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Influence of Human Activities on Wintertime Haze-Related Meteorological Conditions over the Jing–Jin–Ji Region

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ABSTRACT

This work analyzes and discusses the influence of human activities on the meteorological conditions related to winter haze events in Beijing, Tianjin, and Hebei (i.e., the Jing–Jin–Ji region) during 1961–2016, using the results of two numerical simulation experiments based on the Community Atmosphere Model version 5.1.1 (http://www.cesm.ucar.edu/models/cesm1.0/cam/docs/ug5_1_1/book1.html) used in the international Climate Variability and Predictability Programme (CLIVAR) Climate of the 20th Century Detection and Attribution Project (C20C+ D&A). The results show that, under the influence of human activities, the changes in dynamical and thermal meteorological conditions related to winter haze events in the Jing–Jin–Ji region are conducive to the formation and accumulation of haze, and prevent the diffusion of pollutants. The dynamical conditions mainly include the obvious weakening of the East Asian winter monsoon (EAWM) and the enhancement of the near-surface anomalous southerly wind. The thermal conditions include the obvious increase in surface temperature, and the enhancement of water vapor transport and near-surface inversion. The relative contribution of dynamical and thermal conditions to the variation of haze days in the Jing–Jin–Ji region is analyzed using statistical methods. The results show that the contribution of human activities to the increase of haze days in the Jing–Jin–Ji region is greater than that of natural forcing for the study period. To be specific, the dynamical meteorological factors contribute more to the haze days than the thermal meteorological factors. The contribution of thermal meteorological factors is basically the same in both scenarios.

1. Introduction

Weather conditions are crucial in air pollution episodes, and the atmospheric diffusion and dilution of pollutants vary greatly under different weather conditions [1]. Weather/climate factors (or meteorological parameters) that affect haze or aerosol amount have been investigated, including surface temperature, near-surface wind speed, surface relative humidity (RH), precipitation, and sea-level pressure. Most of these studies are based on the statistical relationship between haze days and meteorological variables [2–13]. More recently, some studies have begun to highlight weather/climate factors that could cause increased haze days in China, such as the East Asian winter monsoon (EAWM) and the El Niño–Southern Oscillation [14,15]. In addition, recent new studies reported that the decline of Arctic sea ice under global warming contributes positively to the increase in haze days in eastern China [16–19]. It is important to point out that the feedback between meteorology and aerosol can also play a significant role. Aerosols can decrease the near-surface wind speed and the height of the planetary boundary layer by reducing the solar radiation reaching the surface, further enhancing the surface haze pollution [20].

The formation and accumulation of wintertime haze over eastern China are strongly related to global warming. Wu et al. [21]

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found that the increase in wintertime surface temperature, decrease in surface RH, increase in atmospheric stability, and weakening EAWM caused by global warming all promote an increase in haze days in winter over central–eastern China. Zhang et al. [22] proposed that the wind decline caused by climate warming and the worsening of other meteorological conditions are directly related to local aerosol pollution episodes in Beijing. Moreover, weather conditions can increase the frequency of severe haze in Beijing under global climate change [23]. As suggested by previous studies (e.g., Refs. [24–26]), human activities such as rapid industrialization, rapid modernization, and enormous anthropogenic emissions of greenhouse gases (GHGs) and aerosols can trigger various meteorological disasters by modulating the weather conditions. But, can human activities influence the weather conditions related to haze days? If so, can the impacts be quantified? How much do human activities contribute to haze days? These questions are crucial scientific issues in the fields of both climate change and pollution research, and have attracted increased attention from policymakers and the public.

With the improvement of climate models and computational ability, more research is focusing on the impacts of human activities on the global and regional mean temperature, extreme temperature, and precipitation [27–33]. Furthermore, the profound impacts of aerosol pollution on climate anomalies have aroused considerable concern. For example, Garrett and Zhao [34,35] described how anthropogenic pollution from the mid-latitudes contributes to a strong Arctic warming in winter and spring. Zhao et al. [36] showed that aerosol pollution can enlarge the precipitation area of a tropical cyclone. In addition, Yang et al. [37] showed that the anthropogenic pollution from the Pearl River Delta contributes significantly to the decadal variation of surface air temperature in winter over Hong Kong, China. Li et al. [25] summarized anthropogenic effects on weather and climate using both observations and models. Previous studies on atmospheric pollution have mainly focused on the evaluation [38] and projection [39] of the atmospheric capacity of transporting pollutants using climate models.

