Possible Relationship between the Chukchi Sea Ice in the Early Winter and the February Haze Pollution in the North China Plain

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ABSTRACT

Haze pollution is among the most serious disasters in the North China Plain, dramatically damaging human health and the social economy. The frequency of haze events in February typically varies from the number of haze days in the winter. To improve the understanding of haze pollution in February, this study not only showed the large-scale atmospheric circulations associated with the variation in the haze, but also analyzed its connection with Arctic sea ice. The observational and large ensemble model results both illustrated that the preceding increase in the early-winter Chukchi Sea ice might intensify the February haze pollution. The accumulated sea ice over the Chukchi Sea resulted in a steeper meridional sea surface temperature gradient and a significant and persistent westerly thermal wind. In February, the responsive pattern in the atmosphere developed into a Rossby wave–like pattern, linking the Chukchi Sea ice and the February haze pollution. Modulating by the induced large-scale atmospheric circulations, the horizontal and vertical atmospheric ventilation conditions and the hygroscopic growth conditions enhanced the frequency of haze pollution events.

1. Introduction

Recently, haze pollution has been occurring frequently in China, especially in the North China Plain where more than 300 million people live. Severe haze dramatically damages human health and reducing haze events has become a major challenge in China (Wang 2017). Anthropogenic emissions are generally recognized as the fundamental cause of increases in atmospheric pollution (Yang et al. 2016), especially the long-term increasing trend. Furthermore, many studies have demonstrated

that climate change and climate anomalies substantially contribute to the number of haze days in China (Cai et al. 2017). Concerning external and preceding climate drivers, the anomalies of sea surface temperature over the subtropical Pacific (Yin and Wang 2016a; Gao and Chen 2017) and Eurasian snow cover (Yin and Wang 2017b) drive large-scale atmospheric responses and then impact the local dispersion conditions of haze. Because of the enhanced impacts of snow cover on soil moisture and land surface radiation, the relationship between Eurasian snow cover and December haze in North China significantly strengthened after the mid-1990s (Yin and Wang 2018).

During the recent decades, the Arctic region has warmed about 2 times more than the global average, and the Arctic sea ice (ASI) has melted rapidly (Cohen et al. 2014). The autumn ASI showed significant impacts on the Eurasian winter climate (Wang and Liu 2016; He 2015; Li et al. 2015). The role of ASI with regard to the haze in the eastern region of China was first studied by

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FIG. 1. The variation in the December (black), January (blue), and February (red) haze days from 1979W to 2012W. The linear trends are plotted as dashed lines. The error bar represents one standard error among the measured sites.

Wang et al. (2015). The joint effect of the rapid decline in the ASI extent and the reduction in precipitation and surface winds intensified the haze pollution in the North China Plain after 2000 (Wang and Chen 2016). In addition to the long-term trend, the interannual to interdecadal variations in haze days were strongly negatively correlated with the preceding autumn ASI from 1979 to 2012 (Wang et al. 2015), which has been verified by numerical simulations (Li et al. 2017). Generally, the ASI loss leads to positive sea level pressure anomalies over Eurasia, a northward shift of the East Asia jet stream (EAJS), and weak Rossby wave activity in eastern China south of 40°N during the winter, which favors a more stable atmosphere (Wang et al. 2015). In contrast to the negative correlation between the number of haze days in eastern China and the ASI, the correlation between the haze in the North China Plain and the Beaufort Sea ice was positive, which was used to build a well-performed seasonal prediction model but lacks sufficient physical interpretation (Yin and Wang 2016b, 2017a).

