Possible Relationship between January “Warm Arctic–Cold Eurasia” and February Haze in North China

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ABSTRACT: Haze pollution frequently occurs in North China almost every winter month. However, many previous studies pointed out that the interannual–decadal variations of haze in February were inconsistent with that in early winter, which demonstrated an evident subseasonal change in haze pollution. In this study, we found a close relationship between the “warm Arctic–cold Eurasia” (WACE) pattern in January and the weakened February haze pollution in North China according to monthly composites from 1980 to 2019. Associated with the warming signal in sea ice and the cooling signal in Eurasian soil temperatures, the WACE pattern sustained from January to February. The combined signal of sea ice and soil temperature anomalies and its associated anomalous cyclonic circulations over North China provided an environment conducive to the dispersion of pollutants. The relationship between the WACE pattern and the cyclonic circulation anomaly could also be detected from the large-ensemble CMIP6 simulations. Furthermore, the relationship between the January WACE pattern and the reduction of February haze pollution has been prominently enhanced since the late 1990s, which accurately corresponds to the deep Arctic warming that has emerged since the late 1990s.

SIGNIFICANCE STATEMENT: Haze pollution frequently occurs in North China almost every winter month, but with an apparent subseasonal change. Climate anomalies in the mid- to high latitudes could regulate the variations in haze through atmospheric teleconnection. Our study found a relationship between the “warm Arctic–cold Eurasia” (WACE) pattern in January and the weakened February haze pollution in North China. The lingering signal of the WACE was associated to the anomalous cyclonic circulations over North China in February, which was conducive to the dispersion of pollutants. Furthermore, the relationship between the WACE pattern and February haze pollution has been prominently enhancing since the late 1990s, which accurately corresponds to the emergence of the deep Arctic warming accompanied by the strengthened Eurasian cooling. This investigation is of great significance for subseasonal haze prediction.

KEYWORDS: Climate variability; Air pollution; Atmospheric circulation; Atmosphere-land interaction

1. Introduction

Haze pollution occurs in an environment with weak dispersion and high humidity, which is characterized by low visibility and high concentration of fine particulate matter (PM2.5). Exposure to PM2.5 has harmful effects on economic development, ecological sustainability, and human health (Wang and Chen 2016). For example, it caused 4.2 million premature deaths worldwide in 2015 and up to 0.96 million premature mortalities in 2017 in China (Lu et al. 2019). North China (NC; 35°–43°N, 110°–120°E) is an area with the most serious haze pollution in China, especially in winter (Yin et al. 2015; Gao et al. 2021). However, haze pollution in each month of winter is not consistent and often demonstrates an apparent subseasonal variation (Yin et al. 2019b). It occurs more frequently and seriously in December and January (i.e., the early winter), and the variations in haze days in the two months are relatively similar. The number of haze days in February is dramatically lower, and its interannual variation and trend change are also greatly different from those in early winter (Yin et al. 2019b). Although the variation in haze pollution has always been attributed to human activities directly related to aerosol emissions and global warming (Yang et al. 2016; Li et al. 2018; Cai et al. 2017), the subseasonal variation in haze pollution suggests that certain physical mechanisms and climate factors that influenced haze pollution in early winter and February are not exactly the same. The differences in monthly variation of haze pollution and related climate factors reduce the predictability of haze days in winter.

Previous studies indicate that climate anomalies in the mid- to high latitudes could drive significant large-scale atmospheric responses and subsequently affect interannual–decadal variations in winter haze. Anomalies of these climate
factors impact the regulation of local meteorological conditions through atmospheric teleconnections, thereby affecting the accumulation and generation of haze pollution in NC. The eastern Atlantic–western Russia (EA/WR), western Pacific (WP), and Eurasian (EU) patterns serve as effective atmospheric bridges linking preceding climate external factors and the anomalous anticyclonic circulations over Northeast Asia (Yin et al. 2017). Affected by the enhanced anticyclonic anomalies, the stagnant air in winter is characterized by a shallow boundary layer, low surface wind speeds, and anomalous ascending motions, which limits the horizontal and vertical dispersion of particles and leads to the accumulation of pollutants (Wu et al. 2017; Zhong et al. 2019). Meanwhile, the high relative humidity provides a favorable condition for the hygroscopic growth of pollutants (Ding and Liu 2014).

Arctic sea ice and Eurasian snow cover, two crucial climate forcing factors at mid- to high latitudes, are closely linked to atmospheric circulation and haze pollution. The positive September–October sea ice anomalies over the western Beaufort Sea provide a suitable atmospheric background for the early winter haze pollution in NC, through the bridge of affecting the variation of sea surface temperature over the Bering Sea and the Gulf of Alaska (Yin et al. 2019a). The warmer sea surface efficiently heats the air above and leads to suitable atmospheric backgrounds with a weaker East Asian jet stream and anomalous southerlies to enhance the potential of haze weather. Since the late 1990s, the response of early winter haze pollution to sea ice cover has been significantly strengthened due to the massive melting of multiyear sea ice in the western Beaufort Sea and the replacement of the perennial ice cover by seasonal ice (Li and Yin 2020). Moreover, the accumulated sea ice in the early winter Chukchi Sea results in a steeper meridional sea surface temperature gradient and a persistent westerly thermal wind accompanied by a Rossby wave–like pattern response, which could enhance the February haze pollution (Yin et al. 2019b). In addition to the linkage between Arctic sea ice and haze pollution in NC, the Eurasian snow cover at mid- to high latitudes could also provoke large-scale atmospheric responses with two significant active centers of the EA/WR pattern, thus impacting local dispersion conditions related to haze (Yin and Wang 2017). Due to the enhanced influence of snow cover on soil moisture and land surface radiation, the relationship between Eurasian snow cover and December haze in NC intensifies distinctly after the mid-1990s (Yin and Wang 2018).