Recently, the international Climate Variability and Predictability Programme (CLIVAR) Climate of the 20th Century Detection and Attribution Project (C20C+ D&A) [40] organized by the World Climate Research Program (WCRP) conducted a large pool of sensitive detection and attribution experiments in order to understand anthropogenic and natural influences on climate change. Compared with the Coupled Model Intercomparison Project phase 5 (CMIP5)[†], the C20C+ D&A Project is more suitable for research on anthropogenic influence on the global climate. Based on the output of the C20C+ D&A Project, the influence of human activities on extreme weather and climate events has been investigated [41–48].

However, few researchers have studied anthropogenic influences—including transportation, industry, land use, fossil fuel combustion, and many other aspects—on the meteorological conditions of haze pollution over the Jing–Jin–Ji region, where severe haze events occur frequently [26]. Therefore, using simulation results with and without anthropogenic influences, we herein attempt to analyze the impact of human activities on wintertime haze-related meteorological conditions over the Jing–Jin–Ji region. The remainder of this paper is organized as follows. Section 2 presents the data and methods. The influence of human activities on meteorological conditions is analyzed in Section 3. The contribution of dynamical and thermal meteorological conditions to haze is shown in Section 4. Section 5 provides conclusions and discussion.

[†] http://www.cesm.ucar.edu/experiments/cmip5.html.

2. Data and methods

2.1. Model simulations and data

This study uses the Community Atmosphere Model version 5.1.1 (CAM5.1.1), which was part of the C20C+ D&A Project. CAM5.1.1 is the atmospheric component of the Community Earth System Model version 1.0.3 (CESM1.0.3). Its horizontal resolution is $1.25^\circ \times 0.9375^\circ$ (longitude (lon) $\times$ latitude (lat)), with 30 vertical hybrid height-pressure levels. A finite-volume dynamical core is used in CAM5.1.1. The land surface scheme employs the Community Land Model version 4.0 (CLM4.0).

CAM5.1.1 has been run under two different types of benchmark scenarios in the C20C+ D&A Project. One set of scenario simulations was driven with observed boundary conditions (including observed GHGs, sulfate aerosols/harmful aerosols, black carbon aerosols, dust aerosols, sea salt aerosols, ozone, land cover/use, sea surface temperature (SST), and sea ice coverage (SIC)). This scenario is intended to represent the atmosphere under all forms of observed historical forcing (hereinafter called "All-Hist"). The other scenario is unreal. In this scenario, solar and volcanic forcing is in accordance with All-Hist, but GHG concentrations, ozone concentrations, and aerosol burdens adopt the estimated values from the year 1855. SSTs are calculated according to CMIP5 models[†] under historical natural forcing only. Sea ice concentrations are adjusted according to the temperature–ice relationship, so that the sea ice is in accordance with a cooler temperature. The land cover/use change in this scenario is the same as that in the All-Hist simulations. This scenario is intended to represent the atmosphere without anthropogenic influence (hereinafter called "Nat-Hist"). Thus, in this study, the effect of human activities on the climate system is limited to anthropogenic changes in the composition of the atmosphere. For detailed model information, please see Table 1 and Stone et al. [40].

The outputs of the simulations comprise daily and monthly temperature, precipitation, pressure, wind speed, RH, geopotential height, and so forth[‡].

2.2. Methods

According to previous studies, the meteorological conditions related to wintertime climate variability over the Jing–Jin–Ji region are divided into two categories: dynamical and thermal conditions. Dynamical conditions include the EAWM and the near-surface wind speed, while thermal conditions include surface temperature, RH, and temperature inversion. Therefore, changes in these factors under the All-Hist and Nat-Hist scenarios are contrasted to examine whether or not human activities influence the meteorological conditions related to wintertime haze over the Jing–Jin–Ji region. For the performance of these models, please refer to Risser et al. [47]. We assume that the differences in the spatiotemporal evolution of the meteorological conditions simulated under the two scenarios are caused by the impact of human activities to an extremely large extent.

As mentioned earlier, the study area in this paper is the Jing–Jin–Ji region (36°N–42.5°N, 113°E–120°E) and "winter" is defined as the time period from the beginning of December of one year to the end of February of the next year. Fig. 1 shows the spatial patterns of stations and wintertime haze days in 1961–2016 over this region. As shown in Fig. 1, the number of haze days over the western and southern parts of the Jing–Jin–Ji region and the surrounding areas of Beijing is greater than that in other parts of the study

[‡] http://portal.nersc.gov/c20c/.

Table 1
Simulations of the CAM5.1 model. Resolution: 1.25° × 0.9375° (lon × lat).