In most of the previous studies about haze pollution in the North China Plain (34°–42°N, 114°–120°E), the total haze days in December, January, and February were analyzed as the winter haze days. However, the variations in the frequency of haze events in different months are also different (Fig. 1). The variations in haze days for December and January were relatively similar, with correlation coefficients (between the number of haze days in December and January) of 0.66 and 0.39 before and after detrending, above the 99% and 95% confidence levels, respectively (Table 1). The number of February haze days (HD_F ; 12.5 ± 0.3 days) was dramatically lower than those of the other 2 months (December: 15.8 ± 0.4 days; January: 15.5 ± 0.4 days). The correlation coefficients between HD_F and the number of haze days in December and January were all insignificant before and after detrending (Table 1),

TABLE 1. The correlation coefficients (CCs) among the number of haze days in December, January, and February. OS means original sequence, and DT indicates that the linear trend was removed. One asterisk (*) indicates the result passed the 95% confidence level, and two asterisks (**) indicate the CC passed the 99% confidence level.

CC	Dec		Jan	
	OS	DT	OS	DT
Jan	0.66**	0.39*		
Feb	0.19	−0.11	0.28	0.06

indicating different variations. Yin et al. (2017) and Yin and Wang (2018) noted that more October–November Eurasian snow cover intensified the haze days in December. However, the relationship between HD_F and Eurasian snow cover cannot be identified from October to January (see Fig. S1 in the online supplemental material). In fact, the differences in the monthly variations and the related climate factors reduced the predictability of haze days in the winter. The Arctic Oscillation certainly affects the climate over North China Plain, and thus the correlation coefficients between the HD_F and Arctic Oscillation index from preceding September to February were calculated. However, all of the correlation coefficients with AO in different months were insignificant (figure omitted). Thus, the controlled drivers of HD_F in the middle to high latitudes merit further analysis. Considering the potential impact of ASI, this study focused on the possible relationship between sea ice and HD_F , and the associated physical mechanisms. The investigation in this paper will improve the understanding about the February haze pollution in North China.

The remainder of this paper is organized as follows. The observational and numerical simulated data and the methods are described in section 2. In section 3, the connections between the Arctic sea ice and HD_F , also including the associated atmospheric circulations, are revealed. The physical mechanisms were proposed and verified by the observations in section 4 and numerical models in section 5, respectively. The main conclusions and necessary discussion of the results are included in section 6.

2. Datasets and methods

The $2.5^\circ \times 2.5^\circ$ geopotential height (Z), zonal and meridional wind, relative humidity, vertical velocity, air temperature at different levels, sea level pressure (SLP), and surface air temperature (SAT) data were downloaded from the National Centers for Environmental Prediction–National Center for Atmospheric Research (Kalnay et al. 1996). The monthly sea ice concentrations

from 1979 to 2017 were obtained from the Met Office Hadley Centre, with a horizontal resolution of $1^\circ \times 1^\circ$ (Rayner et al. 2003). The monthly mean Extended Reconstructed sea surface temperature (SST) datasets from 1979 to 2013, with a horizontal resolution of $2^\circ \times 2^\circ$, were available from the National Oceanic and Atmospheric Administration website (Smith et al. 2008). The daily PM_{2.5} concentration and air quality index data from 2014 to 2018 were provided by the Ministry of Environmental Protection of China.

The subdaily (i.e., four times per day) routine meteorological observations (i.e., relative humidity, visibility, wind speed, and weather phenomena data) from 1979 to 2017 were collected by the National Meteorological Information Center, China Meteorological Administration. The observed visibility was routinely used to distinguish the haze weather in meteorology for a long time. According to Yin et al. (2017), the haze data were mainly calculated based on the visibility and the relative humidity measurements, and other weather phenomena affecting visibility (e.g., dust, precipitation, blowing snow, and sandstorms) were excluded. The robustness and representativeness of the calculated haze data were strictly verified and controlled in Yin et al. (2017). The term HD_F represents the mean number of February haze days over the North China Plain.

