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Atmospheric Circulation Patterns Conducive to Severe Haze in Eastern China Have Shifted Under Climate Change

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Key Points:

- Atmospheric circulation anomalies associated with the most severe haze pollution are identified
- Haze formation in eastern China has shifted from causes of local accumulation in northern China to regional transport in southern China
- Climate change under the sustainable and intermediate development scenarios are the ideal paths to reduce haze in China

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract

Regional atmospheric circulation patterns affect haze pollution and they change in the warming climate. Here, the characteristics of atmospheric circulation anomalies conducive to extreme haze occurrence in China and their historical and future trends are examined based on surface observations, reanalysis data, aerosol source tagging technique, and multimodel intercomparison results. December 2016 and 2017 are identified as the worst months of haze pollution over northern and southern China, featuring weakened and strengthened prevailing winds, respectively. During 1980–2019, the atmospheric pattern similar to December 2016 decreased, while that similar to 2017 increased, suggesting that severe haze formation mechanism in eastern China has been shifting from causes of local accumulation to regional transport processes. In the future, climate change under the sustainable and intermediate development scenarios are the ideal paths to reduce haze in China, while high social vulnerability and radiative forcing would cause a severe damage to the environment.

Plain Language Summary

Severe haze pollution occurred in December 2016 and 2017 over different regions of China related to local accumulation and regional transport of aerosols, respectively. During the past four decades, the frequency of atmospheric circulation patterns similar to December 2016 decreased and that similar to 2017 increased. It indicates that haze formation in eastern China has shifted from local accumulation in northern China to regional transport in southern China. The ideal path for China to reduce haze is under sustainable development scenarios whereas high levels of social vulnerability and radiative forcing will cause severe damage to the atmospheric environment in the future.

1. Introduction

With the rapid industrialization and urbanization, haze pollution has become more frequent and serious in China during the recent decades (Reddington et al., 2019). When severe haze hit China in the past, the maximum daily $PM_{2.5}$ (particulate matter less than 2.5 μm in diameter) concentration reached 500 μg m^{-3} in eastern China, which was 20 times higher than the healthy air quality criterion of World Health Organization (Li et al., 2018). $PM_{2.5}$ has various effects on environment and climate. $PM_{2.5}$ harms human health causing cardiovascular and respiratory disease and shortens life expectancy (Zhang et al., 2017). In China, about 1 million people died every year due to $PM_{2.5}$ exposure (Burnett et al., 2018; Cohen et al., 2017). On the other hand, through aerosol-radiation and aerosol-cloud interactions, $PM_{2.5}$ can directly and indirectly affect climate (Yang, Ren, et al., 2020; Yang et al., 2019). Moreover, high concentration of $PM_{2.5}$ in hazing conditions reduces atmospheric visibility and thus endangers road traffic and air transportation (Ding & Liu, 2014; Zhang et al., 2014). Therefore, it is imminent to study the causes of haze in China and the past and future changes of these factors.

Numerous studies have identified anthropogenic emissions (Fu et al., 2016; Reddington et al., 2019; Sun et al., 2018; Yang et al., 2016) and adverse meteorological conditions (Cai et al., 2017; Ding & Liu, 2014; Pei et al., 2020; Wu et al., 2017; Zou et al., 2017) as two key factors leading to the frequent occurrence of severe wintertime haze events in China. Since the promulgation of Air Pollution Prevention and Control Action Plan, the emissions of pollutants in China have significantly decreased (Li et al., 2021; Zheng et al., 2018) and the impact of meteorological conditions on haze pollution has been attracting more attention. Adverse meteorological conditions, including weak winds, low boundary layer height, strong temperature inversions, and high relative humidity closely associated with anticyclonic anomalies over northeastern Asia, can lead to severe haze pollution in northern China (Zhang et al., 2016; Zhong et al., 2019). After the cold frontal transport from the North China Plain to the Yangtze River Delta, $PM_{2.5}$ can accumulate under the control of local high pressure to worsen the air quality in the Yangtze River Delta region (Kang et al., 2019). Li et al. (2018) reported that haze in eastern China was often related to an anomalous high sea level pressure in northeastern Asia and the Pacific Northwest and anomalous high pressure that controlled the East Asian trough or the whole East Asia in the mid-troposphere, resulting in weakened near-surface northwest prevailing winds during winter.

