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Key Points:
- Large-scale circulation anomalies associated with recent most severe haze cases (January 2013 and December 2015) were identified
- The reanalysis data show that the frequency of anomalous atmospheric patterns conducive to the most severe haze increased over 1948-2015
- Large ensemble climate runs show greenhouse warming has significantly increased the probability of the conducive atmospheric patterns

Supporting Information:
- Supporting Information S1

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Attribution of Anthropogenic Influence on Atmospheric Patterns Conducive to Recent Most Severe Haze Over Eastern China

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Abstract Severe haze pollution in eastern China has caused substantial health impacts and economic loss. Conducive atmospheric conditions are important to affect occurrence of severe haze events, and circulation changes induced by future global climate warming are projected to increase the frequency of such events. However, a potential contribution of an anthropogenic influence to recent most severe haze (December 2015 and January 2013) over eastern China remains unclear. Here we show that the anthropogenic influence, which is estimated by using large ensemble runs with a climate model forced with and without anthropogenic forcings, has already increased the probability of the atmospheric patterns conducive to severe haze by at least 45% in January 2013 and 27% in December 2015, respectively. We further confirm that simulated atmospheric circulation pattern changes induced by anthropogenic influence are driven mainly by increased greenhouse gas emissions. Our results suggest that more strict reductions in pollutant emissions are needed under future anthropogenic warming.

Plain Language Summary Extremely severe haze pollution occurred in December 2015 and January 2013 over eastern China with concentrations of $PM_{2.5}$ reaching 500 μg m^{-3}. During such severe haze, atmospheric circulation exhibited an anomalous east-west sea level pressure gradient and a weakened East Asia monsoon. We assess in this work the role of anthropogenic climate change in such large-scale circulation anomalies by using a large ensemble of climate simulations forced with and without anthropogenic forcings. Anthropogenic influence is estimated to increase the probability of the occurrence of anomalous atmospheric pattern similar to that in January 2013 (December 2015) by 45% (27%). We further confirm that the simulated anthropogenic circulation changes are induced mainly by increased greenhouse gas emissions. Results from our study suggest that more strict emission reduction measures are needed to improve air quality under a continuing anthropogenic warming in the upcoming decades and global effort to reduce greenhouse gas emissions can decrease the risk of severe haze over eastern China.

1. Introduction

Haze pollution featuring a high concentration of fine particles with an aerodynamic diameter of 2.5 μm or smaller ($PM_{2.5}$) is one of the most concerned environmental issues in China (Cai et al., 2017; Huang et al., 2014; Liao et al., 2015), because it leads to adverse effects on human health (West et al., 2016), atmospheric visibility (Wang et al., 2009), and on land ecosystem (Yue et al., 2017). In January 2013 and December 2015, severe haze episodes occurred frequently over a large area of eastern China, and the observed maximum daily $PM_{2.5}$ concentrations reached 500 μg m^{-3} (20 times World Health Organization air quality guidelines), which caused massive disruption to economic and societal activities (Gao et al., 2017; Huang et al., 2014; Jiang et al., 2015; Liu et al., 2017; Zhang et al., 2017). It is therefore pressing to understand the factors affecting the occurrence of such serious haze pollution in the wintertime.

Increased air pollutant emissions from China's rapid economic development are primarily responsible for haze pollution during the past decades (e.g., Fu et al., 2016; Wang & Chen, 2016; Yang et al., 2016). For example, Yang et al. (2016) estimated that changes in anthropogenic pollutant emissions contributed about 80%