In addition to the observational and analysis data mentioned above, the simulations from the Community Earth System Model Large Ensemble (CESM-LE) datasets are employed (Kay et al. 2015). The CESM-LE datasets were included to provide evidence for the proposed connections between the Arctic sea ice and haze pollution in North China. Data from the CESM-LE project are publicly available (<http://www.cesm.ucar.edu/experiments/cesm1.1/LE/>). The CESM-LE simulations were completed by the fully coupled CESM model, with CAM5.2 as its atmospheric component. The CESM-LE simulations uses 35 ensemble members at NCAR, with a horizontal resolution of 0.9° latitude $\times$ 1.25° longitude and 30 vertical levels. Each member is subject to the same radiative forcing scenario (historical up to 2005 and representative concentration pathway 8.5 thereafter), but begins from a slightly different initial atmospheric state. The monthly sea ice concentration, sea surface temperature, and meridional and zonal winds were analyzed here.

Linear correlation analyses (Pearson correlation coefficient here) were the basic method when revealing the relationships and associated physical mechanisms. Although it is a measure of the strength and direction of the linear relationship between two variables, significance testing (*t* test here) is necessary. The 95% (99%) confidence level means 95% (99%) certain. Generally, the

correlation exceeded 95% confidence level means that the revealed relationship is statistically significant and can be trusted. It is worth noting that there is still a 5% (1%) possibility to reject the hypothesis. Furthermore, the correlation sometimes does not reflect the real causality. Thus, we also employed the large ensemble numerical simulations to verify and evaluate the proposed relationship and physical mechanisms. In the following study, to facilitate a convenient understanding of the data in this study, months are labeled by the year to which their winter season belonged. For example, the November–January (NDJ) months in the winter of 1979 were labeled NDJ 1979W and the February month in the winter of 1979 (i.e., February 1980) was recorded as February 1979W.

3. Connection between the Arctic sea ice and HD_F

Considering that the correlation with snow cover was insignificant (Fig. S1), the roles of the other effective external drivers in the mid- to high latitudes (i.e., the ASI) were investigated. As shown in Fig. 2a, the significant correlation between the HD_F and NDJ sea ice was regionally located in the Chukchi Sea, instead of in the entire Arctic region. The HD_F was positively correlated with the preceding NDJ Chukchi Sea ice during 1979W–2012W. The spatially mean of sea ice area over the Chukchi Sea (70° – 80° N, 165° E– 20° W) in NDJ was defined as the Chukchi Sea ice index (CSI_{NDJ}) and had a correlation coefficient with HD_F of 0.47 (0.56) after (before) detrending, which was above the 99% confidence level (Fig. 2b). This positive correlation potentially meant that increases in CSI_{NDJ}, to some extent, intensified the February haze pollution in the North China Plain, which still needed physical explanations.

To reveal a possible relationship, the correlation coefficients between the CSI_{NDJ} and the atmospheric circulations (Fig. 3b) and meteorological conditions (Figs. 4b,d,f) were computed after the removal of the linear trend. Considering the lack of previous studies on the features of HD_F, the atmospheric circulations (Fig. 3a) and meteorological conditions (Figs. 4a,c,e) associated with the variation in HD_F were also shown. In the middle to high troposphere, the most significant features in the atmosphere associated with the HD_F were the extensive positive Z500 anomalies from the east of China to the Gulf of Alaska (Fig. 3a). This differed from the anomalous Z500 distribution associated with the winter haze, as reported by Yin and Wang (2016a) and Yin et al. (2017), which was characterized by positive anomalies over North China and Sea of Japan and negative anomalies over the Bering Sea. As shown in Fig. 3a, the broad anticyclonic anomalies occupied the entire region

FIG. 2. (a) The CC between the HD_F and Arctic sea ice concentration from 1979W to 2012W after detrending. The black dots indicate CCs exceeding the 95% confidence level (t test). The green box represents the Chukchi Sea. The letters “NSI” and “CP” indicate the locations of New Siberian Islands and Chukchi Peninsula. (b) The variation in the normalized HD_F (black) and normalized CSI_{NDJ} (blue) from 1979W to 2012W before (dashed line) and after (solid line) detrending.