One conspicuous signal in the mid- to high latitudes that attracted widespread concern is characterized by the warming trend in the Arctic and the cooling trend in Eurasia with a weakened meridional temperature gradient. The Arctic warming is particularly evident near the Barents–Kara Seas with a rate approximately 2–3 times that of the global average, which is referred to as “Arctic amplification” (Francis and Vavrus 2012; Gao et al. 2015). However, extreme cold events have occurred more frequently in Eurasia since the late 1990s, which is in sharp contrast to the warming in the Arctic, forming the pattern termed “warm Arctic–cold Eurasia” (WACE; Inoue et al. 2012; Kim et al. 2014). The existence of WACE could also be detected in surface air temperature (SAT) anomalies, geopotential thickness, and temperature in the midtroposphere (Overland and Wang 2010; He et al. 2020). During the period of the most significant Arctic warming and Eurasian cooling from the late 1980s to the early 2010s (Blackport and Screen 2020), the warming and cooling trend in January are significantly stronger than that in the other two winter months (see Table S1 in the online supplemental material), showing more effective signals. The sharp temperature contrast between the warming Barents–Kara Seas and the cooling Eurasia inevitably leads to a reduction in the large-scale meridional temperature gradient at the mid- to high latitudes (Luo et al. 2016; Outten and Essa 2012; Tao et al. 2019) and influences the upper-level jet stream and Rossby wave activities (King et al. 2016; Zhang et al. 2016). In response to the above changes, climate anomalies develop in the midlatitudes. This raises the question of whether the February haze pollution in NC is linked to the co-occurrence of warm Arctic and cold Eurasia in January. Considering the potential impact of WACE, we focus on the study of a possible relationship between February haze pollution and the WACE in January on an interannual scale, as well as the variation of this relationship on interdecadal scales. Just as haze pollution varies from month to month, WACE also demonstrates subseasonal variabilities (Qi and Pan 2021). The present study will help to deepen the understanding of February haze pollution in NC and provide a new potential predictor for subseasonal prediction of haze pollution.

The rest of the paper is organized as follows: the datasets and methods used in this study are introduced in section 2. The linkage between WACE pattern and haze pollution and its interdecadal strengthening are presented in section 3. The verification and uncertainties of the relationship are described in section 4. Section 5 provides a summary and discussion.

2. Data and methods

a. Data description

The number of haze days is used to reflect long-term variation of haze pollution. It is calculated from long-term meteorological data, mainly based on observed visibility and relative humidity (Yin et al. 2017), which are collected four times per day, at 0200 local time (LT), 0800 LT (0000 UTC), 1400 LT, and 2000 LT. Haze is recognized as when visibility falls below a certain threshold and relative humidity is less than 90%. Most of the visibility observations have switched from manual to automatic since 1 January 2014. Thus, the visibility threshold was 10 km before 1 January 2014; after the switch, the threshold became 7.5 km. A haze day is defined as a day with haze occurring at any of the four times.

Monthly mean meteorological data from 1980 to 2019 are extracted from the NCEP–NCAR reanalysis dataset (2.5° × 2.5°), including geopotential height at 500 hPa (Z500), zonal and meridional winds at 200 and 850 hPa, vertical velocity from the surface to 200 hPa, air temperature from surface to 400 hPa, and wind speed and relative humidity at the surface (Kalnay et al. 1996). The monthly mean boundary layer
height (BLH), sea ice cover, and soil temperature up to 100-cm depth are obtained from the fifth-generation ECMWF reanalysis (ERAS; 1° × 1°; Hersbach et al. 2019). The dataset of Historical and Atmospheric Model Intercomparison Project (AMIP) experimental models (Table S2) that participate in phase 6 of the Coupled Model Intercomparison Project (CMIP6) are used to verify results of the present study. Historical experiments are conducted to simulate historical climate driven by observations and time-varying external forcing, and the results present climate variability and change trend (Luo et al. 2020; Fu et al. 2020). AMIP experiments use observed sea surface temperature and sea ice from 1979 to 2014 as boundary conditions to drive atmospheric general circulation models (Gates et al. 1999). Data from 46 (32) models are available for the Historical (AMIP) experiment when this study was performed; 27 of the 46 historical models have outputs of sea ice and soil temperature.

b. Eady growth rate

The atmospheric baroclinicity is expressed by the Eady growth rate, which is a measure of baroclinic instability through the vertical gradient in the horizontal wind (Bretherton 1966; Eady 1949). The function is given by $\sigma_E = 0.3098 \sqrt{\frac{f}{\partial u/\partial z}}/N$ (Vallis 2006), where $f$ is the Coriolis parameter, $u(z)$ is the vertical profile of the westerly wind, $z$ is the vertical coordinate, and $N$ is the buoyancy frequency [$N^2 = (g/\rho)(\partial \theta/\partial z)$, in which $g$ and $\theta$ are gravitational acceleration and potential temperature, respectively].