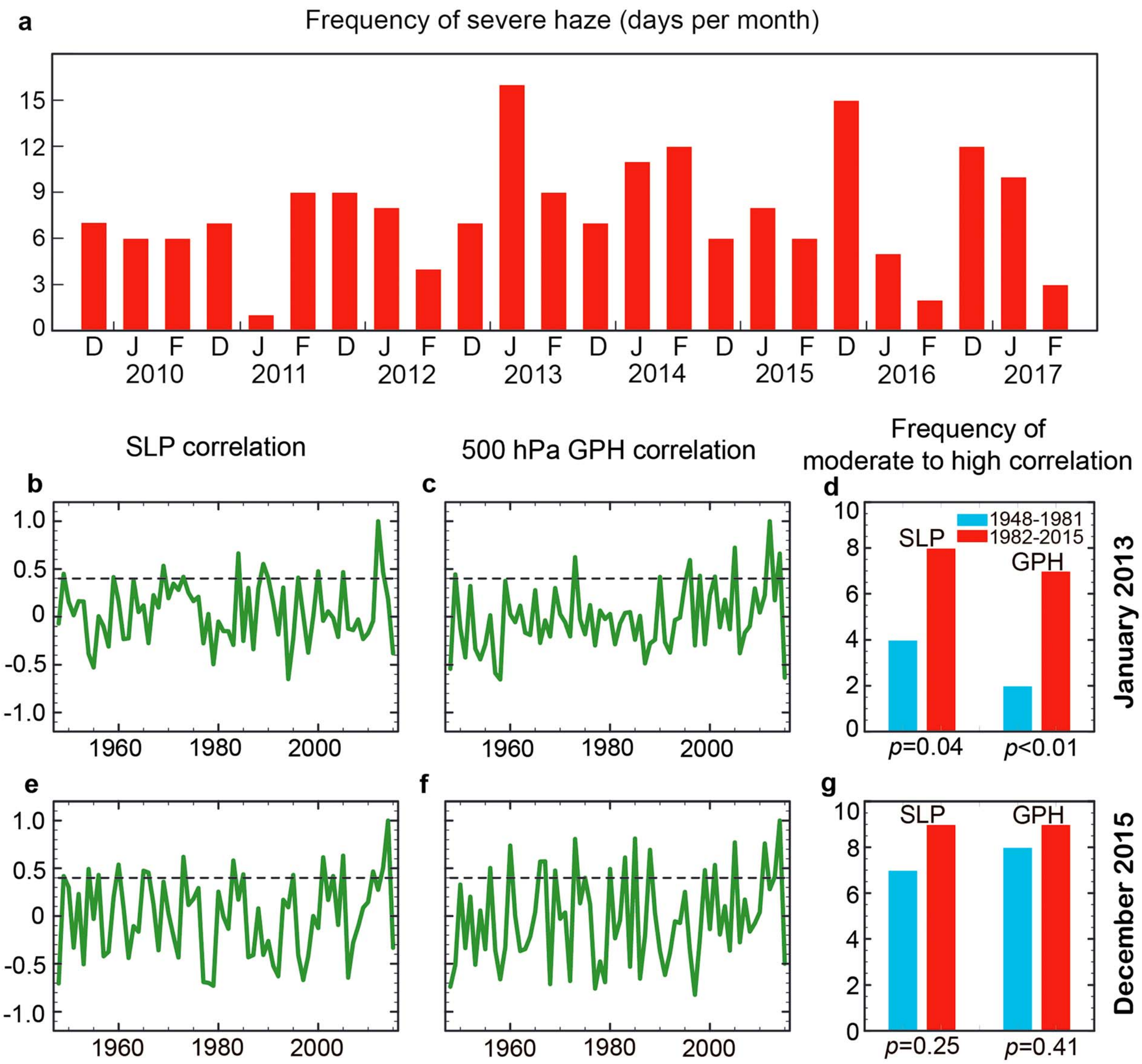

Figure 1. (a) The frequency of winter severe haze (defined by days with $PM_{2.5}$ concentration above 150 μg m^{-3}) near Beijing during 2009–2017, suggesting January 2013 and December 2015 are the most severe cases. (b and c) Time series of pattern correlation between sea level pressure (SLP) (b) or 500 hPa geopotential height (GPH) (c) in January 2013 and all other years (1948–2015). Dashed black lines highlight +0.4 correlation thresholds used here to define "moderate to high correlation." (d) Changes in the frequency of SLP and 500 hPa GPH patterns that have moderate to high correlation (>0.4) with patterns in January 2013. Left columns (blue) represent the occurrence during 1948–1981; right columns (red) represent the occurrence during 1982–2015. Numbers under the column pairs indicate confidence (*P* value). (e–g) The same with (b)–(d), respectively, but for the results for December 2015. Anomalies with respect to the averages over 1981–2010 are used in the calculation of pattern correlations. *P* values associated with the reported changes were derived using a conditional one-tailed binomial test.

to the increasing trend of wintertime $PM_{2.5}$ concentrations averaged over eastern China from 1985 to 2005. To improve air quality, "Air Pollution Prevention and Control Action Plan" was promulgated by Chinese government in 2013. As a consequence, observed annual mean $PM_{2.5}$ concentrations decreased by about 20% over China during 2013–2015 (Zheng et al., 2017) due to effective reductions in major air pollutants (e.g., SO_2 and NO_2), for example, about 50% reduction of SO_2 over North China Plain during 2012–2015 as seen by satellite retrievals (Krotkov et al., 2016). However, observed winter severe haze events did not show reductions in recent years (Figure 1a), highlighting potential importance of atmospheric conditions in influencing the occurrence of severe haze events in winter (Cai et al., 2017).

