Impacts of climate anomalies on the interannual and interdecadal variability of autumn and winter haze in North China: A review

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Abstract From the perspectives of remote sensing and climatic factors like surface meteorological parameters, large-scale atmospheric circulations and external forcing factors (EFFs), the authors synthesize and review spatiotemporal variations of $PM_{2.5}$ over North China and how climate anomalies affect autumn and winter haze variability in North China according to recent studies. This review focuses on both interannual and interdecadal timescales. It is shown that circulations play an important role in influencing haze variability. Atmospheric circulations, which would be modulated by EFFs like sea surface temperature, sea ice and snowpack, can affect the climate variability in haze over North China via modulation of surface-layer parameters that are closely connected with the haze phenomenon. Therefore, EFFs are deemed significant factors impacting the climate variability of haze over North China, serving as paramount precursory signals for haze prediction. Furthermore, this paper suggests potential future research directions for haze variability studies in North China on the basis of summarizing and concluding the associated processes/mechanisms on how climatic factors affect haze variability, which could provide reference for treating and forecasting in situ hazy conditions.

Keywords North China, Haze, Atmospheric circulations, External forcing factors, Interannual and interdecadal variations

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1. Introduction

Haze mainly occurs in the lower troposphere, and its height is about 1–3 km (Wu et al., 2010). In meteorology, the weather phenomenon of haze is principally connected with a plethora of dry fine particulate matter (PM) with an aerodynamic diameter of 2.5 μm or less ($PM_{2.5}$) which suspends evenly in ambient air, thus causing stale air and degraded surface visibility of less than 10 km (Zhang, 2017). In general, haze is accompanied by air pollution (Ding et al, 2009; An et al., 2019), which can pose a deleterious effect on human health (e.g., Xu et al., 2013). As such, the haze issue has aroused considerable concern from both the public and academic sector (e.g., Mu and Zhang, 2014; Wang, 2018).

In recent years, China's rapid socioeconomic development has led to the tremendous consumption of fossil fuels (Zhang et al., 2013), and the level of aerosol concentrations in China is therefore higher (Li et al., 2016b), inducing frequent occurrences of haze events (An et al., 2019). North China incorporates economically developed regions with heavier energy consumption such as the "Capital Economic Circle" and "Xiongan New Area". Influenced by the upstream large-scale terraced topography like the Tibetan Plateau (TP) (Xu et al., 2015, 2016; Wang et al., 2018b) and the localized arc-shaped topography induced by the Yanshan/Taihang Mountains, the North China is one of the areas with the most frequent haze occurrence in China (e.g., Leung et al., 2018; Mao et al., 2019). In particular, after an unprecedented persistent haze episode engulfed a large portion of China in January 2013 (e.g., Wang et al., 2014; Zhang et al., 2014), the Chinese government then attached great importance to air pollution issue, promulgating the "Ten Statements of Atmosphere" (The State Council of the People's Republic of China, 2013) to reinforce the prevention and mediation of haze pollution. And meanwhile, the Beijing–Tianjin–Hebei (BTH) region is regarded as one of the key regions in China with respect to serious and frequent haze weather (Zhang et al., 2019b).

Numerous researches have focused on the climate variability of haze events over North China due to its consequential socioeconomic status, becoming a hotspot of research across sections of the climate community. Although the haze variability can be influenced by anthropogenic emissions (e.g., Yang et al., 2016), this paper only reviews the recent major advances on how climate anomalies affect the haze variability in North China, which would provide scientific support for the Chinese government to formulate long-term anthropogenic emissions planning and conduct annual haze pollution prevention and mitigation in advance. Especially noteworthy is that, the present review is supplementary but distinct from the recent related review articles (Li et al., 2016b; Wu et al., 2016a; An et al., 2019). Li et al. (2016b) and Wu et al. (2016a) highlighted the aerosol and monsoon climate interactions over the large-scale domain of Asia and East Asia respectively, and much attention has been paid to how aerosols affect the monsoon climate and how they interact in summer. Furthermore, although An et al. (2019) discussed impacts of climate change on haze variability in northern China, our paper is a considerable supplement to their summary. Their review mainly focused on emission sources and physical/chemical processes during haze pollution.