c. GEOS-Chem description and experimental design

To verify the conclusions of the present study, the GEOS-Chem model (https://geos-chem.seas.harvard.edu/) is used to simulate PM$_{2.5}$ concentrations and calculate the simulated number of haze days. The GEOS-Chem model is driven by MERRA-2 assimilated meteorological data (Gelaro et al. 2017). The nested grid over Asia (11°S-55°N, 60°-150°E) has a horizontal resolution of 0.5° latitude × 0.625° longitude and 47 vertical layers up to 0.01 hPa. The GEOS-Chem model includes fully coupled ozone–oxygen–nitrite–hydrocarbon and aerosol chemical mechanisms with more than 80 species and 300 reactions (Bey et al. 2001; Park et al. 2004). The PM$_{2.5}$ components simulated by GEOS-Chem include sulfate, nitrate, ammonium, black carbon and primary organic carbon, mineral dust, secondary organic aerosols, and sea salt. The simulation by GEOS-Chem model extends a dimension of reanalysis data and adds PM$_{2.5}$ concentrations as a variable, which is a diagnostic process. The GEOS-Chem model has been widely applied in atmospheric environment study (Dang and Liao 2019; Yang et al. 2016). In our previous work, the simulation capability of the GEOS-Chem model has been evaluated in detail. For example, the model could well capture changes in daily PM$_{2.5}$ and its spatial distribution even in February 2020 (Yin et al. 2021), when the emissions scenario was special due to substantial reduction in emissions caused by the implementation of COVID-19 quarantine. The correlation coefficient between daily PM$_{2.5}$ observations and simulations in February 2020 under the fixed emission scenario reached 0.83 in NC, and the model could realistically reproduce both severe haze events and good air quality events (Yin et al. 2021). From the perspective of the simulation of the winter mean, the model also did a good job in simulating the PM$_{2.5}$ rebound of 12.5% in the winter of 2018 compared to the PM$_{2.5}$ in the winter of 2017, very close to the observed rebound of 10% (Yin and Zhang 2020).

In this study, we simulated PM$_{2.5}$ with changing meteorological conditions in February from 1980 to 1990 and fixed emission at a relatively high level of the year 2010. The emission data in 2010 were from MIX 2010 (Li et al. 2017). The simulation experiments were conducted to examine the variation in PM$_{2.5}$ under different meteorological conditions in February during 1980–2019 and a fixed-emission scenario. According to the technical regulation of the ambient air quality index of the Ministry of Ecology and Environment of the People’s Republic of China, a haze day was defined as a day with daily mean PM$_{2.5}$ concentration exceeding 75 µg m$^{-3}$. Under the fixed-emission scenario of the year 2010, we evaluated the model performance on the simulation of haze days in February 2010. The simulated number of haze days in NC was 10.5 days, which was very close to the observation of 9.8 days. The spatial distribution between the simulation and observations was similar with a spatial correlation coefficient of 0.78. Due to the fixed emission in the model, the sequences of observed and simulated haze days were detrended and then normalized for comparison. The correlation coefficient of the two sequences was 0.57 (above the 99% confidence level) during 1980 to 2019. The simulated sequence was reasonably close to the observed sequence and could reproduce its interannual variation. In addition, we selected one station in two major provinces of North China (i.e., Shanxi and Hebei provinces) respectively to further illustrate the model’s capability to simulate haze days. The simulated number of haze days at these two stations in 2010 was 14.75 and 3.25 days, respectively, which was very close to the observed value of 13 days and 3 days. The correlation coefficient between the observed and simulated haze days after detrending and normalization of these two stations was 0.62 and 0.58 (above the 99% confidence level) during 1980 to 2020, respectively. The above comparison proved that the model could better simulate the variation in observed haze days. The simulation under the fixed-emission scenario excluded the influence of human emissions on haze and better represented the impact of climate condition, which could more purely analyze the connection between the WACE pattern and haze pollution in NC.

3. Results

a. The linkage between WACE pattern and haze pollution

In winter, the WACE pattern with weakening meridional temperature gradient was more significant in January (Table S1). At this time, there was no Northeast Asian cyclone circulation over North China (figure not shown), so this salient signal had a relative weak linkage to synchronous haze pollution in January in NC. However, its relationship with the haze
pollution in the subsequent February was more pronounced. Therefore, our study focused on the linkage between WACE pattern in January and the haze pollution in February. The number of haze days in February over NC (HDNC) showed a strong negative correlation with the co-occurrence of warm Arctic and cold Eurasia (Fig. 1). The area-averaged SAT values in January over the Barents–Kara Seas (65°–80°N, 30°–90°E) and Eurasia (40°–55°N, 70°–110°E) were calculated and denoted as the SATWA and SATCE indices, and the difference between them was defined as the SATWACE index (SATWA minus SATCE) to represent the entire variation of temperature in the Arctic and Eurasia. The positive SATWACE index represented the WACE pattern, indicating the weakening of the meridional temperature gradient. Removing the linear trend to explore the interannual relationship, the correlation coefficient between January SATWACE and February HDNC was $20.39$ (above 95% confidence level; Table 1).