Severe haze episodes always occur in the wintertime under atmospheric conditions (such as low boundary layer height, weak surface wind, strong temperature inversion, and high relative humidity in the lower troposphere) that are favorable for the formation and accumulation of $PM_{2.5}$ (Cai et al., 2017; Chen & Wang, 2015; Wu et al., 2017; Zhang et al., 2014). Thus, how such atmospheric circulation patterns will respond to a changing climate is an important issue for air quality management. Early studies suggested that recent climate variability and change, including declined Arctic Sea ice (Wang et al., 2015), weakened East Asian winter monsoon and northerly winds (Q. Li et al., 2016; Xu et al., 2006; Yang et al., 2016), and dust aerosol-climate feedbacks (Yang et al., 2017), contributed to the frequent occurrence of severe haze pollution over eastern China. Recently, Cai et al. (2017) reported that circulation changes induced by the high greenhouse gas emission (RCP8.5 scenario) will significantly increase the frequency and persistence of weather conditions conducive to winter severe haze in Beijing.

So far, few studies have focused on the cause of anomalous atmospheric conditions conducive to recent severe haze in China. Yin et al. (2017) reported that the positive phase of the East Atlantic/West Russia teleconnection contributed to the occurrence of 2014 winter severe haze by altering local climate anomalies over North China. They further identified that the changes of preceding autumn sea surface temperature in the Pacific and snow cover in Eurasian could stimulate the positive East Atlantic/West Russia pattern that favored the occurrence of severe haze in December 2016 (Yin & Wang, 2017). Zou et al. (2017) attributed the extremely poor ventilation conditions over eastern China in January 2013 to an Arctic sea ice loss in the preceding autumn and an extensive boreal snow cover in the earlier winter. However, Yin and Wang (2017) also pointed out that the relationship between Arctic sea ice loss in the preceding autumn and haze pollution in December is not statistically significant. These findings indicate the complex nature of climate anomalies that favor the formation of severe haze, and more efforts are needed to investigate this issue.

With anthropogenic climate warming, more frequent extreme weather and climate events were observed during the past decades and are evident in climate model projections (Fischer et al., 2013; Intergovernmental Panel on Climate Change, 2013). More frequent air pollution weathers (e.g., stagnant conditions) have been observed and are projected to be worse, at least regionally, under global climate change (e.g., Cai et al., 2017; Horton et al., 2014; Hou & Wu, 2016; Shen et al., 2016). Based on reanalysis data, for example, Hou and Wu (2016) found a significant increasing trend in the occurrence of extreme air pollution meteorology over the continental areas during the past six decades. Cai et al. (2017) projected an increasing frequency of Beijing wintertime severe haze under future global warming. However, little is known about the role of anthropogenic climate warming in the formation of conducive atmospheric conditions that caused the recent most severe haze events over eastern China. Attribution of such high-impact events can provide useful relevant information to policymakers in terms of needs of near-tem mitigation target (Liao & Chang, 2014; Trenberth et al., 2015).

In this study, we present modeling evidence that anthropogenic influence has significantly increased the probability of atmospheric circulation patterns conducive to the severe haze events in January 2013 and December 2015 over eastern China. This is done by using a large number of ensemble members with a climate model designed for the International CLIVAR Climate of the 20th Century Plus (C20C+) Detection and Attribution Project.

2. Data and Method

Surface layer $PM_{2.5}$ concentrations from the U.S. Embassy in Beijing were observed from 2009 to the present, which were used to identify haze pollution in January 2013 and December 2015 as the most severe cases. Climate anomalies associated with these severe haze pollution were calculated using the monthly meteorological fields, including mean sea level pressure (SLP), lower-tropospheric (850 hPa) winds, and midtropospheric (500 hPa) geopotential height (GPH) and winds, from the National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) reanalysis data (Kalnay et al., 1996) at a resolution of 2.5° × 2.5°.

To examine the contribution of anthropogenic influence to the conducive atmospheric patterns, we analyzed monthly meteorological variables from the C20C+ Detection and Attribution Project. Data outputs from large ensemble climate model runs designed for the C20C+ project have been extensively used in the detection and attribution of extreme weather and climate events, such as heatwave, droughts, and intense precipitation (Angélil et al., 2017; Lewis & Karoly, 2015; Ma et al., 2017; Shiogama et al., 2013). We used the data outputs simulated by the atmospheric general circulation model MIROC5 (Shiogama et al., 2013) at a horizontal resolution of 1.4° × 1.4°, which archives and makes available publically climate data outputs ending December 2015. To improve the reliability of attribution, simulated large-scale circulation changes from MIROC5 were also compared with those from the Coupled Model Intercomparison Project phase 5 (CMIP5) multimodel simulations (Taylor et al., 2012).

Two sets of ensemble experiments were employed (summarized in Table S1 in the supporting information): All-Hist and Nat-Hist. In the All-Hist scenario, MIROC5 was forced by historical anthropogenic and natural external forcings plus observed sea surface temperature and sea ice. In the Nat-Hist scenario, anthropogenic forcings and land cover/use were set to preindustrial levels, and anthropogenic contributions to the observed sea surface temperatures and sea ice were removed (Christidis et al., 2013). Both of the All-Hist and Nat-Hist scenarios include a 100-member ensemble from January 2006 to December 2015. Each realization in the two scenarios differs from the other only in its initial state. All of the simulation data have been interpolated to a common resolution of 2.5° × 2.5°.