Scenario	Simulations	Period covered
All-Hist	50	1959-01-01–2017-12-31
	50	1996-01-01–2017-12-31
	300	2010-01-01–2017-12-31
Nat-Hist	50	1959-01-01–2017-12-31
	50	1996-01-01–2017-12-31
	300	2010-01-01–2017-12-31

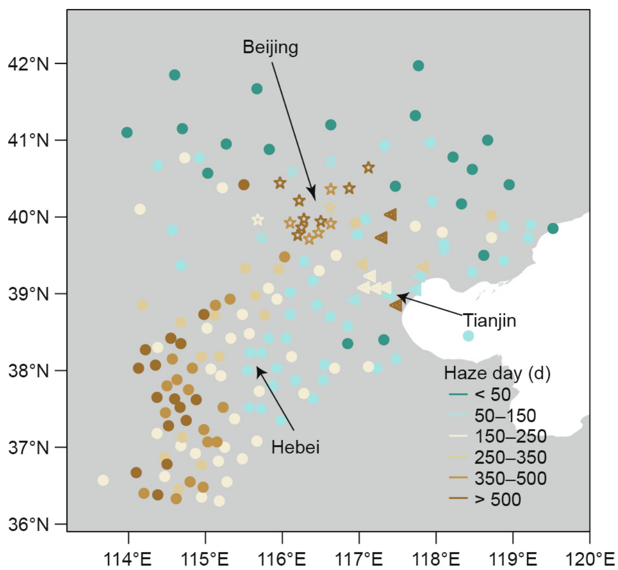

Fig. 1. Spatial distribution of meteorological stations and the total number of wintertime haze days (d) during 1961–2016 over the Jing–Jin–Ji region. The pentagrams (triangles; dots) denote stations within Beijing (Tianjin; Hebei) area.

area. The total number of wintertime haze days was over 500 d during 1961–2016, with an annual average of about 10 d. Haze days are mainly determined based on the daily observed weather phenomena from the National Meteorological Information Center of China; the criteria are listed as follows. The visibility at a fixed time of the day is less than 10 km, the RH at the corresponding time of day is less than 90%, and the haze phenomenon is recorded on that day. Meanwhile, there is no precipitation, blowing snow, snowstorm, sandstorm, dust, smoke, and so forth, which can lead to low visibility.

Because of the renewal of meteorological observation instruments after 2013, we have corrected the visibility data after 1 January 2013 using the method provided by Pei et al. [49]; that is, the original visibility is divided by 0.766. In all 16 typical years (1980, 1981, 1982, 1998, 1999, 2001, 2005, 2006, 2007, 2008, 2010, 2011, 2013, 2014, 2015, and 2016) with five or more wintertime haze days over the Jing–Jin–Ji region were selected. Fig. 2 shows the wintertime haze days from 1961 to 2016. The mean annual number of haze days in winter is 4.6 days. After 2013, a sharp increase in wintertime haze days occurred, with more than 20 wintertime haze days per year. These phenomena are not only caused by the rapid development of the Chinese economy, but are also related to the change in weather conditions, such as the weakening of the EAWM, reduced near-surface wind speed, increase in surface temperature, reduced RH, and formation of temperature inversion [21,50–52].

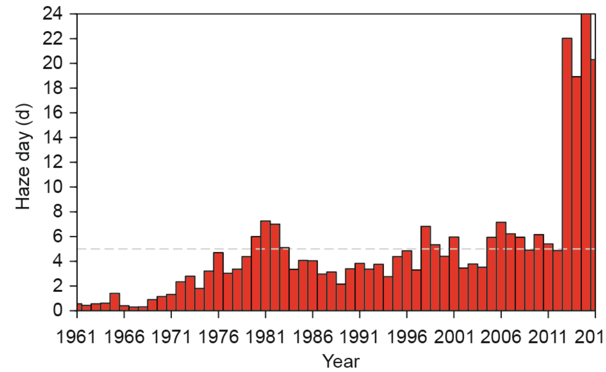

Fig. 2. Time series of wintertime haze occurrence over the Jing–Jin–Ji region during 1961–2016. The horizontal dashed line indicates the haze days of five.

3. Influence of human activities on meteorological conditions related to wintertime haze over the Jing–Jin–Ji region

3.1. Dynamical conditions

The EAWM is one of the most active circulations during the winter in the Northern Hemisphere, and has an important influence on weather and climate over China. It consists of the near-surface northwesterly flow, which steers polar cold air to the south along the east coast of Asia, the Siberian high in the sea-level pressure field, and the East Asian major trough from the east coast of China to Japan at 500 hPa. A strong EAWM often brings severe cold air and northerly wind, which can promote the dilution and diffusion of pollutants. On the contrary, a weak EAWM is closely related to the increase of haze in winter [25]. Therefore, the near-surface wind speed is strongly linked to haze. We have selected the regional mean of the geopotential height field at 500 hPa over 25°N–40°N, 110°E–130°E to represent the strength of the EAWM. The normalized regional mean of the geopotential height at 500 hPa over this region multiplied by −1 is used as the EAWM index (EAWMI) in this paper. An increased EAWMI represents a stronger EAWM, and vice versa [21,53].