After the signal of El Niño–Southern Oscillation (ENSO) was removed by subtracting linear regression of the two indices (i.e., SATWACE and HDNC) onto ENSO from the two indices respectively, the correlation coefficient remained low at $20.37$, indicating that this relationship was independent of the tropical signal. Furthermore, when any temperature signal of the Arctic or Eurasia was removed from this pattern, the correlation coefficient decreased in magnitude dramatically and was no longer significant (Table 1). The overall effect of the WACE pattern was significantly stronger than the sole effect of the Arctic or Eurasia, indicating that temperature changes in the Arctic and Eurasia both played a key role in the subsequent haze pollution in NC, and the temperature contrast between them was a more effective signal. The exploration of the linkage between the WACE pattern in January and the HDNC in February was helpful for subseasonal haze prediction based on the preceding factors.

The simulated February HDNC by the GEOS-Chem model similarly showed corresponding responses to the detrended SATWACE and SATCE indices, which further determined the relationship between WACE pattern in January and haze pollution in February. In the quadrant of the WACE pattern, the simulated HDNC was generally reduced with large anomalies (Fig. 2). The largest anomaly in this quadrant was $-3.26$ days, which was 31% of its February mean. In the opposite WACE phase, it demonstrated opposite responses with positive anomalies for the most part. The most significant anomaly among them was $5.74$ days, up to 54% of its February mean. The response of simulated HDNC anomalies in these two patterns was relatively regular, further confirming the reliability of the relationship. According to the regular response between February haze pollution in NC and temperature in the Arctic and Eurasia, years from 1980 to 2019 were divided into two periods: 1980–1999 (P1) and 2000–2019 (P2). Ex ENSO, SATWA, and SATCE refer to the CCs after the signals of ENSO are removed, and SATWA and SATCE are excluded from SAT, respectively. A single asterisk (*) indicates that the CC is significant above the 95% confidence level, and two asterisks (**) indicate that the CC is significant above the 99% confidence level.

### Table 1. Correlation coefficients (CCs) of HDNC with detrended SATWACE, SATWA, and SATCE indices during periods of 1980–2019, 1980–99 (P1), and 2000–19 (P2). Ex ENSO, SATWA, and SATCE refer to the CCs after the signals of ENSO are removed, and SATWA and SATCE are excluded from SAT, respectively.

<table>
<thead>
<tr>
<th>Period</th>
<th>Obs SATWACE</th>
<th>Obs SATWA</th>
<th>Obs SATCE</th>
<th>Ex ENSO SATWACE</th>
<th>Ex ENSO SATWA</th>
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<th>Ex SATWA SATWACE</th>
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<tr>
<td>1980–2019</td>
<td>$-0.39^*$</td>
<td>$-0.37$</td>
<td>$-0.59^{**}$</td>
<td>$-0.37^*$</td>
<td>$-0.38$</td>
<td>$-0.59^{**}$</td>
<td>$-0.34^*$</td>
<td>$0.30$</td>
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<tr>
<td>1980–99</td>
<td>$-0.37^*$</td>
<td>$-0.48^*$</td>
<td>$-0.51^*$</td>
<td>$-0.34^*$</td>
<td>$-0.48^*$</td>
<td>$-0.51^*$</td>
<td>$0.30$</td>
<td>$0.07$</td>
</tr>
<tr>
<td>2000–19</td>
<td>$-0.21$</td>
<td>$0.23$</td>
<td>$-0.38$</td>
<td>$-0.19$</td>
<td>$-0.50^*$</td>
<td>$-0.21$</td>
<td>$-0.19$</td>
<td>$-0.50^*$</td>
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**Fig. 1.** (a) Correlation coefficients between detrended January SAT and February HDNC. (b) Variations of the original (OS; solid lines) and detrended (Dtr; dashed lines) sequences of SATWA (red), SATCE (blue), SATWACE (black), and HDNC (green). The green boxes in (a) represent the locations of the Arctic, Eurasia, and North China. Black dots in (a) indicate that the correlation coefficients are significant above the 90% confidence level.
into four categories based on the detrended SATWA and SATCE: warm Arctic–cold Eurasia (WACE, SATWA > 0, SATCE < 0), cold Arctic–warm Eurasia (CAWE, SATWA < 0, SATCE > 0), cold Arctic–cold Eurasia (CACE, SATWA < 0, SATCE < 0), and warm Arctic–warm Eurasia (WAWE, SATWA > 0, SATCE > 0). The WACE pattern and its opposite phase (i.e., CAWE) represented opposite SAT anomalies in the Barents–Kara Seas and Eurasia, and the other two represented temperature anomalies of the same sign (i.e., WAWE and CACE). Under the condition of WACE pattern with a weaker meridional temperature gradient, the simulated number of haze days significantly decreased in NC with an average anomaly of −2.2 days (Fig. 3a), which represented 21% of the February mean. In the CAWE phase, the simulated number of haze days exhibited an opposite response with an average increase of 1.1 days (i.e., the 10% of the February mean), but the intensity was not as significant as that under the WACE pattern (Fig. 3b). When the Barents–Kara Seas and Eurasia cooled or warmed simultaneously, the haze pollution in NC would not show any significant response (Figs. 3c,d). Thus, the February haze pollution in NC demonstrated the strongest and most significant anomalies in response to the pattern of Arctic warming and Eurasian cooling in January, indicating that it was highly sensitive to the WACE pattern.