These previous studies provided important information that atmospheric pattern anomalies have largely influenced haze formation in China; however, most studies only paid close attention to a certain region and lacked comparative analyses on the atmospheric patterns and relevant haze events in various regions of China. In addition, aerosol and their precursor emissions are changing rapidly in recent years in part due to clean air actions. The compound effects of emission changes should be screened out in order to understand the impacts of atmospheric conditions on haze pollution. Furthermore, using observational data alone, it is difficult to separately quantify contributions from local emissions/accumulation and regional transport driven by certain atmospheric patterns. Moreover, past and future changes of these atmospheric patterns conducive to severe haze under climate change, which are critical to pollution prevention, deserve more investigation.

Here, $PM_{2.5}$ observations, reanalysis data and multimodel intercomparison results and an aerosol-climate model with the Explicit Aerosol Source Tagging (EAST) method are used to explore the relationship between the atmospheric circulation patterns and heavy pollution events in China, which is of great significance for the control of air pollution, climate change mitigation, and the sustainable development of economy and society.

2. Materials and Methods

In this study, observed hourly $PM_{2.5}$ concentrations in December–January–February (DJF) for years 2009–2019 obtained by the U.S. Embassy in Beijing, Shanghai, and Guangzhou cities (Figure S1 in Supporting Information S1), respectively, located in the three subregions of China (North China Plain [NCP] and the Yangtze River Delta [YRD]/Pearl River Delta [PRD]) are used to characterize haze events. The rapid industrial and economic development and unfavorable meteorological conditions in these three regions had been reported to lead to frequent haze events (Li et al., 2016; Liao et al., 2017; Liu et al., 2019; Mai et al., 2016), and hence it is necessary to examine the atmospheric circulation patterns in these three typical polluted regions to provide a basis for the overall planning of future pollution prevention and control measures in each region. To remove the impact of emission changes on $PM_{2.5}$ variations in observational analysis, the observed $PM_{2.5}$ concentrations are normalized by the monthly SO_2 emissions (precursor gas of sulphate aerosol) over the three polluted regions since that sulphate is a large contributor of $PM_{2.5}$ mass (Cao et al., 2012) and the driver of $PM_{2.5}$ variation in China (Geng et al., 2017). The SO_2 emissions are from the Multi-resolution Emission Inventory for China (MEIC) inventory over 2009–2017 with 2018–2019 data obtained by a linear interpolation. Severe haze day is defined by daily $PM_{2.5}$ concentration greater than 150 μg m^{-3}.

A global aerosol–climate model CAM5 with the Explicit Aerosol Source Tagging (CAM5-EAST, Wang et al., 2014; Yang, Wang, Smith, Ma, & Rasch, 2017, Yang, Wang, Smith, Easter, et al., 2017) is applied in this study to quantitatively attribute the sources of aerosols from different regions. Aerosols from different source regions of interest are explicitly tracked in the CAM5-EAST simulation without perturbing the emissions. The contributions of many source regions including subregions of China and rest of the world to the $PM_{2.5}$ concentrations are quantified to explore the source-receptor relationship in the three cities and are shown in Figure S1 in Supporting Information S1. The CAM5-EAST simulation is performed to cover the focused historical period. Detailed information about the EAST technique, implementation in CAM5 and model evaluation can be found in the previous studies (Ren et al., 2020; Wang et al., 2014; Yang, Lou, et al., 2020; Yang, Wang, Smith, Zhang, Lou, Qian, et al., 2018; Yang, Wang, Smith, Zhang, Lou, Yu, et al., 2018).

To calculate the anomalies of meteorological fields during severe haze pollution events, ERA5 reanalysis data are adopted from 1980 to 2019. Following Li et al. (2018), monthly meteorological variables including sea level pressure (SLP), wind fields (at 850 and 500 hPa) and geopotential height (GPH) at 500 hPa are selected to determine anomalous atmospheric circulation patterns and their variations under climate change.