3.1.1. East Asian winter monsoon

The East Asian trough is an important circulation system in the middle troposphere during the winter in the Northern Hemisphere. Fig. 3 shows a time series of the wintertime 500 hPa geopotential

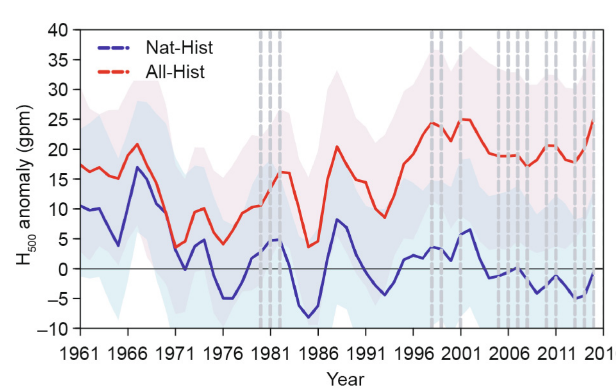

Fig. 3. Time series (moving average) of the regional mean wintertime 500 hPa geopotential height (H_{500}) anomaly over the Jing–Jin–Ji region under the All-Hist (red curve) and Nat-Hist (blue curve) scenarios compared with the average for 1981–2010 under the Nat-Hist scenario. The shading represents the range of 25%–75% in 100 simulations, solid curves represent the medians of 100 simulations, and gray dotted lines represent the years with more haze days. 1 gpm = 9.8 $J\cdot kg^{-1}$.

height (H_{500}) over the Jing–Jin–Ji region under the scenarios with (All-Hist) and without (Nat-Hist) human-activity forcing. Under the All-Hist scenario, the wintertime height over this region is significantly higher than under the Nat-Hist scenario, especially after the 1990s; therefore, human activities have a major effect on the geopotential height field in the middle troposphere. Moreover, the wintertime geopotential height fields in both scenarios over the Jing–Jin–Ji region undergo relatively consistent stage changes—that is, the decline stage (1960s–1970s) and the wavelike rise stage over a nearly 20-year period (1980s–2000s). From the beginning of the 21st century, the geopotential height field changes into a relatively stable period, with a small range of change. It is clear that under the influence of human activities, the Jing–Jin–Ji region is basically under the control of positive height anomalies. On the one hand, change in the geopotential height field is accompanied by an adjustment of the wind field; on the other hand, it will affect the change in surface temperature through the rising/cooling and sinking/warming of air flow. Details on the changes in wind and surface temperature will be discussed in Section 3.1.2 and Section 3.2.1, respectively.

Further analysis of the time series of the EAWMI (Fig. 4) shows that the strength of the EAWM presented a rising trend under both scenarios before the 1980s, and that the intensity under the Nat-Hist scenario was generally greater than the intensity under the All-Hist scenario. After that, the strength of the EAWM under the All-Hist scenario weakened significantly, while the strength of the EAWM under the Nat-Hist scenario increased gradually. Since the mid-1980s, the interdecadal weakening trend of the EAWM under the All-Hist scenario is obvious, which is basically consistent with the observed results [21,54]. In addition, all of the years with more hazy days occurred during the weakening stage of the EAWM. This finding suggests that under the influence of human activities, the EAWM weakened significantly. The cold air was inactive; thus, the number of stable-weather days increased and the atmospheric diffusion of particulate matter weakened. At the same time, the Chinese economy entered into a rapid development stage, with the amount of particulate matter produced by urban populations, industry, and motor vehicles increasing substantially. This was also conducive to the increase in haze days over the Jing–Jin–Ji region.

3.1.2. Changes of near-surface wind

The strength of the EAWM directly affects the near-surface wind speed, and the near-surface wind is the key driving force for the dilution and transportation of pollutant particles. Fig. 5 shows that the near-surface (925 hPa) zonal wind speed influencing the Jing–Jin–Ji region has shown a significant decreasing trend

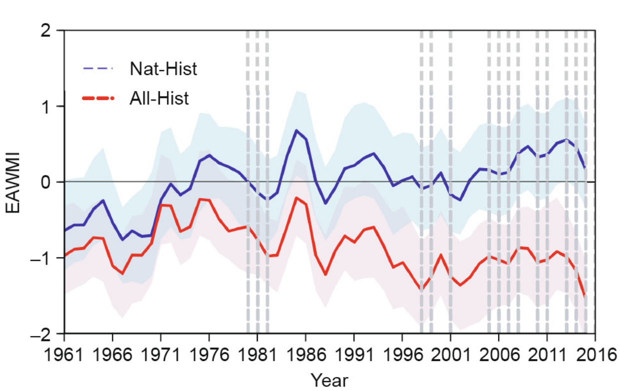

Fig. 4. Normalized time series (moving average) of EAWMI under the All-Hist (red curve) and Nat-Hist (blue curve) scenarios compared with the average for 1981–2010 under the Nat-Hist scenario. The shading represents the range of 25%–75% in 100 simulations, solid curves represent the medians of 100 simulations, and gray dotted lines represent the years with more haze days.