The rest of this paper is structured as follows. Section 2 summarizes the spatiotemporal characteristics of $PM_{2.5}$ based on remote sensing. Section 3 describes meteorological parameters connected to haze variability. In Section 4 and Section 5, we discuss climatic factors tied to interannual and interdecadal haze variability and associated mechanisms, respectively. Conclusions and discussions are given in Section 6. Finally, future directions are suggested in Section 7.

2. Spatiotemporal characteristics of $PM_{2.5}$ based on remote sensing

Since $PM_{2.5}$ is an important contributor to hazy conditions, various surface $PM_{2.5}$ products estimated from satellite-derived aerosol optical depth (AOD) with higher spatial and temporal resolution were developed (van Donkelaar et al., 2016), emerging as considerable supplements to the conventional ground-measured $PM_{2.5}$ observations. Considering the numerous AOD retrieval algorithms and the marked spatiotemporal variability in the relationship between $PM_{2.5}$ and AOD, an advanced statistical model suitable for surface $PM_{2.5}$ estimation in China (viz. the geographically weighted regression model employing the land use information, the fused satellite-derived AOD and the meteorological data from different regions and seasons) was therefore developed by Ma et al. (2014) to predict the surface $PM_{2.5}$ concentrations over China. Results show that model-predicted spatiotemporal patterns of $PM_{2.5}$ concentrations over China are quite similar to the observations.

The aforementioned AOD-derived $PM_{2.5}$ data have been widely used in revealing the spatiotemporal variations of $PM_{2.5}$ over North China. For example, Ma et al. (2014) found that the North China is a major particulate pollution region, which is most severe in winter season and the next is autumn; Peng et al. (2016) and Tao et al. (2016) suggested that there existed a drastic increase in $PM_{2.5}$ concentrations or AOD over the southern part of North China from 1999 to 2006, but the considerable reduction in 2007-2008 was related to the air pollution control for the 2008 Beijing Olympic Games. Moreover, Han and coauthors (Han et al., 2014, 2015, 2016) pointed out that the high urbanization level with enormous people in the BTH region could exert substantial influences on the increasing trend in local $PM_{2.5}$ concentrations.

Surface observations also indicate that haze in North China mainly occurs in boreal winter (December–February; DJF) and autumn (September–November; SON) (e.g., Chen and Wang, 2015; Mao et al., 2019), which concurs with the above results of $PM_{2.5}$ concentrations based on remote sensing. Furthermore, from the climatological perspective, because the temporal coverage of the haze days data is much longer than the surface $PM_{2.5}$ data and AOD data, more studies have concentrated on how climate anomalies affect variations of haze days. Therefore, in the following sections, we mainly focus on recent developments of climate variability of haze days in SON and DJF in North China.

3. Principal meteorological parameters connected to haze variability

Recent studies suggested that, on both interannual and interdecadal timescales, the haze variations in North China are closely tied to surface-layer meteorological parameters. For instance, Zhang et al. (2018) suggested that the recent interdecadal enhancement of haze over Beijing was associated with the simultaneous weakening of northerly surface winds from Lake Baikal, which was partially attributed to the warming in the upper boundary layer; Pei et al. (2018) revealed that the dampened negative meridional wind anomaly at 850hPa in North China could bring less cold and dry air to this region, favoring the formation and maintenance of wintertime persistent haze events on the interannual timescale.