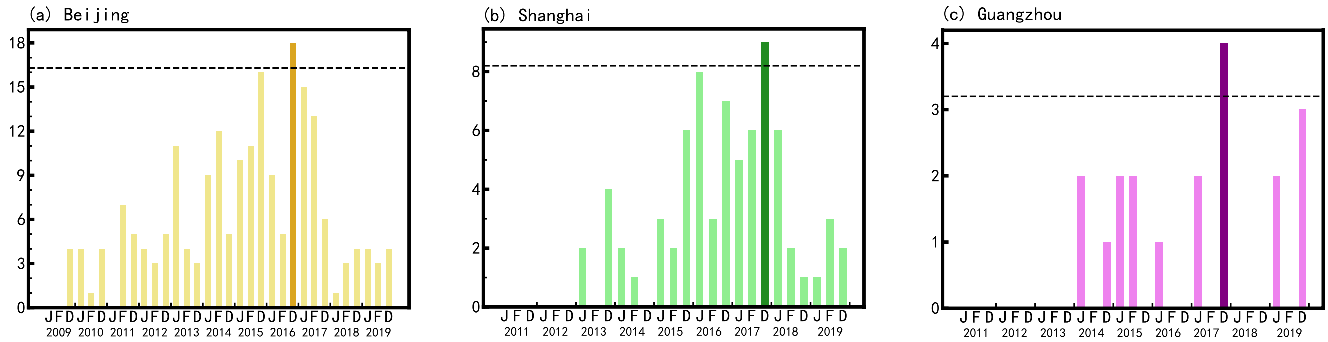

Figure 1. Time series of frequency of severe haze (days in each month with daily $PM_{2.5}$ concentration greater than 150 μg m^{-3}) in Beijing, Shanghai and Guangzhou (a–c), after the influence of emission changes is removed by normalizing the frequency to monthly SO_2 emissions. The dark-colored bars represent the most severe months having the highest frequencies of hazy days.

For the trends in circulation patterns conducive to severe haze under future climate change, the multimodel future simulations from the Scenario Model Intercomparison Project (ScenarioMIP) under the Coupled Model Intercomparison Project Phase 6 (CMIP6) are utilized, together with the CMIP6 historical results as baseline cases. Four future scenarios for the Shared Socioeconomic Paths (SSPs), including SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5 are the focus of this study, allowing for comprehensive analysis of future changes in meteorological conditions and air pollutants. Totally 25 models, including ACCESS-CM2, ACCESS-ESM1-5, AWI-CM-1-1-MR, BCC-CSM2-MR, CAMS-CSM1-0, CESM2-WACCM, CMCC-CM2-SR5, CanESM5, EC-Earth3, EC-Earth3-Veg, EC-Earth3-Veg-LR, FGOALS-f3-L, FGOALS-g3, GFDL-ESM4, IITM-ESM, INM-CM4-8, INM-CM5-0, IPSL-CM6A-LR, MIROC6, MPI-ESM1-2-HR, MPI-ESM1-2-LR, MRI-ESM2-0, NorESM2-LM, NorESM2-MM, TaiESM1, are used to analyze future trends of anomalous circulation patterns.

3. Results

3.1. Atmospheric Circulation Patterns Conducive to Severe Haze

The frequency of severe winter haze days during 2009–2019 in Beijing, Shanghai, and Guangzhou representing the top polluted three subregions of China is shown in Figure 1. The most frequent haze pollution in Beijing occurred in December 2016, with 18 haze days in the month. The most frequent haze pollution in Shanghai and Guangzhou during the observed time period was in December 2017, when Shanghai and Guangzhou had 9 and 4 haze days, respectively. The frequency was less than that in Beijing but not neglected given that the background level of $PM_{2.5}$ is normally low. Although the emissions of air pollutants were significantly reduced, the severe haze in winter has not been much improved, indicating that large-scale circulation anomalies played an important role (Krotkov et al., 2016). In this study, December 2016 and 2017 are used as the most severe haze months to analyze for the relationship between atmospheric circulation anomalies and severe haze pollution over NCP in northern China and YRD/PRD in southern China, respectively, under climate change.

Atmospheric circulation anomalies that are conducive to the extreme haze over China in December 2016 and 2017 are characterized in Figure 2. When the most severe haze occurred in NCP (December 2016), an abnormal SLP gradient between the low pressure over China and the high extended from Northwest Pacific to northeastern China, relative to the 40-year climotology during 1980–2019, was observed (Figure 2a). The abnormal pressure gradient reduced the prevailing northwesterly winds in the lower troposphere in winter over the NCP region. In the mid-troposphere, an abnormal anticyclone appeared over NCP (Figure 2b). Under the control of this anomalous high pressure, the atmospheric boundary layer was stable and the prevailing northwesterlies were pushed to the north, leading to poor dispersion conditions, local aerosol accumulation, and haze formation in NCP.

The atmospheric circulation anomaly in December 2017 was significantly different from that in December 2016. In December 2017, a low pressure located over the Sea of Japan and northeastern China along with an anomalous high pressure over China in both low- and mid-troposphere, which strengthened the prevailing northerly winds in eastern China (Figures 2c and 2d). As a result of the northerly wind anomalies, more aerosols were transported