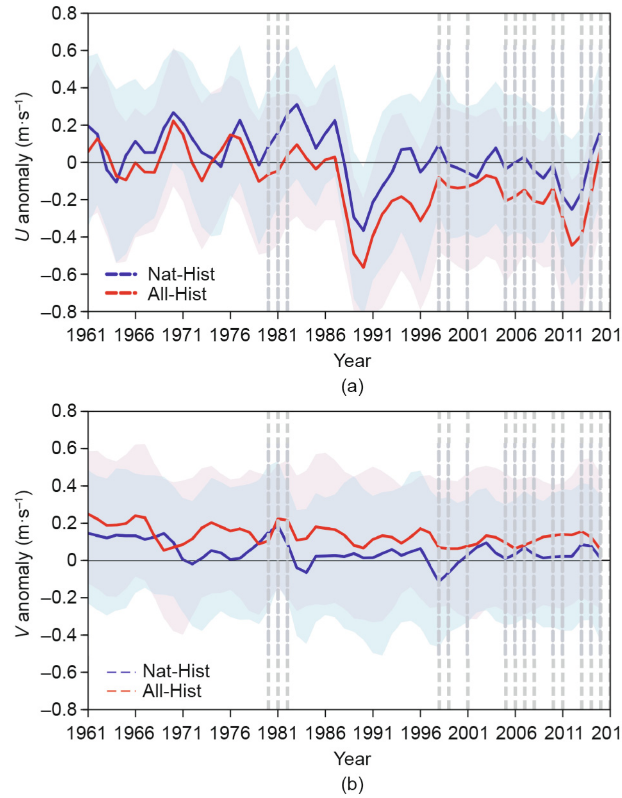

Fig. 5. Time series (moving average) of the (a) wintertime near-surface zonal (U) and (b) meridional (V) wind speed anomaly ($m\cdot s^{-1}$) under the All-Hist (red curve) and Nat-Hist (blue curve) scenarios compared with the average for 1981–2010 in the Nat-Hist scenario. The shading represents the range of 25%–75% in 100 simulations, solid curves represent the medians of 100 simulations, and gray dotted lines represent the years with more haze days.

since the mid-1980s under the All-Hist and Nat-Hist scenarios, and the evolution trends under both scenarios are almost the same. However, the near-surface zonal wind speed decreases more significantly under the All-Hist scenario (Fig. 5(a)). Also, the southerly wind speed under the All-Hist scenario is stronger than that under the Nat-Hist scenario (Fig. 5(b)). This means that the southerly wind speed increases significantly under the influence of human activities, which is conducive to the northward transportation of pollutants from the southern part and the area south of the Jing–Jin–Ji region. Meanwhile, it decreases the diffusion of near-surface pollutants over the Jing–Jin–Ji region. These results indicate that under the influence of human activities, the weakening of westerly wind and the enhancement of southerly wind at low levels, which are accompanied by the weakening of the EAWM, are partly responsible for the increased haze days.

3.2. Thermal conditions

The results in Section 3.1 show that human activities do have a certain impact on the dynamical meteorological conditions related to haze. This section will mainly analyze the influence of anthropogenic activities on thermal meteorological conditions related to haze.

3.2.1. Changes in temperature

Fig. 6 shows a time series of wintertime surface temperature under the All-Hist and Nat-Hist scenarios. Under the All-Hist scenario, the wintertime temperature over the Jing–Jin–Ji region experienced an interdecadal variation in the mid-1980s, which was consistent with the interdecadal variation of the EAWM. Before

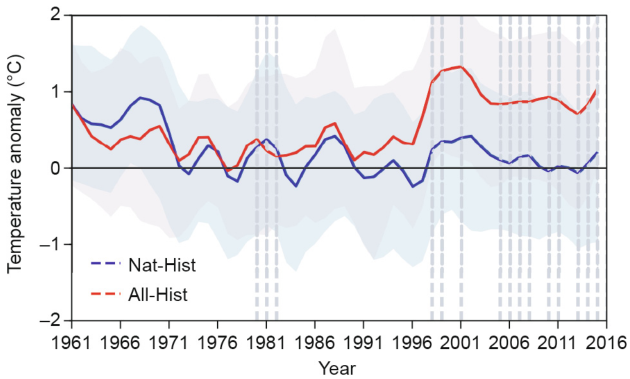

Fig. 6. Time series (moving average) of the wintertime surface temperature anomaly under the All-Hist (red curve) and Nat-Hist (blue curve) scenarios compared with the average for 1981–2010 under the Nat-Hist scenario. The shading represents the range of 25%–75% in 100 simulations, solid curves represent the medians of 100 simulations, and gray dotted lines represent the years with more haze days.