of the East Asia deep trough, making it significantly weak and moving it eastward. The induced anomalous air flows (i.e., the southerlies from the east of China to the central Siberian plateau) confined the meridional northerly from the high latitudes to the North China Plain. At 200 hPa, the responded east winds, at the bottom of the broad anticyclonic anomalies, weakened the EAJS. Thus, the Rossby wave activities along the EAJS and the cold air were weakened, resulting in a warmer land surface in the North China Plain (Fig. 4c). The atmospheric circulations at the mid- to high level correlated with the CSI_{NDJ} were fairly similar to those correlated with the HD_F , such as the broad Z500 anomalies from the east of China to the Gulf of Alaska and the weak and northward EAJS (Fig. 3b). Although there were weak negative anomalies in the atmosphere, the key area (i.e., the east of China) was steadily controlled by the anticyclonic circulations. In addition, there was a Rossby wave-like pattern propagated from the east of China (+) through Lake Baikal (−), the Sea of Okhotsk (+), the Chukchi Peninsula (−), and the Gulf of Alaska

FIG. 3. The CC between both the (a) HD_F and (b) CSI_{NDJ} and the large-scale atmospheric circulations. The atmospheric circulations included wind at 200 hPa (arrow) and geopotential height at 500 hPa (shading) from 1979W to 2012W. The black dots indicate the CC exceeded the 90% confidence level (t test). The linear trend was removed. The green box represents the North China Plain.

(+). Although the negative atmospheric centers seemed to be somewhat weak, this wave train appeared to bridge the CSI_{NDJ} and HD_F . The pivotal anticyclonic circulation anomalies over the east of China, especially the anomalous southerly, were barotropic and extended to the lower troposphere and the land surface (Figs. 4a,b).

Near the surface, the local meteorological conditions, which were influenced by the CSI_{NDJ} (Figs. 4b,d,f), were also in good agreement with the patterns aggravating haze pollution (Figs. 4a,c,e). The significantly negative SLP anomalies over China and the positive anomalies over the North Pacific weakened the pressure gradient causing the winter monsoon (Figs. 4c,d). The climate pattern, from low to high latitude, manifested as the weaker East Asian winter monsoon pattern. The associated southerly not only restricted the cold airflow to the North China Plain, but also led to a more humid environment (Figs. 4a,b). To some extent, the horizontal dispersion conditions were limited; therefore, the polluted aerosols could not be blown away. Through moisture absorption, the haze nuclei grew rapidly, resulting in a relatively low visibility. Affected by the weakening of the north wind, the SAT over the North

FIG. 4. The CC between both the (a),(c),(e) HDF and (b),(d),(f) CSI_{NDJ} and the meteorological conditions. The meteorological conditions included (a),(b) surface wind (arrow) and relative humidity (shading), (c),(d) SLP (shading) and SAT (contour), and (e),(f) thermal inversion potential (shading) and surface upward motion (contour) from 1979W to 2012W. The black dots indicate the CC exceeded the 90% confidence level (t test). The linear trend was removed. The green box represents the North China Plain. The thermal inversion potential was defined as the air temperature at 850 hPa minus SAT.

China Plain was warmer (Figs. 4c,d). The thermal inversion potential was defined as the air temperature at 850 hPa minus SAT, which was positive over the North China Plain (Figs. 4e,f). The enhanced atmospheric temperature inversion was remarkably unfavorable for the vertical dispersion of pollutants, leading to high levels of fine particulate pollution. Furthermore, there was slight convergence, as indicated by the upward motion near the surface (Figs. 4e,f). This convergence transported the aerosols emitted in the surrounding areas to the North China Plain, but it could not disturb the thermal inversion layer. The converging and local aerosols both accumulated and reached a high concentration easily. Thus, statistically, the preceding CSI_{NDJ} anomalies triggered atmospheric Rossby wave–like pattern in February, which resulted in limited horizontal and vertical ventilation conditions over the North China Plain. Under such local meteorological conditions, the aerosol emissions concentrated easily (i.e., haze pollution frequently happened).