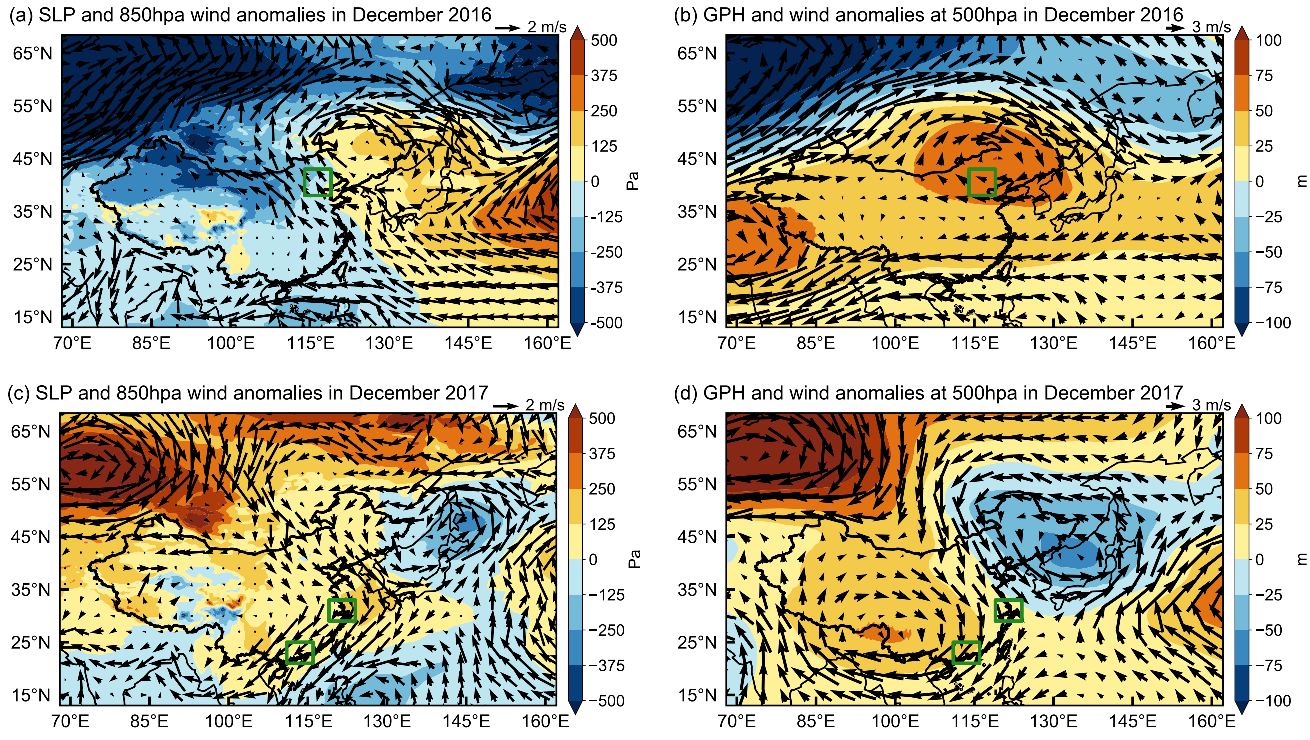

Figure 2. Atmospheric circulation anomalies observed in December 2016 and December 2017 (a)–(d). Observed anomalies in sea level pressure (SLP, hPa, shaded) and 850 hPa winds (m s^{-1}, vector) (a), and geopotential height (GPH, m, shaded) and winds at 500 hpa (m s^{-1}, vector) (b), in December 2016 relative to the 40-year average (1980–2019). (c) and (d) are same as (a) and (b), respectively, but for December 2017. The green boxes mark the cities, Beijing in (a) and (b) and Shanghai and Guangzhou in (c) and (d), that had haze pollution during the corresponding month.

from the polluted northern China to the south, accounting for the severe haze pollution over YRD and PRD in December 2017.

The sudden increases in aerosol concentrations to form severe haze pollution are either from local emissions due to a stagnant condition or from imported contribution by atmospheric transport related to the anomalous circulation patterns. To further examine the mechanism for the impact of atmospheric circulation anomaly on haze pollution, the CAM5-EAST model is used to quantify sources of aerosols in the three cities we focused on. Figure S2 in Supporting Information S1 shows the contributions of individual source regions to the differences in $PM_{2.5}$ concentrations between the severe haze months and normal conditions, and the values are also summarized in Table S1 in Supporting Information S1.

The contribution of NCP local emissions accounts for 91% of the $PM_{2.5}$ concentration increase in Beijing during the most severe haze pollution in December 2016, consistent with the weakening of prevailing winds in NCP (Figure 2a). It indicates that local emissions are the dominant factor of haze pollution in NCP. Over Shanghai, NCP is the only positive contributor and emissions from NCP and southern China contribute 68% and 46% to the $PM_{2.5}$ increase in Guangzhou, respectively, in December 2017. It affirms that the most severe haze pollutions over YRD/PRD in southern China in December 2017 were due to the anomalously strong regional transport associated with the strengthened northerly winds.