The parameters tied to the haze variability in autumn and winter are quite similar (e.g., Yin and Wang, 2016b; Yin et al, 2017; Wang et al., 2019b). When above-normal haze days occur in North China, the surface air is mainly in a stagnant state (Zhang et al., 2019b). Thus, cold air in North China is inactive and weakened, with vitiated atmospheric horizontal and vertical dispersal ability for $PM_{2.5}$ (e.g., Cai et al., 2017). In such a scenario, the lower-level North China and its surroundings are dominated by southerly wind anomalies and the surface winds are decreased (Yin et al., 2017; Wang et al., 2019b), facilitating transportation and accumulation of substantial $PM_{2.5}$ and water vapor in front of the Yanshan/Taihang Mountains. Due to aerosol–radiation interactions, the higher $PM_{2.5}$ concentrations favor the strengthening of the inversion layer and thus a reduction in the planetary boundary layer height (PBLH) (Tie et al., 2017; Zhang et al., 2018; Guo et al., 2019); whilst the lower PBLH in turn curbs the vertical dissipation of water vapor and $PM_{2.5}$, trapping them in a shallower boundary layer. This positive feedback loop mechanism could further increase the near-surface relative humidity (RH) and $PM_{2.5}$ concentrations, and meanwhile the elevated RH is conducive to hygroscopic growth and aqueous-phase heterogeneous chemistry reactions for $PM_{2.5}$ (Ding and Liu, 2014; Tie et al., 2017; An et al., 2019). To sum up, when there are more SON/DJF stagnant days in North China, the positive feedback loop effect between surface-layer meteorological parameters and $PM_{2.5}$ is marked, and their synergy could establish favorable environmental conditions for haze formation and development, thus augmenting the in situ haze frequency. In addition, the mid-to-lower tropospheric descent over North China can also strengthen the low-level stability, decreasing the PBLH and further leading to more haze days there (Ding et al.,2017; Wu et al., 2017a).

Given the close relationship between haze and stagnant days, researchers have constructed related stagnant weather indices to explore the quantitative connection between haze variability over North China and meteorological variables (e.g., Huang et al., 2018; Zhang et al., 2018). Primarily, there are two indices reflecting the stagnant weather. First, the Parameter Linking Air Quality and Meteorological Elements (PLAM) index (Wang et al., 2012), which is based on wind direction and velocity, RH and atmospheric stability, etc. A high PLAM index means a more favorable environment for formation and accumulation of pollutants (Zhang et al., 2019b). Second, the Boundary-layer Air Stagnation Index (BSI; Huang et al., 2018). The BSI was modified on the basis of prior studies (Wang and Angell, 1999; Huang et al., 2017), which is more applicable in China. Specifically, the BSI consists of daily maximal ventilation, real latent instability and precipitation, which is significantly and positively correlated with $PM_{2.5}$ concentrations. Therefore, it can better signify the variations in $PM_{2.5}$ concentrations over seriously polluted areas like North China.

To summarize, **Table S1** (Supporting Information) lists four categories of meteorological parameters closely associated with SON/DJF haze variability in North China—namely, dynamic parameters (e.g., 10-m wind velocity), thermal factors (e.g., 2-m air temperature), moisture conditions (e.g., 2-m RH), and air stability (e.g., temperature inversion). Note that although precipitation is key to the wet deposition of aerosols (e.g., Xu et al., 2017), $PM_{2.5}$ concentrations in North China are insignificantly correlated with rainfall owing to there being relatively less precipitation in DJF (Cai et al., 2017; Chen et al., 2018). Instead, they are positively and significantly correlated with the surface RH (e.g., Tie et al., 2017; Leung et al., 2018). In stark contrast, because of the elevated DJF precipitation in southern China, $PM_{2.5}$ concentrations there are significantly and negatively correlated with wintertime rainfall variability (He et al., 2019).