3. Results and Discussions

3.1. Recent Most Severe Haze Events and the Associated Large-Scale Circulation

To establish the linkage between severe haze pollution and climate anomalies, January 2013 and December 2015 were selected as the most severe cases when many severe and persistent haze events occurred. In January 2013, the observed $PM_{2.5}$ concentration reached unprecedented high level with daily value over 500 μg m^{-3}, affecting about 800 million people over eastern China. Similarly, a series of severe haze events occurred in December 2015, when for the first time, an official red alert was issued in Beijing and a set of reduction measures were taken to reduce population exposure. The wintertime $PM_{2.5}$ concentrations at U.S. Embassy in Beijing during 2009–2017 (Figure S1) confirm the severity of these haze events in January 2013 and December 2015. Figure 1a shows that the frequency of severe haze (daily $PM_{2.5}$ concentrations over 150 μg m^{-3}) in January 2013 (16 days) and December 2015 (15 days) is the highest. It also demonstrates that winter severe haze has not improved despite a notable reduction in air pollutant emissions (Krotkov et al., 2016), which emphasizes the importance of atmospheric conditions in affecting the occurrence of severe haze. Furthermore, severe haze always features a large spatial scale over eastern China. Figure S2 shows that wintertime $PM_{2.5}$ concentrations at U.S. Embassy in Beijing are consistent with those averaged over 79 observation sites located in the Beijing-Tianjin-Hebei region; for example, the correlation coefficient between these two $PM_{2.5}$ time series during 2015–2016 reaches 0.86. Such characteristics reinforce the notion that large-scale circulation anomalies play an important role.

The circulation anomalies that were conducive to the formation of severe haze in January 2013 are given in Figures 2a and 2b. With respect to the climatology (1981–2010), there was an anomalous SLP gradient between a low over China and a high off the east coast extending to Northeast Asia, which led to reduced winter prevailing near-surface cold northwesterlies (Figure 2a). In the midtroposphere, an anomalous high pressure was located at the climatological location of the East Asia trough, which made the associated northwesterlies extend to the north, weakening the cold and dry northwesterly flows to eastern China (Figure 2b). Zou et al. (2017) reported that such atmospheric patterns could be explained by changes in cryospheric forcing, for example, when Arctic sea ice reached its minimum value in the autumn of 2012. Compared with circulation anomalies in January 2013 forced by cryospheric changes, anomalous atmospheric patterns in December 2015 reflected the impact of 2015/2016 extreme El Niño (Chang et al., 2016; Zhai et al., 2016). In December 2015, an anomalous high SLP off the east coast developed and covered a large fraction of the northwest Pacific, and the associated warm and humid southerlies extended to eastern China (Figure 2c). Accordingly, in the midtroposphere an anomalous high pressure dominated the circulation pattern over the whole area of East Asia (Figure 2d). Previous studies also confirmed that the anomalous southerlies associated with the east-west SLP gradient and weakened East Asia trough are the main features favoring the formation and accumulation of $PM_{2.5}$ over eastern China (e.g., Cai et al., 2017; Chen & Wang, 2015; Zhang et al., 2014, 2016).

3.2. Increased Frequency of Atmospheric Circulation Patterns Conducive to the Recent Most Severe Haze Identified in NCEP/NCAR Reanalysis

Here we examine long-term trends in the occurrence of patterns exhibiting high spatial similarity to those in January 2013 and December 2015. Figures 1b and 1c/Figures 1e and 1f show the time series of pattern