the mid-1980s, the temperature over the Jing–Jin–Ji region was lower and the haze days were less frequent. After that the situation was opposite to the situation before the mid-1990s. The temperature remained at a high level in the early 21st century, and the number of active haze years increased accordingly. Under the Nat-Hist scenario, the wintertime temperature over the Jing–Jin–Ji region remained at the average level since the 1970s.

3.2.2. Changes in RH and water vapor transportation

RH is an important condition for haze formation. Compared with other seasons, the number of rainy days in winter over the Jing–Jin–Ji region is significantly lower [13]. The effect of RH mainly manifests as moistening in haze formation [55]. The time series of RH under the All-Hist and Nat-Hist scenarios are similar (Fig. 7). The RH under both scenarios showed a significant interdecadal increase from the mid-1980s to the mid-1990s, after which it decreased dramatically. The increase in RH under the All-Hist scenario was larger than the increase under the Nat-Hist scenario, indicating that human activities may increase the RH over the Jing–Jin–Ji region. To some extent, the rise in RH will increase the water absorption of particulate matter in the dry atmosphere over northern China, resulting in an increase in haze days.

3.2.3. Change in temperature inversion

Haze intensity is related not only to the instability of atmospheric stratification in the lower troposphere, but also to the

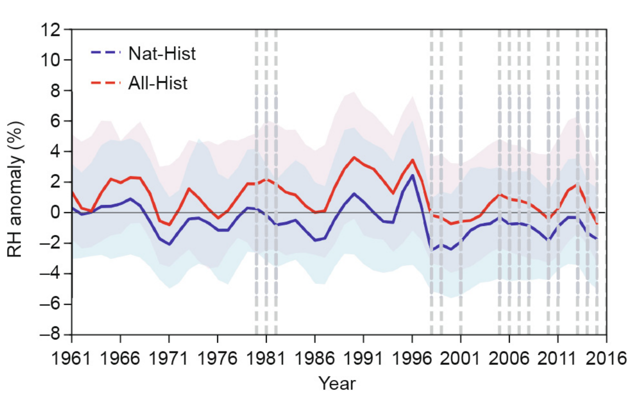

Fig. 7. Time series (moving average) of the wintertime surface RH anomaly under the All-Hist (red curve) and Nat-Hist (blue curve) scenarios compared with the average for 1981–2010 under the Nat-Hist scenario. The shading represents the range of 25%–75% in 100 simulations, solid curves represent the medians of 100 simulations, and gray dotted lines represent the years with more haze days.

inversion of the near-surface temperature. To study the situation of the near-surface inversion, Fig. 8 shows vertical sections of wintertime temperature over the Jing–Jin–Ji region under the All-Hist and Nat-Hist scenarios. Under the All-Hist scenario, the temperature in the middle troposphere presents a more consistent increase, and gradually develops toward the upper level after the mid-1990s. Since the 21st century, the warming of the temperature in the middle troposphere has become more obvious, with a warming amplitude of more than 1.0 °C. However, under the Nat-Hist scenario, the temperature in the middle troposphere does not show a continuous and obvious warming phenomenon, except in the 1960s and 1970s. This indicates that, under global warming, thermal conditions in the low levels are not conducive to the diffusion of pollutants, and the features of temperature inversion are evident.

4. Contribution of dynamical and thermal meteorological conditions to haze days

The foregoing analyses show that the dynamical and thermal effects of the atmosphere have a major impact on the occurrence of haze days. Although aerosols related to human activities are linked to haze days [50], further research is required on how much the meteorological conditions influenced by human activities contribute to haze days. In this section, we analyze the contributions of dynamical and thermal meteorological conditions to haze formation under the All-Hist and Nat-Hist scenarios.