4. Factors tied to interannual haze variability and associated

mechanisms

4.1 Connections with circulation anomalies

As one of the most active Northern Hemisphere wintertime atmospheric circulations (Chen et al., 2014), the East Asian winter monsoon (EAWM) is a crucial large-scale circulation governing DJF haze variability in central and eastern China (e.g., Gao and Li, 2015; Niu et al., 2010; Cheng et al., 2016; Li et al., 2016a). A host of studies have demonstrated that, on the interannual timescale, there are stably significant out-of-phase relationships between wintertime haze days (WHDs) and EAWM intensity, irrespective of the version of EAWM index (e.g., Li et al., 2016a; Wu et al., 2016b; Zhang et al., 2016; Wang et al., 2019a). For example, Li et al. (2016a) explored the links between various EAWM indices [viz., 850-hPa coastal East Asian wind speed index, 500-hPa East Asian trough (EAT) index and 300-hPa East Asian subtropical jet (EASJ) index] and WHDs, pointing out that a weakened EAWM—namely, the attenuated wind speed and EAT and more northward shift of the EASJ—corresponds to a higher number of WHDs in central and eastern China.

Specifically for North China, because it is located in the "heart" region of EAWM (Luo and Wang, 2017), the EAWM circulations could exert more significant and direct impacts on the haze variability there (e.g., Zhao et al., 2018a). For example, there were quite few haze days in Beijing in the winter of 2017, but a very large number in 2016. Yan et al. (2018) suggested that the pronounced difference in EAWM intensity in these two years (much stronger in 2017 but much weaker in 2016) was the main reason for this phenomenon. In the year of 2017, the intensified EAWM featured by strengthened Siberian High and EAT and more southward EASJ could lead to the frequent cold air activity and enhanced surface northerly winds over North China, which was conducive for the formation of local dry conditions and unstable stratification and for the dispersion of airborne pollutants. Such environmental conditions can result in few haze days. The completely opposite situation took place in the year of 2016, thus triggering quite more haze days in Beijing. As a matter of fact, the occurrence of a DJF Northeast Asian anticyclonic anomaly (NEAACA for short) is closely related to the weakened EAWM (e.g., Yin et al., 2019a, 2019b), and it is a critical circulation system responsible for a higher WHDs in North China (Yin et al., 2017). A weaker EAWM favors eastward and northward withdrawal of the EAT over the vicinity of the Bering Sea, and a northward shift of the EASJ. As such, a high-pressure anomaly predominates over Northeast Asia (Ding et al., 2014), facilitating the NEAACA formation. The NEAACA has a quasi-barotropic structure (Yin et al., 2019b), and this structure is more evident in the mid-to-lower troposphere **(Figures 1a)**. In fact, the NEAACA delineates the repressed EAWM with southerly wind anomalies on its western flank, corresponding to a lower PBLH and weaker surface winds (Yin et al., 2017). Under such circumstances, the atmospheric horizontal and vertical dispersal ability for pollutants is suppressed, facilitating transportation and accumulation of substantial pollutants and water vapor over North China. Hence, the warm, humid and stabilized environmental conditions responsible for the generation and development of haze can be easily established. Furthermore, as in winter, the SON NEAACA **(Figure 1b)** is likewise a key system for a higher number of autumnal haze days (AHDs) in BTH. In fact, the emergence of SON NEAACA also indicates the suppressed cold air intensities in North China, favoring formation of conducive ambient conditions for localized haze occurrences (Wang et al., 2018a, 2019b). Thus, it can be inferred that the SON/DJF NEAACA could engender locally favorable conditions for a higher AHDs/WHDs in North China via the inhibition of the southward invasion of concurrent middle and high latitude cold air and, meanwhile, via the accumulation of myriad local and nonlocal pollutants and water vapor within a narrower space over North China. Note that in years with extremely high number of AHDs or WHDs (e.g., the winter 2014), the NEAACA is particularly pronounced (Yin et al., 2017). Moreover, the EAWM or NEAACA is linked to teleconnections like Eurasian and eastern Atlantic/western Russia (EA/WR) patterns (e.g., Gao and Chen, 2017; Yin et al., 2017), which can be modulated by external forcing factors (EFFs). The details will be discussed in the following sections.