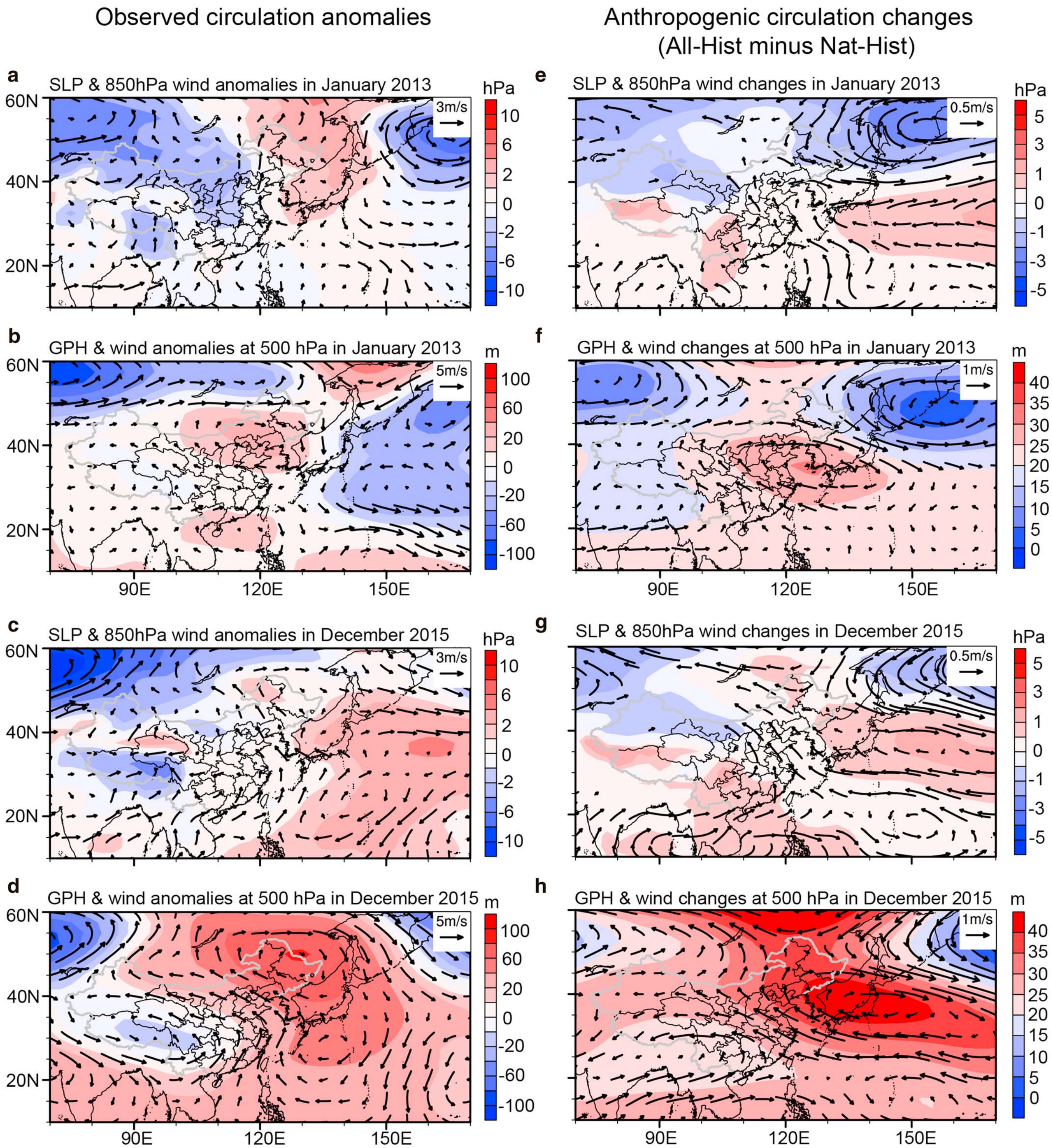

Figure 2. The observed (a–d) circulation anomalies in January 2013 and December 2015 resemble the simulated (e–h) circulation changes induced by anthropogenic influence (All-Hist minus Nat-Hist). (a and b) Observed anomalies in sea level pressure (SLP, hPa, shaded) and 850 hPa wind (m s^{-1}, vector) (a), and 500 hPa geopotential height (GPH, m) and 500 hPa wind (m s^{-1}, vector) (b), in January 2013. (c and d) The same as (a) and (b), respectively, but for values in December 2015. (e–h) The same as (a)–(d) but for simulated anthropogenically induced circulation changes estimated by the difference between All-Hist and Nat-Hist scenario averaged over 100 runs of MIROC5 model. Observed circulation anomalies are with respect to the 30 year averages (1981–2010).

correlation between SLP or 500 hPa GPH anomalies over (90–160°E, 25–60°N) in January 2013/December 2015 and all the other years (1948–2015). Although the time series of pattern correlation have no statistically significant trend for both SLP and GPH, we found increased frequency of years between 1948–1981 and 1982–2015 that exhibited a moderate to high correlation (pattern correlations >0.4, Swain et al., 2016) with the GPH or SLP pattern observed in January 2013 (Figure 1d) and December 2015 (Figure 1g). Especially for patterns in January 2013, the increased frequency is statistically significantly above the 95% confidence level, as estimated by a *P* value using a conditional one-tailed binomial test (Swain et al., 2016).