4. Associated physical mechanisms

The connection between the CSI_{NDJ} and HD_F was adequately supported by the analysis of large-scale atmospheric circulations and local meteorological conditions. However, the accompanying question (i.e., the physical mechanisms of the impacts of CSI_{NDJ} on atmospheric circulations) was still unclear. In the high latitudes, the memory effect aging of sea ice and SST is probably 1 month, and the impact of the air circulations on the sea surface is also significant and must be considered (Gao et al. 2015). The correlation coefficients between the CSI_{NDJ} and the NDJ SST around the Chukchi and Bering Seas were significantly negative (i.e., -0.79), exceeding the 99% confidence level. Sea ice with high albedo reflects solar radiation back to the atmosphere (Zhang et al. 2017) and blocks the direct exchange of energy between the air and sea. The accumulated CSI_{NDJ} significantly reduced the net short-wave radiation at surface (Fig. S2) and thus resulted in a locally cooler SST in the Chukchi Sea and Bering Strait (Fig. 5a). Most likely, this cold water current was transported by the Oyashio to the Bering Sea (Konstantin 2000), leading to an extension of the cooler SST. In the central North Pacific, covariant positive NDJ SST anomalies existed, with a correlation coefficient with CSI_{NDJ} of 0.36, above the 95% confidence level. The SST gradient between the negative and positive anomalous centers intensified. To further verify the proposed impacts of CSI_{NDJ} on this SST gradient, the NDJ SST difference between central North Pacific and Chukchi and Bering Seas was plotted in Fig. 6.

FIG. 5. (a) The CC between the CSI_{NDJ} and both the NDJ SST (shading) and wind at 850 hPa (arrow) in January from 1979W to 2012W. The white dots indicate the CC exceeded the 95% confidence level (t test). The green (black) box represents the North China Plain (Chukchi area). (b) The CC between the SST_c and wind at 850 hPa (arrow) in January from 1979W to 2012W. The SST_c was calculated as the mean NDJ SST within the black boxes in (b), which were significantly correlated with CSI_{NDJ} . The linear trend was removed. Letters “A” and “C” represent the center of the cyclonic and anticyclonic circulations, respectively.

The CSI_{NDJ} and SST difference varied consistently from the interannual to decadal time scale, with correlation coefficient 0.75 after detrending (above the 99% confidence level).

Theoretically, the steeper meridional SST gradient induced significant westerly thermal wind anomalies. There is persistent warm advection to the south of the climatic Aleutian low (Zhou and Wang 2014). Thus, the Aleutian low and the East Asia deep trough weakened and moved eastward in January, which manifested as anticyclonic anomalies over the Sea of Okhotsk and cyclonic circulation over the Bering Sea in the anomalous fields (Fig. 5a). Furthermore, the anticyclonic anomalies were located broadly and extended to 35°N. Similar patterns of anomalous circulations at 850 hPa were revealed by Li and Wang (2013). To strengthen the explanation of the anticyclonic and cyclonic anomalies, the correlation coefficient between the January wind at 850 hPa and the NDJ SST around the Chukchi and Bering Seas was calculated (Fig. 5b).

FIG. 6. The variation in the normalized CSI_{NDJ} (solid) and the normalized NDJ SST difference between central North Pacific and Chukchi and Bering Seas (dashed) from 1979 to 2012. The linear trends are removed.

