mean anomalies of geopotential height and winds vector in 500 hPa in boreal winter. Mean changes of 1.5°C warming periods and 2.0°C warming periods relative to the reference periods in RCP4.5 and RCP8.5 are shown in (a) and (b), and (c) and (d), respectively. HIS represents 1986–2005, RCP4.5(1.5) represents 2019–2038, RCP8.5(1.5) represents 2015–2034, RCP4.5 (2.0) represents 2041–2060, RCP8.5(2.0) represents 2028–2047. All changes of geopotential height in 500 hPa exceeds the 95% confidence level (white dots)

vehicle emissions, and secondary pollutants (Zhang *et al.*, 2013a; Huang *et al.*, 2014), which are not included in our study. Because of the complexity of emission sources and chemical processes, there is few studies to date quantitatively assessed the simulated PM directly under the global warming. Therefore, we indirectly discuss the change of pollutant concentration in the future from the view of relevant meteorological factors. The air environment carrying capacity is projected by the ensemble to decrease and in almost the entire region except central China by the end of the 21st century (Han *et al.*, 2017). Earlier researches shows that the effect of meteorological factor induced by global warming can account for 11–28% of the changes of air pollution days over eastern China (Chen *et al.*, 2019). In recent years, the Chinese government has implemented effective controls on pollution emissions. Thus, an analysis of haze events using a coupled climate model considering the integrated and complicated effects from both climate change and human activities is required in future research.

5 | CONCLUSION

This study aimed to predict the occurrence of winter haze events in Beijing under 1.5 and 2.0°C global warming scenarios based on the NCEP dataset and CMIP5 model simulations; and depict meteorological factors related to winter haze events using HWI index. Our results suggested that the ensemble mean of models from CMIP5 can effectively characterize the spatial pattern and frequency of Beijing's winter haze events. Compared with the historical period (1986–2005), the occurrence of winter haze events in Beijing increases markedly during the global warming periods (2020–2050s), a 6–8% rise in the occurrence of winter haze events, in detail, is predicted. We also found the frequency of winter haze events under RCP8.5 is higher than RCP4.5 in the 1.5°C global warming period, but maintains the same level with RCP4.5 in the 2.0°C global warming period, for both the normal haze events and severe haze events. In other words, warming of 2.0°C will not necessarily result in more frequent haze events in Beijing, especially for RCP8.5 scenario. Last but not least, the predicted increase in Beijing's winter haze events could be greatly attributed to stronger atmospheric inversions, weaker East Asian winter monsoons, and a shallowing East Asian trough induced by global warming.

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