b. Associated anomalous atmospheric circulation and possible mechanisms

Accompanying the WACE pattern, an anomalous Rossby wave–like train occurred in the atmospheric circulation. The downstream-propagating wave train propagated from the positive anomaly center of Z500 in the Ural region that was associated with the WACE pattern to Northeast Asia (Fig. 4a). The anomalous cyclonic circulation in Northeast Asia was a crucial circulation system for haze pollution (Feng et al. 2020). Under the modulation of the above circulation anomalies in February, the BLH generally became higher, the wind speed increased, and the humidity decreased. Together they strengthened vertical and horizontal dispersions of particles,

![Diagram](https://example.com/diagram.png)

**Fig. 2.** Anomalies of the simulated February HDNC by the GEOS-Chem model and corresponding SATWA and SATCE indices in January from 1980 to 2019. The linear trend is removed. The anomalies were obtained by calculating the simulated February HDNC for each year minus its mean during 1980–2019. The four quadrants respectively represent the distributions under the patterns of warm Arctic–cold Eurasia (WACE), warm Arctic–warm Eurasia (WAWE), cold Arctic–cold Eurasia (CACE), and cold Arctic–warm Eurasia (CAWE). Each dot represents one year during 1980–2019. The value next to each dot represents the anomaly of the simulated HDNC; red indicates positive values and blue indicates negative values. The hollow and solid circles represent the years in 1980–99 (P1) and 2000–19 (P2), respectively.
leading to unfavorable conditions for the accumulation of particulate matter (Figs. 4b,c; see also Fig. S1a). The obvious anomalous descending motions under the abnormal cyclonic circulation transmitted stronger upper westerly momentum and cold air downward, reducing the accumulation of pollutants in narrow spaces (Fig. S1b). Under the strong regulation of the WACE pattern to meteorological conditions in February through circulation anomalies, the haze pollution in NC significantly decreased. Similarly, in response to the CAWE pattern, an abnormal anticyclonic circulation appeared over Northeast Asia in February, whose intensity was much weaker than that in the WACE pattern (Fig. S2a). Under the regulation of the abnormal anticyclonic circulation, the meteorological conditions related to haze also changed in response (Figs. S2b–e). These changes provided a favorable environment for the accumulation of pollutants and weakened the diffusion of particulate matters. However, the intensity of the abnormal meteorological conditions was also weaker than that under the WACE pattern, and the anomalies were generally not significant (Figs. S2b–e). The strong difference in anomaly intensity of atmospheric circulation and meteorological conditions under the WACE and CAWE
pattern indicated that the relationship between the WACE pattern and haze days in North China was more stable and effective.

Composite results of WACE years were analyzed to highlight the climate anomalies under the WACE pattern to find the possible mechanisms. Figures 5a and 5b showed the composite results of the differences in Arctic sea ice and Eurasian soil temperature in February compared to January under the WACE pattern. We found that the signals of warming Arctic and cooling Eurasia in January did not really disappear. Instead, they were continued to make connection with the surface–atmosphere system. The Arctic warm signal sustained into February, and the sea ice melted more in February compared to January (Fig. 5a). The Eurasian cold signal was also sustained into February, and the soil temperature became cooler persistently and was colder than in January (Fig. 5b).

The area-average differences between February and January in sea ice over the Barents–Kara Seas and soil temperature in Eurasia were defined as the SICd and SoilTd indices respectively (the value of February minus the value of January). The two indices were normalized and added together (defined as the SICSTd index) to represent the continued signal of WACE in February. The negative SICSTd index indicated a further decrease in Arctic sea ice and a lower Eurasian soil temperature in February than that in January.

The decrease in Arctic sea ice and the cooling of soil temperature in Eurasia continued to weaken the large-scale temperature gradient at the mid- to high latitudes and strengthened the temperature gradient at the mid- to low latitudes. The correlation between the SICSTd index and
atmospheric baroclinicity showed a negative anomaly at around 60°N and a positive anomaly at around 30°N (Fig. 5c), indicating that the weakened baroclinicity at mid- to high latitudes and enhanced baroclinicity at mid- to low latitudes was associated with the sea ice loss and Eurasian soil cooling. The increase in baroclinicity was consistent with the higher occurrence and stronger intensity of cyclones. The adjustment of atmospheric baroclinicity was conducive to the formation of two activity centers associated with the EA/WR teleconnection (Fig. 5c), a positive center in Ural Mountain and a negative center in Northeast Asia. The cyclonic anomalies over NC, which was defined as the area-averaged geopotential height at 500 hPa over 35°–50°N, 95°–140°E (denoted as $Z_{500NC}$), was strengthened. Its correlation coefficient with WACE pattern was −0.47 (above 99% confidence level), which indicated that the connection between the key circulation and the WACE was stronger than that solely with the Arctic warming. Modulated by the above atmospheric circulations, the horizontal dispersion and vertical exchange (Fig. 4; see also Fig. S1) in NC both were favorable for the diffusion of pollutants, so that the haze days were weakened (Fig. 3a).