3.2. Shifting Patterns From Local Accumulation to Regional Transport

Historical variations of the atmospheric circulation patterns conducive to severe haze pollution are essential for understanding the observed haze events during the past few decades in China. Figure 3 shows the correlation between SLP or 500 hPa GPH anomalies in December 2016/2017 and the same fields in each year during 1980–2019, as well as the frequency of the patterns of moderate to high correlation (>0.5) with those in December 2016/2017. It is interesting that both the frequencies of SLP and GPH that have moderate to high correlation with

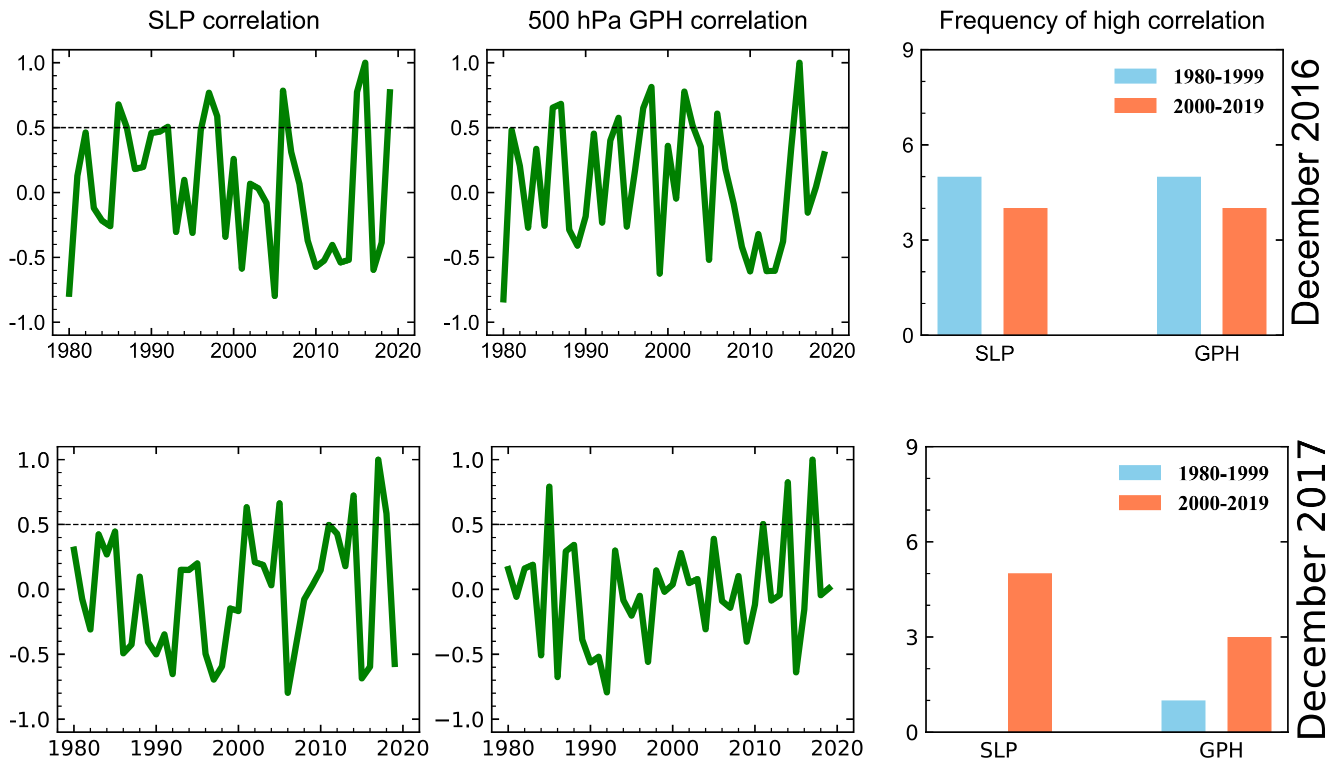

Figure 3. Time series of pattern correlation between SLP (left) or 500 hPa GPH (middle) anomalies over East Asia and western Pacific (90°–160°E, 20°–60°N) in December 2016 (top)/2017 (bottom) and those in December of each year during 1980–2019. The dotted lines mark the correlation threshold of +0.5, which is used to define "moderate to high correlation." The bar chart (right) represents the frequency of SLP and 500 hPa GPH that have moderate to high correlation (>0.5) in December 2016/2017 during 1980–1999 (blue) and 2000–2019 (orange). Anomalies relative to the averages over 1980–2019 are used in the calculation of correlations.

those in December 2016 decreased during 1980–2019 (i.e., less frequent in 2000–2019 than in 1980–1999). It indicates that although the anthropogenic emissions have increased during the past four decades, the occurrence of circulation patterns conducive to extreme haze over NCP in northern China was decreasing, in favor of the regional air quality improvement. On the contrary, the frequency of atmospheric circulation anomalies similar to that in December 2017 increased significantly from 1980–1999 to 2000–2019. It implies that the variation in atmospheric circulation might have been responsible for the intensification of severe haze over YRD and PRD in southern China since 1980s.