This anomalous pattern in January that was characterized by “west anticyclonic–east cyclonic” anomalies could be stimulated by the persistent SST anomalies significantly correlated with CSI_{NDJ} . Influenced by the significant westerly anomalies in January from the Kamchatka Peninsula to the central North Pacific, the locations of the center of negative and positive SST anomalies both shifted southward by about 5° in February (Fig. 7). Therefore, the meridional temperature gradient could not support the broad, anticyclonic anomalous circulation, which was cut off into two parts (i.e., the anticyclonic anomalies at the New Siberian Islands and northeast Pacific). Furthermore, anomalous activity centers in the atmosphere were induced both upstream and downstream. The Rossby wave–like pattern formed and the centers were distributed in the East China Sea (+), Lake Baikal (−), New Siberian Islands (+), Chukchi Peninsula (−), Gulf of Alaska (+), and east Pacific (+). This Rossby wave–like pattern was also identified at the middle to high level (Fig. 3b) and linked the CSI_{NDJ} and HD_F .

As shown by vertical motions, this Rossby wave–like pattern was clearer in the lower troposphere than in the mid- to high troposphere (Fig. 8). Significant downdrafts and updrafts over each side of the Chukchi Sea were stimulated (Fig. 8b) and then propagated through an alternatively ascending and descending motion (Fig. 8) along the pathway that resembles the great circle shown in Fig. 7. The anticyclonic anomalies in the East China Sea caused a significant southerly that blew to the North China Plain. This anomalous southerly reduced the surface wind speed and resulted in a calm environment (Zhong et al. 2019). The warm and humid airflow at 850 hPa favored the occurrence of a thermal inversion layer and supported sufficient moisture for the growth of the haze particles. Furthermore, the anomalous southerly and the convergence near the surface transported the pollutants emitted by the surrounding cities and aggravated the local concentration of the aerosols in the North China Plain. The vertical motion was upward

above the polluted area (Fig. 8), indicating that the high-altitude clear and dry air and momentum could not dive downward and hardly disperse the accumulated haze pollution near the surface (Sun et al. 2017). Thus, the horizontal and vertical atmospheric ventilation conditions and the hygroscopic growth conditions enhanced the frequency of haze pollution.

5. Causality verification by CESM-LE simulations

The possible linkage between the CSI_{NDJ} in the early winter and the HD_F was statistically discussed in the above analyses. Here, the CESM-LE data were also used to verify the robustness of this statistical relationship and associated physical mechanisms (i.e., to explore whether these physical processes existed in the large ensemble model simulations). With the same time as observations, the variables from CESM-LE from 1979W to 2012W are employed. The lowest and highest 5 years

FIG. 7. The CC between the CSI_{NDJ} , SST (shading), and wind at 850 hPa (arrow) in February from 1979W to 2012W. The white dots indicate the CC exceeded the 95% confidence level (t test). The heavy solid line links the centers of the cyclonic and anticyclonic circulations. The linear trend was removed. The letters “A” and “C” represent the center of the cyclonic and anticyclonic circulations, respectively. The green (black) box represents the North China Plain (Chukchi area).

FIG. 8. The (a) 120°E and (b) 60°N cross section CCs between the CSI_{NDJ} and both the omega (shading) and vertical motion wind (arrow) in February from 1979W to 2012W. The black dots indicate the CC exceeded the 95% confidence level (t test).

of CSI_{NDJ} in each ensemble members were selected to construct the composite maps. The LowCSI experiments denoted the composite results (including the sea ice, SST, and atmospheric circulations) are calculated as the differences between the mean of lowest five CSI_{NDJ} years and the mean status during 1979W–2012W (Fig. 9), while the results of HighCSI experiments are the differences between the mean of five highest CSI_{NDJ} years and the mean status during 1979W–2012W (Fig. 10).

In the LowCSI case, the sea ice coverage in the Chukchi Sea dramatically declined in the five low CSI_{NDJ} years in comparison to the mean status during 1979W–2012W (Fig. 9a). The sea ice, out of the Chukchi Sea, also decreased. Then the decline of NDJ sea ice favored increased SST over the Chukchi Sea, Bering Sea, and Gulf of Alaska (Fig. 9c), which is in good accordance with the observed analysis in Fig. 5a. Both of the significantly negative SST anomalies over central North Pacific and the evident SST gradient were also well reproduced by the model. Furthermore, the westerly thermal wind and its location were fairly similar to the observed results. The SST anomaly pattern in February, revealed in the observational diagnostics (Fig. 7), was also captured by the large ensemble