c. Interdecadal strengthening linkage

The linkage between the WACE pattern in January and the following February haze pollution in NC has been significantly strengthened after the late 1990s, accurately corresponding to the stronger connection between Arctic and Eurasia temperature and haze pollution in NC (Table 1). Therefore, we divided the first and last two decades into two subperiods (P1: 1980–99 and P2: 2000–19) to further explore the reasons for the strengthening linkages in the latter subperiod. During P1, the correlation coefficient between SAT$_{WACE}$ and HD$_{NC}$ was only −0.37 (not significant; Fig. S3a). In contrast, the correlation coefficient increased to −0.59 (above the 99% confidence level) during P2 (Fig. S3b). After the ENSO signal was removed, the relationship between SAT$_{WACE}$ and HD$_{NC}$ still dramatically strengthened, indicating that the reason for the enhanced linkage was not caused by ENSO signal (Table 1). The distributions of simulated HD$_{NC}$ related to the
WACE and its opposite pattern were more regular in P2, with the exception of only one year (Fig. 2), and the anomalies of simulated haze days were also more intense and distinct during P2 than during P1 (Figs. 6a,b). Meanwhile, the linkage between the atmospheric circulation and the WACE pattern was obviously strengthened in P2, and the cyclonic anomalies over NC became more significant (Figs. S4a,b). Regulated by the stronger cyclonic circulation, the associated meteorological condition showed larger anomalies (Fig. 6c; Figs. S4c–j), which led to more effective horizontal and vertical diffusion of pollutants. The relative humidity in P2 did not weaken as much as that in P1, mainly because the center of greatest humidity decrease appeared in central China instead of in NC. Associated with the WACE pattern in January, the overall meteorological condition and its effects on February haze pollution in NC were enhanced prominently in the late 1990s.

Comparing the correlation of SATWA and SATCE with HDNC in the two subperiods, it was found that the relationship between SATWA and HDNC only slightly strengthened in P2, while the correlation of SATCE sharply increased (Table 1). The relationship between HDNC and SATWA stably remained at a high level and superimposed a significantly enhanced connection between HDNC and SATCE in the P2 period, which worked to further weaken the meridional temperature gradient and enhance the relationship between SATWACE and HDNC after the late 1990s.

The enhanced connection with SATCE during P2 may be attributed to the frequent occurrence and increasing intensity of Eurasian cooling. Eurasian below-average temperatures occurred more frequently in winters with deep warming compared to shallow, near-surface warming over the Barents–Kara Seas (He et al. 2020). The rapid tropospheric warming trend over the Arctic that occurred after the late 1990s indicated a deep warming in the Arctic. Composite results of WACE years showed that the deep warming above the Barents–Kara Seas could extend up to 500 hPa and maintained a strong intensity in P2 (Fig. 7b). In contrast, the strong warm anomaly only penetrated 700 hPa during P1, suggesting that it was mainly a shallow warming (Fig. 7a). The midtropospheric temperatures anomaly above the Arctic reached up to 1.9°C in the latter period, about 0.9°C higher than that in the period of 1980–99. When the middle troposphere above the Arctic became warmer, it stimulated southward propagating Rossby wave trains and weakened the midlatitude jet stream, both of which were conducive to southward transport of cold air, making the Eurasian cooling more frequent and stronger in P2 (Fig. 7b; He et al. 2020). Under the maintenance of
FIG. 7. Composite analysis of January temperature along 0°–120°E (Temp; unit: °C) under the WACE pattern during (a) 1980–99 and (b) 2000–19. Composite analysis of the differences in February relative to January under the pattern of warm Arctic–cold Eurasia, including sea ice cover (SIC Diff; unit: 1) and soil temperature (SoilTemp Diff; unit: °C) during (c),(e) 1980–99 and (d),(f) 2000–19. Correlation coefficient between −1 × SICSTd index and geopotential height at 500 hPa (shading; unit: gpm) and averaged atmospheric baroclinicity from the surface to 400 hPa (contours; unit: day⁻¹) during (g) 1980–99 and (h) 2000–19. The linear trend is removed. The green boxes in (c) and (d) and in (e) and (f) represent the locations of Arctic and Eurasia respectively. Black dots and the contours in (g) and (h) indicate that the composite results and correlation coefficients are significant above the 95% confidence level.
Arctic warming and the strengthening of Eurasian cooling, the sea ice loss and soil temperature cooling both intensified during P2 (Figs. 7e,f), making a stronger and broader connection with Ural blocking high in February (Figs. 7g,h). Meanwhile, the positive and negative center distribution of the baroclinicity was more meridional than P1, which accompanied by a more significant anomalous cyclone over NC (Figs. 7g,h). Regulated by the strong abnormal circulation, the changes in meteorological conditions associated with haze enhanced (Fig. S4), which caused the reduction of haze pollution over NC more distinct in P2 than in P1. The interdecadal strengthening linkage between the WACE pattern and mid-latitude climate anomalies were associated with the midtropospheric warming above the Arctic, suggesting that internal atmospheric variability played an important role in the interdecadal change.