The regional atmospheric circulation is affected by both natural climate internal changes and human factors, including Arctic Oscillation (Lu et al., 2020), Pacific Decadal Oscillation (Zhao et al., 2016), Arctic sea ice (Wang et al., 2015), and global warming (Cai et al., 2017). In the year with high Arctic Oscillation Index (AOI), the weakened East Asian trough causes a decrease of the meridional winds, making the meteorological condition unfavorable for the dispersion of air pollutants, which significantly impacts haze pollution in northern and central China (Lu et al., 2020). In 2016, AOI was greater than 1, explaining the anomalous atmospheric circulation pattern conducive to serious haze pollution in December 2016. In addition, the historical years with abnormally high AOI (>1) identified by Lu et al. (2020) were 1988, 1989, 1991, 1992, 1999, 2006, and 2016, which was likely the reason for the decrease in occurrence frequency of the circulation anomaly pattern in 1980–2019 that is similar to December 2016. In contrast, the December 2017 pattern with strengthened northerly winds increased, potentially due to the less frequent high-AOI years after 2000 compared to pre-2000.

Nevertheless, the frequency of atmospheric circulation pattern similar to December 2016 with weakened lower tropospheric winds is decreasing, while the December 2017 pattern with strengthened winds is increasing. The transition of atmospheric circulation anomalies from the 2016-type to the 2017-type suggests that the haze formation mechanism in eastern China is shifting from the local accumulation in northern China to regional transport in southern China under historical climate change.