4.2 Modulation mechanisms of EFFs

The main EFFs for interannual changes in haze variability over North China are sea surface temperature (SST), Eurasian snow cover (ESC) and Arctic sea ice (ASI), among which ESC and ASI are collectively referred to as the “cryospheric forcing” (Zou et al., 2017). It is important to point out that these EFFs are different from those in the climate change field, which are beyond the “five spheres” of the climate system (Ding and Wang, 2016). In this Review, EFFs are specifically for the atmosphere. These EFFs can indirectly and remotely affect the haze variability in North China and other subregions of China by driving/regulating the related circulations, such as the EAWM circulations. Note that, due to the huge heat capacity of the ocean, SST is strongly persistent and it is a slow-varying variable compared to atmospheric circulations. Therefore, SST variations often precede changes of atmosphere (e.g., Wang et al., 2009; He et al., 2019). The cryospheric forcing has similar characteristics (e.g., Yin and Wang, 2018). In light of this, EFFs can be used as important precursory signals for haze variability, holding a possibility for its climate prediction. Next, for simplicity, we mainly review the processes and mechanisms of how EFFs lead to a higher number of haze days in North China. The situation is opposite when there are fewer haze days.

4.2.1 SST forcing

El Niño–Southern Oscillation (ENSO) is the leading mode of the interannual variability of tropical air–sea interactions (Rasmusson and Wallace, 1983). ENSO can transmit the impacts of SST anomalies (SSTA) in the tropical central and eastern Pacific (CEP) to East Asian areas through the Pacific–East Asian teleconnection, which can further exert remarkable influences on the East Asian winter climate (Wang et al., 2000). As such, numerous studies have been carried out to explore the relationship between WHDs in China and ENSO. Results have shown that ENSO has a noticeable effect on the number of WHDs in southern China, whereas the effect on North China is insignificant (e.g., Zhao et al., 2018b; He et al., 2019). The main reason is that in warm ENSO phase (El Niño) years, a simultaneous anomalous anticyclone in lower troposphere over the western North Pacific (WNP) (WNPAC for short) can be easily induced through a Rossby wave response in the tropical atmosphere (Zhang et al., 1996, 1999). Hence, southern China is controlled by southwesterly wind anomalies to the northwestern flank of this anticyclone, along with obvious ascending motion in situ. Under such circumstances, there is increased local precipitation, leading to enhanced atmospheric wet deposition effects. Therefore, the number of WHDs in southern China tends to be lower than normal in warm ENSO phase years, and vice versa for its negative phase years (e.g., Li et al., 2017; Cheng et al., 2019; He et al., 2019). Nonetheless, because the WNPAC lies more southward (Zhang et al., 2017), the response of low-level winds over North China to ENSO is therefore insignificant, with quite decreased southerly wind anomalies. Consequently, the number of WHDs in North China only shows very weak positive correlations with ENSO in general (Li et al., 2017; Zhao et al., 2018b). However, recent research identified that in certain super El Niño years (e.g., the year of 2015), the SSTA in the equatorial CEP can render the haze more serious in North China during its mature phase by strengthening both the WNPAC and NEAACA **(Figure 2)**. As such, enormous amount of water vapor over WNP could be advected to North China, favoring hygroscopic growth of haze particles; and meanwhile, various pollutants over southern China and East China could be readily transported towards North China. As such, favorable environmental conditions for a higher number of haze days in late autumn and early winter can be established (Chang et al., 2016; Yuan et al., 2017; Zhang et al., 2019a).