As previously described, dynamical conditions include H_{500}, the EAWMI, and the near-surface zonal (U) and meridional (V) wind speed. Thermal conditions include temperature, RH, and temperature inversion. To examine the independence of each meteorological factor, we calculated the correlation coefficients between these factors, and found that there is a significantly negatively correlation between H_{500} and the EAWMI, with a temporal correlation coefficient (TCC) of −0.91. There is also a significantly positively correlation between H_{500} and near surface air temperature (T_{as}), with a TCC of 0.74. Therefore, when establishing the multiple linear regression (MLR) equations, we removed the factor H_{500}. Although there are also some correlations between the other factors, the correlation coefficients are small. Based on the above analyses, the MLR equations of wintertime haze days over the Jing–Jin–Ji region during 1961–2016 were established as follows:

The linear regression equation under the All-Hist scenario is

$$\text{Haze days} = -2.735\text{EAWMI} - 2.527U - 12.179V + 2.244T_{as} - 3.266$$

The linear regression equation under the Nat-Hist scenario is

$$\text{Haze days} = 2.1777\text{EAWMI} + 4.1085U - 0.5391V - 4.2665T_{as} + 0.6966$$

The units for haze days, EAWMI, U, V, and T_{as} are d, gpm (1 gpm = 9.8 J·kg^{-1}), m·s^{-1}, m·s^{-1}, and °C, respectively.

Fig. 9 shows the time series of observed and simulated wintertime haze days under the two scenarios. The dynamical and thermal meteorological factors are considered separately and jointly, respectively. It can be seen that there is a good consistency between the regressed haze days by all factors under the two scenarios and the observed values (Table 2). The correlation coefficients of the two are 0.48 and 0.37, respectively, exceeding the 99% confidence level, which basically reflects the growing trend in observed wintertime haze days over the Jing–Jin–Ji region (especially after 2010), and the regression values can explain 22.5% and 14.2% of the total variations. This finding indicates that human activities positively contribute to the changes in wintertime haze days over the Jing–Jin–Ji region. Similarly, when only considering dynamical meteorological factors, the TCCs between the regressed and observed values under the scenarios of All-Hist and Nat-Hist

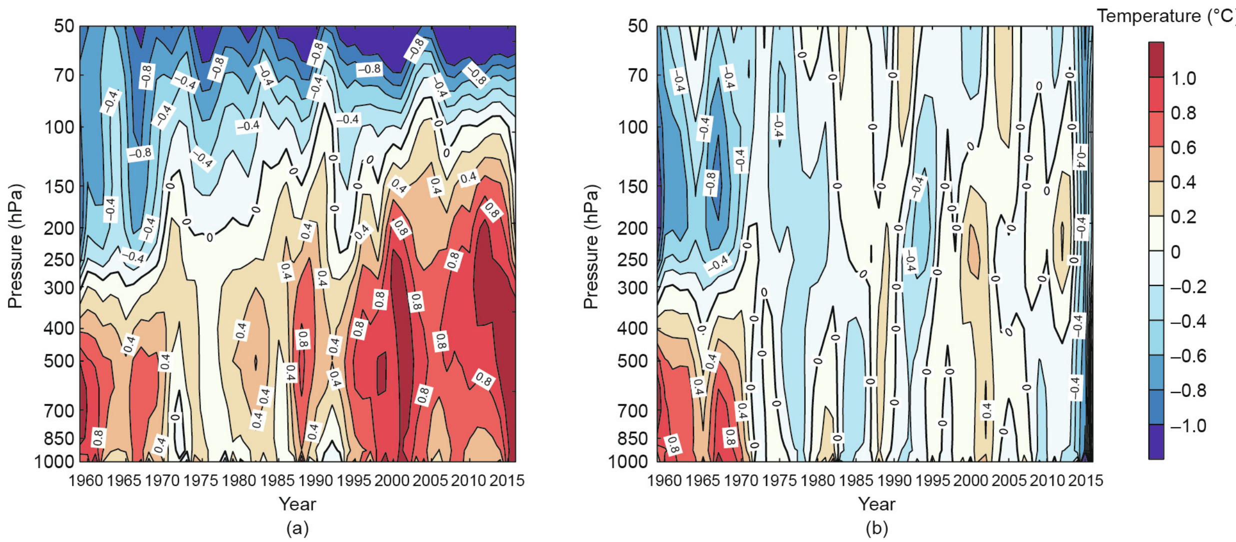

Fig. 8. Vertical cross-sections of wintertime temperature anomaly under the (a) All-Hist and (b) Nat-Hist scenarios, compared with the average for 1981–2010 in the Nat-Hist scenario. Reproduced from Ref. [9] with permission of Royal Meteorological Society, ©2020.