CESM-LE simulations (Fig. 9d). The HighCSI experiments may be identified as the converse case to LowCSI, and almost opposite responses were obtained. There were significantly positive sea ice coverage anomalies in the Chukchi Sea and Bering Sea (Fig. 10a), whose intensity was close to those in the LowCSI experiments. As expected, significantly cooler NDJ SST occurred over the Chukchi Sea, Bering Sea, and Gulf of Alaska, and warmer sea surface existed to their south side (Fig. 10b). These SST anomalies could also be found in February, but the location was a little southward (Fig. 10d), which is in good agreement with the observed results and opposite with the LowCSI experiments.

The composite results from the LowCSI simulations indicate that the decreased CSI_{NDJ} also accounted for the development or the propagation of the similar Rossby wave-like pattern (Fig. S3). The anomalous Rossby wave-like pattern led to anomalous northwesterly wind from Siberia to North China at 850 hPa (Fig. 9b), which strengthened the East Asian winter monsoon. Therefore, these atmospheric circulations associated with the decreased CSI_{NDJ} contributed to the well-ventilated conditions over North China, and vice versa. Consistent with the observed results, the linkages

FIG. 9. Composite difference of (a) NDJ sea ice concentration (unit: %), (b) wind at 850 hPa in February, (c) NDJ SST, and (d) SST in February between five lowest CSI_{NDJ} years and the mean during 1979W–2012W (i.e., the LowCSI experiments). The dotted regions in (a) indicate the composite differences are significant at the 95% t test confidence level. The black box in (a) represents the Chukchi area. The light and dark gray shading regions in (b)–(d) indicate where composite differences are significant at the 95% and 99% t test confidence level, respectively. Results are based on 35 ensembles of CESM-LE simulations.

between the Chukchi Sea ice in the early winter and the HD_F -related atmospheric circulation also exist in CESM-LE simulations. Meanwhile, the corresponding physical mechanisms were also well reproduced by the large ensemble members. The performances of numerical models in the middle to high latitudes were consistently limited, and sometimes identical results could not be found from the experiments with positive and negative anomalies (Sun 2014; Yin and Wang 2016a). However, the results from CESM-LE here successfully captured major features and general physical processes as expected, both from the HighCSI and LowCSI experiments.

6. Conclusions and discussion

The variation in the number of haze days in February was significantly different from that in December and January and was analyzed in this study. The relationship between the HD_F and NDJ sea ice of the Chukchi Sea was closely positive, indicating that the increase in CSI_{NDJ} intensified the February haze pollution in the North China Plain. The connection between the CSI_{NDJ}

and HD_F can be adequately explained by the associated large-scale atmospheric circulations and local meteorological conditions. For convenience, schematic diagrams of the associated physical mechanisms were provided (Fig. 11). The proposed physical mechanisms are verified both by the observational analysis and the large ensemble CESM-LE simulations and can be explained as follows. The accumulated CSI_{NDJ} resulted in locally cooler SST in the Chukchi Sea and Bering Sea, and a consequently steeper meridional sea surface temperature gradient. Then, significant anticyclonic anomalies over the Sea of Okhotsk and cyclonic circulation over the Bering Sea in January were stimulated by the westerly thermal wind. In February, the meridional temperature gradient shifted southward, and the broad, anomalous anticyclonic circulation was cut into two parts, one in the New Siberian Islands and one in the northeast Pacific. Furthermore, a Rossby wave-like pattern formed and linked the CSI_{NDJ} and HD_F . The anticyclonic anomalies in the East China Sea caused a significant southerly anomalous wind blowing to the North China Plain. The reduced surface wind speed, thermal inversion layer and sufficient moisture