Aside from ENSO, the SSTA in the midlatitude North Pacific and North Atlantic sectors may also exert profound impacts on the number of AHDs and WHDs in the plain areas of North China or the BTH region (e.g., Yin and Wang, 2016b; Yin et al., 2017; Wang et al., 2019b). For instance, Yin and Wang (2016b) argued that previous autumnal negative SSTA in the subtropical WNP can persist into the following winter, leading to a weakening of the EAT and northward displacement of the EASJ (i.e. suppressed EAWM). As such, significant southerly wind anomalies prevail over North China, resulting in a higher number of WHDs. On the interannual timescale, the above SSTA might indirectly cause the greater number of AHDs or WHDs in North China via exciting the NEAACA (e.g., Yin et al., 2017; Wang et al., 2019b). Generally, the pathways by which these remote SSTA regulate the NEAACA variability can be divided into two types. The first type, which is the most common way, focuses on the zonal eastward propagation of Rossby wavetrains. These wavetrains are usually of quasi-barotropic structure and more conspicuous in the mid-to-upper troposphere, propagating along the westerly jet which serves as the waveguide, and further facilitating generation and enhancement of the downstream NEAACA. For example, Wang et al. (2019b) corroborated that, through the localized air–sea interplay, the SON subtropical North Atlantic (SNA) SST warming can stimulate a middle and high latitude Rossby teleconnection wavetrain **(Figure 3)** to generate and reinforce the simultaneous NEAACA, leading to a higher number of AHDs in the BTH region. Similar wavetrains could also be detected in winter. Prior SON SST warming in the central North Atlantic could excite a positive phase of the EA/WR pattern to strengthen the subsequent DJF NEAACA (Yin et al., 2017). Moreover, antecedent October–November SST cooling in the WNP in collaboration with SST warming in the Gulf of Alaska and CEP could also induce a positive phase of the Eurasian pattern to enhance the ensuing DJF NEAACA (Yin et al., 2017). The second type, meanwhile, underlines the role of meridional overturning circulation. For example, Wang et al. (2019b) reported that positive SON SSTA in the WNP can greatly intensify localized ascending motion, resulting in subsidence over Northeast Asia **(Figure 3)** via an anomalous meridional overturning circulation and thus reinforcing the SON NEAACA. Besides, Zhang et al. (2019c) found another meridional regulation mechanism when studying how SSTA in the southern Indian Ocean affect the number of WHDs in North China. When the DJF SST is higher than that of the previous autumn, a Walker-like circulation can be triggered to cause the predominant descending motion over the Maritime Continent, favoring the formation of anti-Hadley circulation. As such, the DJF NEAACA centered around the Sea of Japan could be excited through the meridional overturning circulation. Thus, the number of WHDs in North China tends to be more than normal.

4.2.2 Cryospheric forcing

Recent continuous reduction in ASI has augmented Arctic amplification (Screen and Simmonds, 2010), which contributes to considerable winter climate anomalies in East Asia (e.g., Wu et al., 2011). Therefore, previous studies focused on exploring possible links between haze variability over China and ASI. Results have substantiated that prior SON ASI can exert remarkable impacts on subsequent wintertime haze variability (e.g., Wang, et al., 2015; Wang and Chen, 2016; Zou et al., 2017), manifesting the lagged effects of ASI. Reduction in ASI can result in a northward shift of the track of cyclone activity in eastern China, and the in situ Rossby wave activity is dampened, leading to a weakened EAWM and above-normal stagnant days. Therefore, a higher WHDs in eastern China is induced.

However, it is important to point out that not all sea-ice anomalies in the Arctic Circle have significant impacts on the wintertime haze variability in North China. Instead, local sea-ice anomalies often play a key role. For example, Yin et al. (2017) identified that the previous SON sea-ice concentration (SIC) gradient over the Arctic, i.e. positive SIC anomalies over the