4. Verification and uncertainties

The relationship between the January WACE pattern and February haze pollution in North China was further verified by extensive multimodel CMIP6 simulations. In the verification of the relationship between WACE pattern and the key cyclonic circulation over North China, the full 46-model ensemble mean could reproduce the negative anomalies over North China in the February circulation, but this signal was not very clear (Fig. 8b). Then the simulation performance of each model was calculated (Fig. 8a), and a majority of the models (36 out of 46) simulated the negative correlation between SAT_{WACE} and Z500_{NC}. Among them, the correlation coefficients of 12 models passed the significance test at the 90% confidence level, and their ensemble mean reproduced a significant cyclonic circulation anomaly that was conducive to the diffusion of haze pollution (Fig. 8c). We also wondered why the remaining 34-model ensemble mean only simulated a weak signal (Fig. 8d), although their positive and negative anomalies were correct. Therefore, based on the simulation ability of this relationship, the models were divided into two categories with good and bad simulation performance in order to explore their ability to simulate the linkage between the changes in Arctic sea ice and Eurasian soil temperature and the WACE pattern. As expected, the simulation capabilities of these two categories also differed greatly. The 14 models that had a good ability to simulate the significant relationship between the SICStd index and Z500_{NC} index also showed a better consistency between the WACE pattern and the anomalies of Arctic sea ice and Eurasian soil temperature in January (Fig. 9e). In the remaining models, the performance of this linkage was relatively weak (Fig. 9f), especially in the consistency with Eurasian soil temperature anomalies. The relationship we explored began with the SICStd index and the WACE pattern itself. Sure enough, the simulation ability of this relationship, the models were also divided into two categories with good and bad simulation performance in order to explore their ability to simulate the WACE pattern itself. Sure enough, the simulation abilities of the two categories for WACE pattern were also very different. The 12-model ensemble mean that showed a significant relationship between WACE pattern and cyclonic circulation could also present the January WACE pattern (Fig. 8e); in the remaining models, the WACE pattern could not be simulated (Fig. 8f). The differences in two categories of models indicated that the relationship could be reproduced when the signal of the WACE pattern appeared, which was consistent with the observation, proving the reliability of the mechanism. Some models had difficulty reproducing the January WACE pattern, so there was a certain uncertainty. Overall, 90% of the models simulated a higher negative correlation between SAT_{WACE} and HD_{NC} than between SAT_{WA} and HD_{NC} (Fig. 8a), supporting the hypothesis that the temperature contrast between the Arctic and Eurasia was a more effective factor that influenced haze pollution in NC.

Similarly, the sea ice and soil temperature data from the CMIP6 models was used to confirm the linkage to February circulation. The overall 27-model ensemble mean could capture the cyclonic circulation anomaly (Fig. 9b), but with a westward center. Twenty-five of the 27 CMIP6 models simulated the negative correlation between the SICStd index \((X - 1)\) and the Z500_{NC} index (Fig. 9a), indicating that this relationship could be generally detected in CMIP6 models. The correlation coefficients of 14 models passed the 90% confidence level, whose ensemble mean showed a stronger and more pronounced anomalous cyclonic circulation over NC (Fig. 9c), similar to the observed results (Fig. 5c). In the remaining models, the signal of the key circulation system was relatively weak. Therefore, based on the different simulation ability of this relationship, the models were also divided into two categories to explore their ability to simulate the linkage between the changes in Arctic sea ice and Eurasian soil temperature and the WACE pattern. As expected, the simulation capabilities of these two categories also differed greatly. The 14 models that had a good ability to simulate the significant relationship between the SICStd index and Z500_{NC} index also showed a better consistency between the WACE pattern and the anomalies of Arctic sea ice and Eurasian soil temperature in January (Fig. 9e). In the remaining models, the performance of this linkage was relatively weak (Fig. 9f), especially in the consistency with Eurasian soil temperature anomalies. The relationship we explored began with the WACE pattern, so the differences suggested that the model with good simulation ability in capturing the linkage between January WACE pattern and the anomalous Arctic sea ice and Eurasian soil temperature could also simulate a more significant relationship between the SICStd index and the February crucial circulation system, indicating a better reflection of the overall linkage. The models varied widely in simulating the linkage between the January WACE pattern and the anomalies of Arctic sea ice and Eurasian soil temperature, demonstrating some uncertainty.

Using CMIP6 historical models to verify the relationship between January WACE pattern and February haze pollution in NC, there were great differences among models. Many studies have suggested that large intermodel spread and uncertainties existed in the CMIP6 simulation of Arctic temperature and extreme events in Eurasia (Cai et al. 2021; Zhao et al. 2021). Not all CMIP6 models supported the link between Arctic warming and severe winter over midlatitude Eurasia, implying their diverse ability in capturing the WACE pattern (Ye and Messori 2021). The surface Arctic warming was generally well captured in the CMIP6 models, but was weaker in magnitude, and most models missed the warming in the middle and upper troposphere (Cai et al. 2021; Davy and Outten 2020). Only a few models reproduced the signal of Eurasian cooling, and it was generally much weaker than in the reanalysis data (Ye and Messori 2021). The simulation of the WACE pattern reflected the spatial distribution of SAT, but could not accurately simulate the observation and its interannual variability (Davy and Outten 2020). The above studies indicated that some of the CMIP6 models had limited ability to capture the SAT anomalies of the WACE pattern.
According to Blackport and Screen (2021), the varying performances in reproducing the WACE pattern possibly come from internal variability and do not necessarily indicate model deficiency. In either case, the varying ability of models to simulate the WACE pattern presented in the observations was a possible reason why not every individual model could detect the relationship between the WACE pattern and circulation. The model simulation capabilities need to be further improved to better diagnose physical processes.