Since climate anomalies presented above can be affected by natural climate internal variability, such as El Niño (Chang et al., 2016) and the Pacific Decadal Oscillation (Zhao et al., 2016), as well as changes in cryospheric forcings, it is impossible to unequivocally attribute a single event to anthropogenic climate change. However, global climate warming may cause such circulation anomalies to occur more frequently or exacerbate them (Cai et al., 2017). For example, favorable weather conditions conducive to Beijing severe haze have increased significantly by 10% for HWI > 0 events and by 25% for HWI > 1 events (HWI: Haze Weather Index, see definition in Cai et al., 2017; higher HWI denotes more conducive to severe haze pollution), during the years of 1982–2015 relative to 1948–1981, and anthropogenic climate change might have played a role, as suggested by Cai et al. (2017). It is should be noted that the HWI in Cai et al. (2017) was defined to characterize daily weather conditions for severe haze, while monthly atmospheric patterns (e.g., SLP) were used in this study to describe large-scale circulation background against which the recent most severe haze events occurred. As such, the increase of 10% in haze frequency in 1982–2015 relative to 1948–1981 calculated by averaging over all the days with conducive weather conditions (conditions with HWI > 0) in Cai et al. (2017) should not be compared with the calculated increase in frequency of atmospheric patterns exhibiting high spatial similarity to those in January 2013 and December 2015 between 1948–1981 and 1982–2015 (Figures 1d and 1g).

3.3. Attribution to Anthropogenic Influence Using Large Ensemble Climate Simulations

To examine the anthropogenic influence on atmospheric circulation patterns conducive to recent most severe haze using a large ensemble of climate runs, we first evaluated the performance of the MIROC5 model. Figure S3 shows that the simulated circulation patterns averaged over a 100-member ensemble under the All-Hist scenario could reasonably capture the observed spatial patterns from near surface to the midtroposphere around East Asia. Figures 2e and 2f show anthropogenic influence on circulation changes in January 2013, which was estimated by the difference of simulated atmospheric patterns (All-Hist minus Nat-Hist). For each scenario, the simulated results were calculated by averaging 100-member simulations.

Under anthropogenic influence, there was an anomalous zonal SLP gradient between a low over land and a high off the east coast and a meridional SLP gradient over the northwest Pacific, which led to anomalous southerlies around eastern China (Figure 2e). In the midtroposphere, an anomalous high pressure was located over East Asia, which reduced the clean northwesterly flows to eastern China (Figure 2f). The anthropogenically induced circulation changes in January 2013 are consistent with the observed patterns (Figures 2a and 2b), which demonstrate the important role of anthropogenic influence in the occurrence of anomalous atmospheric patterns in January 2013. Similarly, an anthropogenic influence on circulation anomalies in December 2015 is confirmed, which is supported by the analogous atmospheric patterns from near surface to the midtroposphere between the observed anomalous circulations (Figures 2c–2d) and the simulated anthropogenically induced circulation changes (Figures 2g–2h). The magnitudes of the circulation changes induced by anthropogenic influence cannot totally account for the circulation anomalies observed in January 2013 or December 2015, which suggests that the unexplained portion may be caused by atmospheric internal variability.

We further quantified the role of an anthropogenic influence by examining the frequency of patterns exhibiting high spatial similarity to those in January 2013/December 2015 under the All-Hist and Nat-Hist scenarios. First, the spatial correlations between simulated and observed SLP anomalies over (90–160°E, 25–60°N) in January 2013/December 2015 were calculated. Both observed and simulated circulation anomalies are with respect to the 10 year averages (2006–2015). Figure S4 shows that simulated circulation anomalies averaged over 100-member runs under the All-Hist scenario are not capable to reproduce the observed anomalies. We compared in Figure 3 the observed large-scale circulation anomalies in January 2013/December 2015 with the simulated values from "the best run ensemble" that was selected from the