Barents–Kara–Laptev Sea and negative SIC anomalies over the East Siberian Sea, can persist into the ensuing winter and trigger positive-phase Eurasian and EA/WR teleconnections to promote the formation and strengthening of the DJF NEAACA **(Figure 4)** via ice–air interactions. Note that latest studies suggested that local ASI anomalies may regulate subseasonal haze variability in North China (Yin et al., 2019a, 2019b). Yin et al. (2019a) argued that positive SIC anomalies over the Beaufort Sea in the prior September to October **(Figure 5a)** can stimulate local circulation anomalies to cause subsequent elevated SST in the Bering Sea and the Gulf of Alaska in November **(Figure 5b)**. The above SST warming can excite a large-scale Rossby teleconnection emanating from Northeast Asia and passing through the Bering Sea in December–January, with a vigorous positive anomaly center over areas of North China and the Sea of Japan, resulting in an enhancement of the concurrent NEAACA **(Figures 5c, 5d)**. Under such circumstances, the humidity is higher and the PBLH is lower in North China, which are together responsible for a higher contemporaneous number of haze days in North China. Furthermore, Yin et al. (2019b) identified that the variability of February haze days is significantly correlated with the preceding November–January Chukchi Sea ice. The prior positive SIC anomalies over the Chukchi Sea can lead to concurrent SST cooling in the Bering Sea and the Gulf of Alaska as well as SST warming in North Pacific Ocean through complex dynamic and thermodynamic processes connected to local ice–air interactions, enhancing the steep meridional temperature gradient over northern Pacific and thus leading to anomalous in situ thermal westerlies. Thermal westerlies could in turn reinforce the adjacent air–sea interactions, and a large-scale Rossby-like wavetrain is then induced to transmit the influences of the Chukchi SIC anomalies to North China, leading to the development and sustainability of the subsequent February NEAACA. Thus, a higher number of February haze days in North China is induced.

In addition, the midlatitude ESC anomalies could also significantly affect the subseasonal number of haze days in North China (Yin and Wang, 2018). Previous positive ESC anomalies over the areas of East Europe and West Siberia in October–November can stimulate an EA/WR teleconnected wavetrain through complicated land–atmosphere interactions. The Rossby wave energy can be dispersed to Northeast Asia via this wavetrain to promote the development and strengthening of the ensuing December NEAACA, which could drive a higher concurrent haze days in North China.

To summarize, on the interannual timescale, the major circulation closely related to SON/DJF haze variability in North China is the NEAACA. In winter, the NEAACA is associated with a weakened EAWM. Hence, the near-surface cold air activity over North China is attenuated with prevailing southerly wind anomalies, providing favorable dynamic and thermodynamic environmental conditions for more WHDs in North China. In autumn, the appearance of an NEAACA also signifies simultaneous conducive circumstances resembling those in winter, leading to a higher AHDs. In terms of EFFs, factors such as SST, ASI and ESC can remotely modulate the NEAACA, mainly through zonal middle and high latitude teleconnections or meridional overturning circulations. The NEAACA further induces a higher AHDs/WHDs via modulation of the meteorological variables tied to haze variability. **Figure 6** sketches out the principal circulations and EFFs affecting the number of WHDs in North China on the interannual timescale, in which the NEAACA is a paramount bond linking remote EFFs and haze variability in North China through the above atmospheric processes/patterns.

5. Factors tied to interdecadal haze variability and associated mechanisms

Analogous to the interannual changes, the interdecadal variations of WHDs in North China also have a significant anti-correlation with the EAWM. For instance, the weakening of the EAWM in the years of 1986–2010 was key to more decadal WHDs (Wu et al., 2016b). Because EAWM was in a weaker state during this epoch, there was a continuously increasing (decreasing) trend in surface-layer temperatures (winds), with elevated temperature inversion potential. In such a scenario, the atmospheric horizontal and vertical dissipation capacity for pollutants was weakened, providing favorable environmental conditions for a higher number of WHDs in situ. Furthermore, by utilizing a winter haze weather index (HWI) based on 500-hPa zonal winds, temperature anomalies between the 850 hPa and 250 hPa and averaged meridional wind anomaly at 850 hPa, Cai et al. (2017) found that the meteorological conditions in 1982–2015 were more conducive for the occurrences of DJF haze events especially for the formation of severe haze events compared to those in 1948–1981, which is considered to be influenced by conspicuous climate and large-scale circulation changes. Meanwhile, Zhang (2017) demonstrated that although the haze days had decreased after the implementation of “Ten Statements of Atmosphere” in 2013, the severe haze days in Beijing continuously increased, reaching 12 days, 18 days and 25 days in winters of 2014, 2015 and 2016 respectively, suggesting the potential role of global warming on the extremely high HWI values in Beijing.