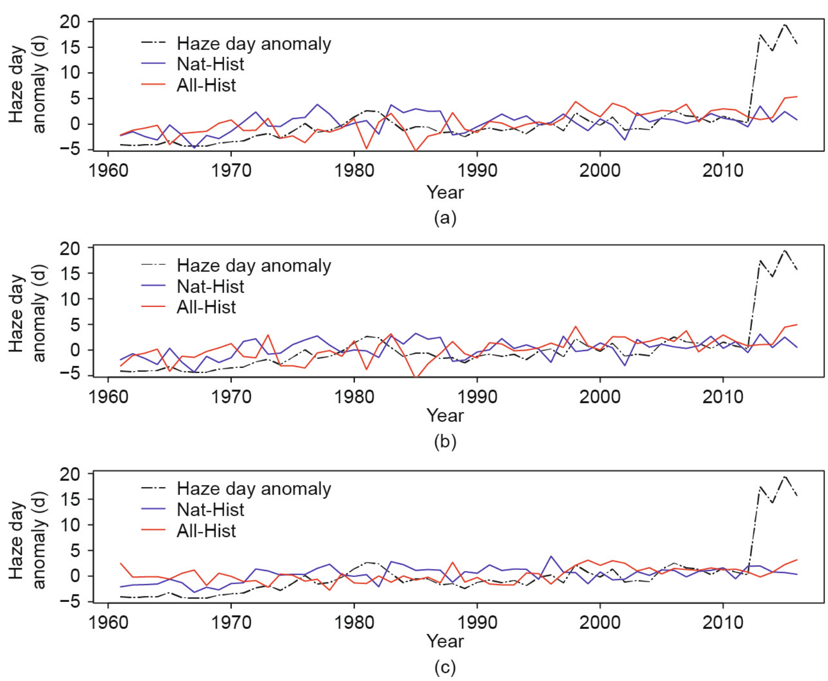

Fig. 9. Time series of observed wintertime haze day anomaly (dashed curves; day) and multiple linear regression of wintertime haze days with dynamical and thermal factors (solid curves; days) during 1961–2016. (a) All factors; (b) dynamical factors; (c) thermal factors.

Table 2
Statistic results of dynamical factors, thermal factors, and both.

Statistical analysis	All factors		Dynamical factors		Thermal factors	
	Nat-Hist	All-Hist	Nat-Hist	All-Hist	Nat-Hist	All-Hist
F test	*	*	—	*	**	—
Analytic variance	14.2%	22.5%	12.4%	20.1%	8.5%	8.4%
TCC	0.37	0.48	0.35	0.45	0.29	0.29

Single and double asterisks denote statistic results exceeding the 95% (*) and 99% (**) confidence level, respectively.

are 0.45 and 0.35, respectively, which can account for 20.1% and 12.4% of the total variance, respectively. Note that the variance contribution under the All-Hist scenario is obviously larger than that under the Nat-Hist scenario. When only considering the thermal factors, the TCCs are both 0.29, suggesting that the variance contributions under both scenarios are basically identical.

Based on the above statistical analyses, the contribution of human activities (under the All-Hist scenario) to the increase in wintertime haze days over the Jing–Jin–Ji region is greater than the contribution of natural forcing alone, where the contribution of dynamical factors is greater and the contributions of thermal factors in both scenarios are basically similar.

5. Conclusions and discussion

In this paper, the influence of human activities on meteorological conditions related to wintertime haze events over the Jing–Jin–Ji region is analyzed under two scenarios (All-Hist and Nat-Hist) using the simulation results from CAM5.1, which was part of the C20C+ D&A Project. The main conclusions are as follows:

Under the influence of human activities, the dynamical conditions related to wintertime haze events over the Jing–Jin–Ji region—including the obvious weakening of the EAWM, enhancement of abnormal southerly wind in the lower troposphere, and reduction in near-surface wind speed—all hinder the diffusion of haze.

Under the influence of human activities, the thermal conditions related to wintertime haze events over the Jing–Jin–Ji region—including an obvious increase in temperature, the enhancement of water vapor transportation, a rise in RH, and temperature inversion—have greatly strengthened the formation and accumulation of haze.

The relative contributions of dynamical and thermal factors show that the contribution of human activities to increased haze days over the Jing–Jin–Ji region is greater than that of natural forcing, and the contribution of dynamical factors is greater than thermal factors. The contributions of thermal factors under both scenarios are basically the same.

These results have qualitatively diagnosed the impacts of human activities on haze-related meteorological conditions. In the future, we will detect and attribute the contribution of human activities on haze-related meteorological conditions quantitatively using the "optimal fingerprint" method. Other meteorological factors that can affect the occurrence of haze will also be investigated. In this study, only a number of samples from one model were selected; the results of multiple models and multiple samples can be used for further analyses in future studies.

Furthermore, in addition to haze-related meteorological parameters, other factors such as aerosol emission sources [56], ozone [57], and even afforestation [58] have been linked to haze variations in China. Therefore, further exploration of these factors could be conducive to a better understanding of haze formation in China.

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Compliance with ethics guidelines

Ying Xu, Yanju Liu, Zhenyu Han, Botao Zhou, Yihui Ding, Jie Wu, Tongfei Tian, Rouke Li, and Jing Wang declare that they have no conflict of interest or financial conflicts to disclose.

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