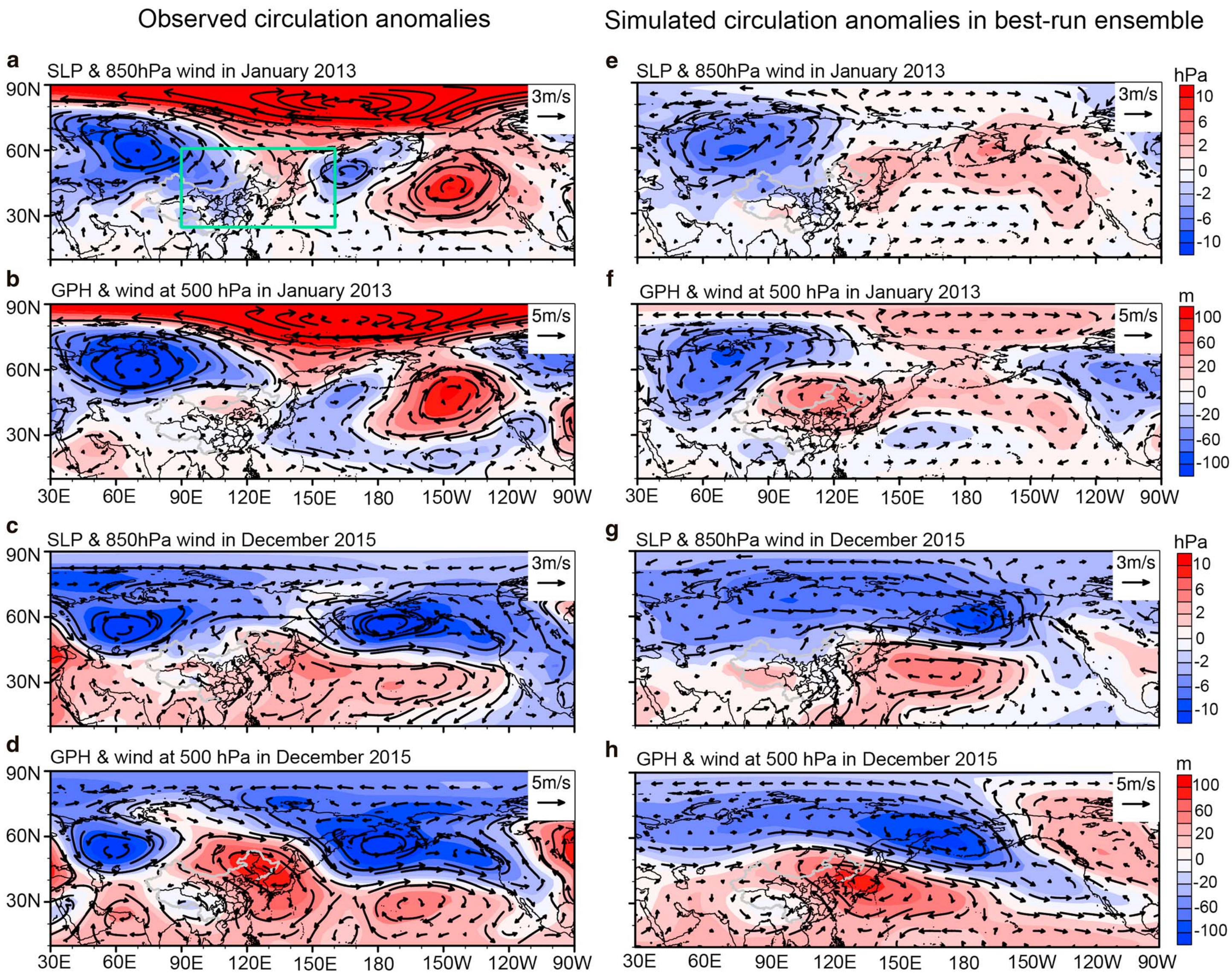

Figure 3. The observed (a–d) large-scale circulation anomalies in January 2013 and December 2015, and the simulated values (e–h) from the best run ensemble (six members) that was selected by spatial correlations. (a and b) Observed anomalies in sea level pressure (SLP, hPa, shaded) and 850 hPa wind (m s^{-1}, vector) (a), and 500 hPa geopotential height (GPH, m) and 500 hPa wind (m s^{-1}, vector) (b), in January 2013. (c and d) The same as (a) and (b), respectively, but for values in December 2015. (e–h) The same as (a)–(d) but for simulated anomalies from the best run ensemble under All-Hist scenario. The best run ensemble is defined as the runs having a spatial correlation between simulated and observed SLP anomalies over (90–160°E, 25–60°N, green box) that exceeds 0.6 for January 2013 (five members) and 0.8 for December 2015 (six members). Both observed and simulated circulation anomalies are referenced to the 10 year averages (2006–2015).

runs for having a spatial correlation of SLP pattern anomalies exceeding 0.6 for January 2013 (five members) and 0.8 for December 2015 (six members). The simulated circulation anomalies averaged over the best run ensemble can reasonably reproduce the observed patterns. If different correlation thresholds are used (e.g., 0.5 for January 2013 and 0.6 for December 2015, see Figure S5), simulated circulation anomalies still show similar patterns.

We further compared the frequency of pattern correlations exceeding a certain threshold that indicates a similar pattern to those observed in January 2013/December 2015, using 100-member runs under the All-Hist and Nat-Hist scenarios. We found that the frequency of conducive patterns increases notably under anthropogenic influence. Among the 100 realizations, the frequency of SLP pattern correlation that exceeds 0.4 (a moderate to high correlation) increased from 11 events under the Nat-Hist scenario to 16 events under

Table 1
The Frequency of Simulated Sea Level Pressure Pattern Anomalies Similar to those Observed in January 2013/December 2015 Identified by Using Different Correlation Thresholds Under All-Hist and Nat-Hist Scenarios