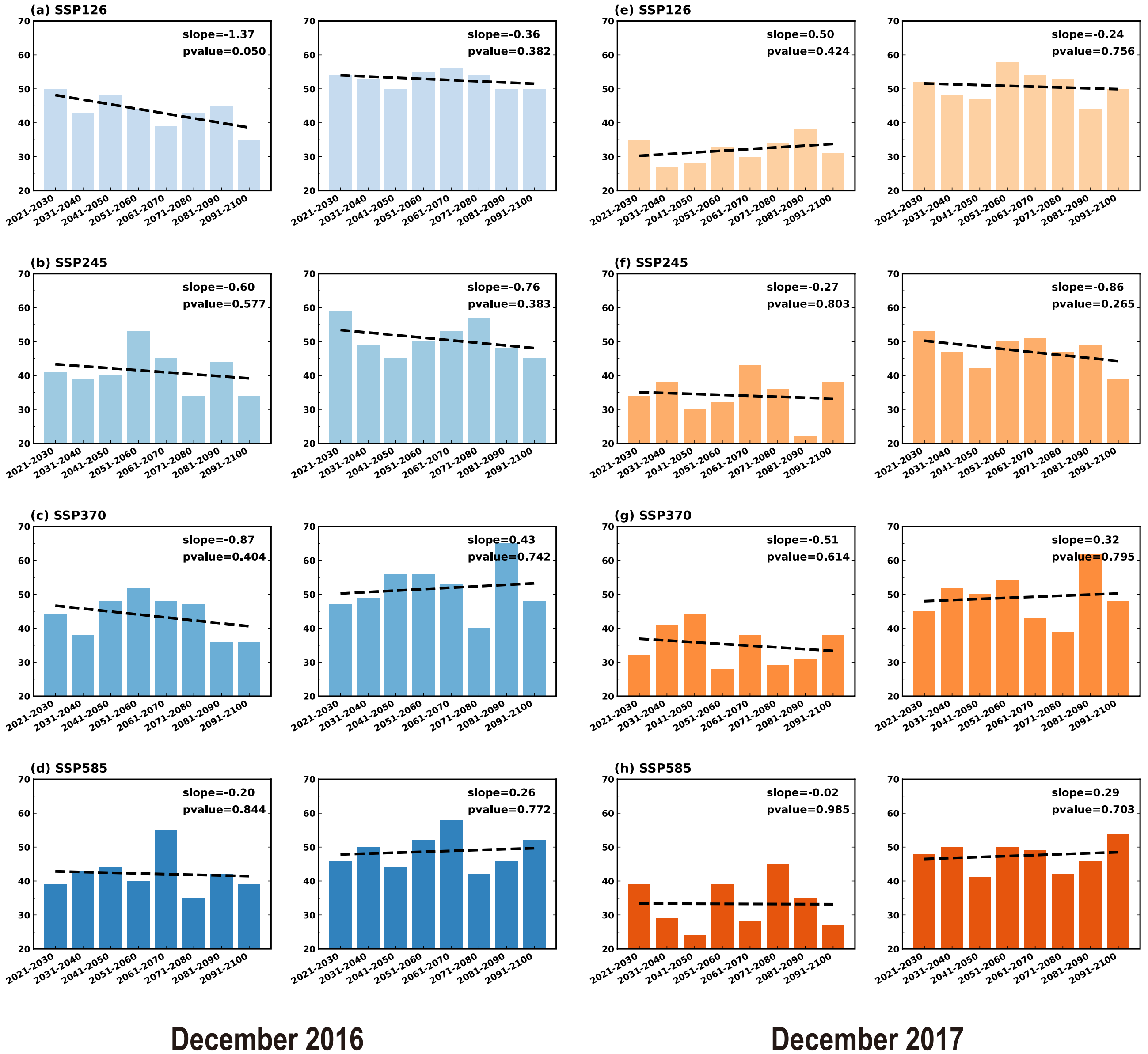

Figure 4. Frequency of SLP and 500 hPa GPH that have moderate to high correlation (>0.5) in December 2016 (a–d)/2017 (e–h) in each 10-year interval during 2021–2100 under four SSPs furture scenarios of CMIP6. It is calculated by the sum of the moderate to high correlation coefficients of the 25 models for each decade. The four SSPs are SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5 (from top to bottom). The slope and P values of linear regressions during 2021–2100 are shown in the upper right of each panel. The linear trends of SLP and GPH in each model grid were removed before the correlation coefficient is calculated.

3.3. Future Trends of Atmospheric Circulation Patterns

Projection of the trends of the atmospheric circulation patterns conducive to haze in China under future climate change is important for the policy making. Here, meteorological variables simulated by 25 climate models under four future climate policy scenarios, including SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5 that represents sustainable, medium, local, and conventional development, respectively, are used to characterize the future regional circulation patterns. The frequencies of haze-conducive atmospheric patterns are shown in Figure 4. It should be noted that most of future trends are not statistically significant due to the diverse results of the 25 models analyzed in this study, so they only represent a possible future change for the consideration.

Under the SSP1-2.6 and SSP2-4.5 scenarios, both the frequencies of SLP and GPH patterns similar to those in December 2016 show downward trends during 2021–2100 (Figures 4a and 4b), whereas the changes are opposite for SLP and GPH patterns under the SSP3-7.0 and SSP5-8.5 scenarios (Figures 4c and 4d). For the circulation patterns similar to that in December 2017 (Figures 4e–4h), only the SSP2-4.5 presents downward trends for both SLP and GPH over 2021–2100, while their trends are in the opposite directions under other scenarios. It suggests that the sustainable and medium development scenarios are the ideal paths to the fresh air in China from the perspective of circulation changes. The efforts for moderate to low social vulnerability and radiative forcing, international cooperation, land use change for more forests under SSP1-2.6 and SSP2-4.5 are essential for both the climate change mitigation and air quality improvement.

Figure S3 in Supporting Information S1 depicts the frequencies with correlation coefficients greater than 0.5 between the atmospheric circulation anomalies in December 2016/2017 and those in the historical 50 years (1965–2014) and future 50 years (2045–2094) from the 25 CMIP6 climate models. Under the SSP3-7.0 and SSP5-8.5 scenarios, atmospheric circulation anomalies similar to those in December 2016 or 2017 are more frequent in the future than in the historical period, which can be partly attributed to the upward trends in the frequency and magnitude of Arctic Oscillation in a warmer change related to increases in anthropogenic greenhouse gases (Shindell et al., 1999). It indicates that vicious competition between nations, high social vulnerability, and high anthropogenic radiative forcing can lead not only to a slow economic growth and warmer climate, but also to a severe environmental damage. The importance of international win-win cooperation and the development of green economy should always be promoted.