FIG. 10. Composite difference of (a) NDJ sea ice concentration (unit: %), (b) wind at 850 hPa in February, (c) NDJ SST, and (d) SST in February between five highest CSI_{NDJ} years and the mean during 1979W–2012W (i.e., HighCSI experiments). The dotted regions in (a) indicate the composite differences are significant at the 95% t test confidence level. The black box in (a) represents the Chukchi area. The light and dark gray shading regions in (b)–(d) indicate where composite differences are significant at the 95% and 99% t test confidence level, respectively. Results are based on 35 ensembles of CESM-LE simulations.

associated with this anomalous southerly favored the occurrence of haze. The horizontal and vertical atmospheric ventilation conditions and the hygroscopic growth conditions enhanced the frequency of haze pollution.

Typically, the Chinese New Year (i.e., the most important festival in China) is in February. During this period, people always enjoy a 7-day holiday, and most factories, an important source of pollution, are closed. The aerosol emissions by factories are therefore reduced. However, the mean $PM_{2.5}$ concentrations during the holiday were slightly higher than those during the workday during 2015–17 (Fig. 12). A possible reason for this is the lighting of fireworks to celebrate the Spring Festival. The aerosol emission level was not markedly different during this 7-day holiday, compared to the other days around. Under similar background of aerosol emission levels, the impacts of meteorological conditions still work mainly as usual. Thus, the proposed physical mechanisms were not obviously affected by the artificial holidays.

Confirmed, the fundamental drivers for haze pollution were the anthropogenic emissions. Now that local

emissions were not significantly decreased due to the 7-day holiday, the reasons for the lower number of haze days in February than those of the other 2 months (Fig. 1) is still an open question needed further studies. In the last two decades, the CSI_{NDJ} increased from 1995W to 2000W, declined from 2000W to 2007W, and has increased since 2007W. The variation in HD_F demonstrated similar features. The linkages between these two large-scale variations were not discussed in depth here and need further attention. As noted by Yin et al. (2017), most meteorological observations have switched from manual to automatic since 1 January 2014. Thus, our studies used the data from 1979W to 2012W. Although the continuity of haze data after 2014 potentially influenced the analysis, the observations were still valuable. The 31-yr running correlation coefficients between CSI_{NDJ} and HD_F were calculated; they were slightly below the 95% confidence level during 1986W–2016W (Fig. 13). However, the correlation between HD_F and January–February sea ice of the Bering Sea intensified and exceeded the 95% confidence level during 1986W–2016W. The change in the correlation can possibly be attributed to the varying external

FIG. 11. Schematic diagrams of the associated physical mechanisms. (a) The accumulated CSI_{NDJ} caused the NDJ meridional temperature gradient on the sea surface and then exerted significant anticyclonic and cyclonic circulations at 850 hPa in January. (b) The meridional temperature gradient shifted southward in February. A Rossby wave-like pattern formed and linked the CSI_{NDJ} and HD_F . The anomalous atmospheric circulations at 850 hPa were plotted by a dashed line.

forcing mechanisms or possibly be caused by the data quality. The reasons underlying the positive SST anomalies in the central North Pacific, which had a correlation coefficient with CSI_{NDJ} above the 95% confidence level, are also an open question. One conjecture, which requires

FIG. 12. The variation in the $PM_{2.5}$ concentration (solid) and AQI (dashed) around Chinese New Year holiday (CNYH; denoted by green lines) from 2015 to 2017. The mean $PM_{2.5}$ concentrations are plotted as straight lines.

FIG. 13. The 31-yr running CC between HD_F and BSI (blue) or CSI_{NDJ} (red) from 1979W to 2016W. The dashed lines represent the 95% confidence level. The BSI was calculated as the January–February mean sea ice area over the Bering Sea (57° – 65° N, 160° – 177° W).

future verification, is that the simultaneous anticyclonic circulation over the east subtropical Pacific enhanced the radiative heating of the sea surface (Fig. S2) and further transported warmer seawater from the subtropics to the central North Pacific (Fig. S4).

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