Correlation Threshold	All-Hist	Nat-Hist	Changes (percentage)	*P* Value
		January 2013		
0.4	16	11	5 (45%)	0.080
0.5	12	5	7 (140%)	0.004
0.6	5	2	3 (150%)	0.051
		December 2015		
0.4	61	48	13 (27%)	0.006
0.5	57	40	17 (43%)	$<$0.001
0.6	41	26	15 (58%)	$<$0.001
0.7	24	12	12 (100%)	$<$0.001
0.8	6	2	4 (200%)	0.016

Note. The statistical significance of frequency changes is indicated by a *P* value using a conditional one-tailed binomial test.

the All-Hist scenario for January 2013, and from 48 to 61 for December 2015. Namely, anthropogenic influence has increased the probability of the occurrence of similar circulation patterns conducive to severe haze by about 45% in January 2013 and 27% in December 2015, respectively. We also tested the sensitivity to higher correlation thresholds, for example, $r > 0.5$, and found that the frequency increase is greater in percentages (Table 1).

3.4. Discussions

Figure S6 shows simulated large-scale circulation changes in the Northern Hemisphere driven by anthropogenic influence, suggesting a weakened winter monsoon supported by a northward and eastward shifting of the East Asia trough and a pattern of the positive phase of the Arctic Oscillation in mean SLP in both January 2013 and December 2015 due to anthropogenic influence. We note that the simulated large-scale circulation changes by anthropogenic influence in this work resemble the well-documented climate response to greenhouse warming in many previous studies (e.g., Fyfe et al., 1999; Hori & Ueda, 2006; Shindell et al., 1999; Xu et al., 2016). Also, the simulated large-scale circulation changes calculated by (All-Hist minus Nat-Hist) in this study are similar to the projected future changes in large-scale circulation relative to the present day by CMIP5 (shown in Figure S7) under RCP8.5, a scenario with large increases in greenhouse gases but decreases in aerosols. Furthermore, previous studies reported that the increase in anthropogenic aerosols over the past decades could influence wintertime regional circulation over eastern China. Xu et al. (2006) showed that the radiative forcing of anthropogenic aerosols had a small impact on the weakening of the East Asian winter monsoon during 1969–2000. Jiang et al. (2017) found that anthropogenic aerosol radiative forcing could intensify East Asian winter monsoon circulation via accelerated jet stream around 40°N and the westward shift of the East Asian trough. These regional circulation changes induced by anthropogenic aerosols are different from the large-scale circulation changes simulated in this study. As such, we infer that the simulated atmospheric pattern changes induced by anthropogenic influence in MIROC5 are mainly driven by increased greenhouse gas emissions.

The anthropogenic influence has significantly affected the climate anomalies conducive to severe haze over eastern China in January 2013 and December 2015, when other climate extreme events also occurred, including extreme Arctic sea ice loss in the preceding autumn of 2013 and extreme El Niño event in the winter of 2015. Garcia-Menendez et al. (2017) highlighted that natural climate variability is important in assessing the impacts of climate change on air quality projection. In consideration of a near-term air quality management strategy, a better understanding of the combined effects of anthropogenic climate warming and atmospheric internal variability on severe haze occurrences is urgently called for. In addition, the warming effect induced by future decreases in $PM_{2.5}$ over China for the sake of air quality improvement was simulated to be significant (K. Li et al., 2016; Westervelt et al., 2015), which may pose a potential adverse aspect for future atmospheric dispersion conditions around East Asia. These processes should be further quantified using fully coupled chemistry-climate models (Raes et al., 2010). In the present study, although anthropogenically induced circulation changes simulated in the MIROC5 model are consistent with those simulated by CMIP5 multimodels under the high greenhouse gas emission scenario, to further enhance the confidence in the attribution of circulation anomalies conducive to severe haze, a multimodel ensemble approach (Cai et al., 2017) to allow for different model representations of the climate system is desirable.

4. Conclusions

In this study, atmospheric pattern anomalies associated with the recent most severe haze cases (January 2013 and December 2015) were presented, which were characterized by a reduced land-sea thermal contrast in the near-surface (supported by an anomalous SLP gradient) and a northward and eastward shifting of the East Asia trough. Based on the simulated difference (All-Hist minus Nat-Hist) in large ensemble climate model (MIROC5) runs, we found that the simulated anthropogenically induced circulation changes in January 2013 and December 2015 resemble the anomalous atmospheric patterns observed for these 2 months. We quantified the anthropogenic influence by examining the frequency of simulated SLP patterns exhibiting high spatial similarity to those in January 2013 and December 2015. Anthropogenic influence was estimated to increase the probability of the occurrence of anomalous atmospheric pattern similar to that in January 2013 (December 2015) by 45% (27%). We further confirmed that the simulated anthropogenic circulation changes are consistent with the large-scale circulation changes induced by increased greenhouse gas emissions. Our results highlight that more strict emission reduction measures are needed to improve air quality under a continuing anthropogenic warming in the upcoming decades.

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