4. Conclusions and Discussions

High concentration of $PM_{2.5}$ is extremely harmful to human health, atmospheric visibility, green economy, and other environmental/societal aspects. This paper studies the characteristics of atmospheric circulation anomalies during the most severe wintertime haze pollution and historical and future trends of relevant atmospheric circulation patterns that are conducive to the haze pollution in China under the changing climate. After the impact of emission changes being removed, December 2016 and 2017 are identified to be the most severe haze months over NCP and YRD/PRD, respectively. The atmospheric circulation anomaly in December 2016 was characterized by an anomalous SLP gradient between a low pressure over China and a high pressure extended from Northwest Pacific to northeastern China, which reduces the lower tropospheric northwesterly winds over the NCP region, together with the stable boundary-layer condition under high pressure, leading to poor dispersion conditions. In contrast, the December 2017 atmospheric circulation anomaly is characterized by a low pressure over the Sea of Japan and northeastern China, along with a high pressure over China in both the low- and mid-troposphere, strengthening the prevailing northerly winds in eastern and southern China. The northerly wind anomaly leads to aerosol transport from polluted northern China to the south.

After studying the historical variations of the atmospheric circulation patterns leading to extreme haze pollution, we find that the atmospheric circulation pattern with weakened winds similar to December 2016 has been decreasing during 1980–2019, while the pattern similar to December 2017 with strengthened winds has been increasing. The change in atmospheric circulation anomalies from the 2016-pattern to the 2017-pattern suggests that severe haze formation in eastern China is shifting from local accumulation in northern China to regional transport in southern China under the historical climate change.

Trends of atmospheric circulation patterns favoring haze in China under future climate change are also studied. Decreasing trends in frequencies of SLP and GPH patterns similar to those in December 2016/2017 are projected to occur under SSP1-2.6 or SSP2-4.5 scenarios. This suggests that sustainable and intermediate development scenarios are the preferred paths for both the global climate change mitigation and the clean air target in China in the future. Vicious competition between countries, high social vulnerability, and high anthropogenic radiative forcing (SSP3-7.0 and SSP5-8.5) in the future will not only lead to a slow economic growth and warmer climate, but also cause a severe damage to the environment compared to current days.

In this study, we found that the occurrence frequency of atmospheric patterns conducive to extreme haze in China is expected to increase under high emission-based climate change in the 21st century (SSP3-7.0 and SSP5-8.5), which is in accordance with Cai et al. (2017) that future weather conditions in favor of haze formation in Beijing would worsen under RCP8.5 (Representative Concentration Pathway 8.5) scenario. The increase was attributed to mean state changes, including accelerated temperature increases in the lower atmosphere, weakened East Asia winter monsoon, and increasing sea level pressures over the North Pacific related to the upward trends in the frequency and magnitude of Arctic Oscillation. The decreasing trends under SSP1-2.6 or SSP2-4.5 may be influenced by effective environmental pollution control such as lower anthropogenic radiative forcing, lower CO_2 emissions, and a modest temperature increase. However, due to the differences in simulation performance between models, the future prediction needs further data and analysis to provide a reference for haze prevention and control measures.

Note that the correlation coefficients calculated in this study are over a large domain over East Asia and western Pacific bigger than eastern China. However, averaged over the years with moderate to high correlations (>0.5), the atmospheric circulation pattern anomalies (Figure S4 in Supporting Information S1) are almost the same to those in December 2016/2017 in eastern China (Figure 2). The available $PM_{2.5}$ observational data cover 10 years. Anomalous atmospheric circulation patterns favoring severe haze may not be completely included in this study. And we normalize the $PM_{2.5}$ with the monthly SO_2 emissions to minimize the impact of reducing emissions. However, this approach may bring some uncertainties for the $PM_{2.5}$ also composed of nitrates and other secondary organic aerosols, in addition to sulphate. Future work could use the model simulation to minimize the effects of emissions reduction by fixing emissions. Nevertheless, our results suggest that severe haze in China is shifting from the local accumulation in northern China to regional transport in southern China due to atmospheric circulation changes under the historical climate change. A joint prevention and control of air pollution is required in the current environmental situation. In the future, climate change under the sustainable and intermediate development scenarios are the ideal paths, with global effort in reducing greenhouse gases, helping for the decreasing severe haze in China.

Data Availability Statement

Observed hourly $PM_{2.5}$ concentrations for years 2009–2019 are provided by the U.S. Embassy. The monthly SO_2 emissions (2000–2017) are from the MEIC inventory (https://zenodo.org/record/5706561, last access: November 2021). The CAM5 model is available at http://www.cesm.ucar.edu/models/cesm1.2/(last access: November 2021). Our CAM5-EAST model code and results can be made available upon request. Meteorological data from 1980 to 2019 obtained by ERA5 reanalysis data (https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5, last access: June 2021). The multi-model historical and future simulations under the Coupled Model Intercomparison Project Phase 6 (CMIP6) are from https://esgf-node.llnl.gov/search/cmip6/ (last access: November 2021).

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