5. Conclusions and discussion

The warm Arctic–cold Eurasia pattern is a large-scale meridional temperature gradient weakening phenomenon in the mid- to high latitudes. The present study focused on the overall changes in the WACE pattern, rather than only considering the individual linkage between the Arctic temperature and climate in midlatitudes. Through this exploration, we indicated that the overall change of the January WACE pattern was closely related to the reduction of February haze pollution in Northern China (NC) (Fig. 10). Linked to the warming signal in Arctic sea ice and cooling signal in Eurasian soil, the sea ice showed further loss and soil temperatures became cooler in February, which was associated with two activity centers of the EA/WR teleconnection. Under the regulation of the abnormal cyclonic circulation over NC, the meteorological conditions provided a favorable environment for the diffusion of pollutants. The linkage between the WACE pattern and the key circulation over NC was further verified by the CMIP6 models, which supported the argument of the present study that the temperature contrast between the Arctic and Eurasia was a more effective signal related to haze pollution in NC. Furthermore, this relationship had significantly enhanced after the late 1990s, which corresponded to the emergence of the deep Arctic warming accompanied by the strengthened Eurasian cooling (Fig. 10). The co-occurrence of the warmer Arctic and colder Eurasia enhanced the lingering of this signal into February, linked to a stronger cyclonic anomaly over NC in P2. Although the significance of the soil temperature cooling during P2 did not enhance greatly in the Eurasian region, the amplitude and significance of this signal increased distinctly in the surrounding areas to
the south, which indirectly reflected the enhanced persistence of the WACE signal in P2. The change of sea ice could affect the heat exchange of the sea surface, and the turbulent heating anomalies could excite the wave activity in the atmosphere (Xu and Fan 2020), which was a possible way to connect with circulation anomaly. Both haze pollution and temperatures in the Arctic and Eurasia showed subseasonal variations. Exploring the relationship between January WACE and February haze pollution was of great significance for subseasonal haze prediction. Meanwhile, the subseasonal variation of WACE pattern also played an important role in the super sandstorm in Mongolia and northern China in the spring of 2021 (Yin et al. 2021). The future change in the WACE pattern, a possible precursory signal of extreme events, deserves our continuous attention.

In this work, the CMIP6 model was used to validate the relationship between the WACE pattern and the key cyclonic circulation in February, and the uncertainty of the relationship was also analyzed. We indicated that the simulation ability of the WACE pattern and its relation was a prerequisite to reproduce the mechanism. However, numerical experiments on the effects of sea ice and soil temperature are lacking. To explore the role of sea ice, 32 AMIP models were used to investigate the connection between sea ice and February circulation. We selected the years during 1980–2014 in which the sea ice in February compared to January decreased or increased by more than 0.8 standard deviations to composite the February atmospheric circulation in AMIP models. The AMIP model ensemble means drove negative anomalies over NC, but the center was somewhat southward (Fig. S5a). Among them, 17 models simulated a negative Z500NC index, and their ensemble mean showed a significant abnormal cyclone over NC (Fig. S5c). The 17-model ensemble mean could also capture the WACE pattern in February (Fig. S5d), indicating a better ability to capture the overall relationship, while the remaining models basically could not capture this signal. Therefore, when the model could capture the linkage between the WACE pattern and the Arctic sea ice loss, it was able to simulate the relationship between the sea ice loss and the February circulation anomaly. The differences suggested that the response of atmosphere to sea ice forcing in different models was inconsistent, indicating an internal variability. In future work, we will perform idealized experiments to further explore the role of sea ice.

FIG. 9. (a) Correlation coefficients between February Z500NC and SICStd (×−1) from the 27 CMIP6 models. The red bars show the correlation coefficients calculated by reanalysis data. The light green bars denote the multimodel ensemble mean correlation coefficients. (b) All-model, (c) 14-model, and (d) 13-model ensemble mean correlation coefficients between SICStd (×−1) and geopotential height at 500 hPa (shading) and zonal winds at 200 hPa (contours). Also shown are the (e) 14-model and (f) 13-model ensemble-mean correlation coefficients between January SICSt and SAT. The green shading in (a) represents models that pass the 90% confidence level. The dashed lines in (a) indicate the correlation coefficients are significant above the 90% and 95% confidence levels. Black dots in (b)–(f) and green lines in (b)–(d) indicate that the correlation coefficients are significant above the 95% confidence level. The green boxes in (e) and (f) represent the locations of the Arctic and Eurasia.
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Data availability statement. The monthly mean meteorological data are obtained from NCEP–NCAR Reanalysis datasets (http://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.html). The boundary layer height, sea ice cover, and soil temperatures are available from the ERA5 dataset (https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels-monthly-means?tab=overview). The number of haze days can be obtained from the authors upon request. The emissions for 2010 can be downloaded from http://geoschemdata.wustl.edu/ExtData/HEMCO/MIX/v2015-03/.

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FIG. 10. Schematic diagrams of the associated physical mechanisms. The WACE surface anomaly in January sustained its signal into February, associated with further sea ice loss and Eurasian soil temperatures cooling in February. The continuation of the WACE signal was linked to an abnormal cyclone over North China in February. Under the control of this abnormal cyclone, the anomalous northerly appeared near the ground, resulting in the increase of wind speed, which was conducive to the diffusion of particles and caused the reduction of haze pollution. The relationship significantly strengthened since the late 1990s (P2), which was attributed to the emergence of deep Arctic warming in the late 1990s, accompanied by frequent and intensified Eurasian cooling. Under the strengthened WACE pattern, the sea ice loss and soil temperature cooling both intensified, making a stronger connection with the anomalous cyclone over North China in February, thus causing a significant reduction in haze pollution during P2.


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