In terms of EFFs, it is identified that the east–west “warm cover” characterized by high-level warming and low-level cooling can readily form over the regions from TP to eastern China. This cover was induced by the enhanced downdraft airflow and the weakened wind zone on the eastern side of the TP, suggesting the “harbor” effect of TP (Xu et al., 2015). In the winters of 2001–2012, the thermal conditions on the TP experienced an epochal enhancement, which caused strengthened mid-level warming and weakened low-level warming (Xu et al., 2015; Zhu et al., 2018). As a result, the above-mentioned “warm cover” showed an increasing trend. Under such circumstances, the EAWM was weaker, and the resultant weakening of wind speed in the middle and lower troposphere seriously suppressed the dispersion of contaminants, resulting in frequent occurrences of DJF haze in North China during this period. Moreover, basin-scale

SSTA, such as Pacific Decadal Oscillation (PDO) and Atlantic Multidecadal Oscillation (AMO), are the consequential EFFs affecting the interdecadal variability of WHDs in North China (Xiao et al., 2015; Zhao et al., 2016; An et al., 2019). The positive phase of PDO corresponds to an enhanced and westward (southward) shift of the Aleutian Low (Mongolian High) in winter, inducing strengthened descending motions over North China and its adjacent areas (Zhao et al., 2016). Thus, the lower-level atmosphere is extremely stabilized and the wind speed is smaller, leading to a higher decadal number of WHDs since the mid-1980s through subduing the dispersion of aerosols in situ. Furthermore, when a warm phase of AMO exists in the previous summer, the air–sea interactions in the North Atlantic are pronounced, persisting into the following winter to trigger a quasi-barotropic planetary-scale Rossby wavetrain (Xiao et al., 2015). This wavetrain is closely tied to the positive phase of Arctic Oscillation, driving a vigorous anticyclonic anomaly dominating areas over North China **(Figure 7)**. The above conditions are not conducive to the intrusion of cold air from middle and high latitudes into North China, and the local EAWM intensity is decreased, inducing more in situ WHDs. As a summary, **Figure 7** shows the pathways by which climate anomalies trigger a higher number of WHDs in North China on the interdecadal timescale, underlying the crucial remote forcing effects of PDO and AMO.

6. Conclusions and discussions

North China is one of the most frequent hazy zones in China. As revealed by remote sensing data and ground-based observations, haze events in North China are mainly concentrated in autumn and winter. In light of meteorological parameters, atmospheric circulations and EEFs, this paper reviews and summarizes the main recent advances in the impacts of climate anomalies on SON and DJF haze variability in North China, focusing on both interannual and interdecadal timescales. Overall, atmospheric circulations, which are driven and regulated by various EFFs, can affect haze variability through influencing the meteorological variables tied to haze variability. The changes in EFFs often precede circulations, which can be employed as precursory signals for haze prediction. To better support the operational prediction of, and future investigations into, haze variations in North China on interannual and interdecadal timescales, **Table S2** (Supporting Information) summarizes the detailed information about the major EFFs (i.e., SST and cryospheric forcing) reported in recent years.

The meteorological variables responsible for a higher WHDs in North China are analogous to those for a higher AHDs. In general, a higher AHDs/WHDs corresponds to the increased number of stagnant days, along with lower-level southerly wind anomalies, localized reduced wind speed and PBLH and enhanced RH, which provides favorable meteorological conditions for transportation, accumulation, and in situ formation of secondary aerosol pollutants via the hygroscopic growth and aqueous-phase heterogeneous chemistry reactions in association with the positive feedback loop effect.

On the interannual timescale, the EAWM is an important large-scale circulation system affecting haze variability in North China. The dampened EAWM hampers the intrusion of mid-to-high latitude cold surges with dry and pristine air into North China. As such, the atmosphere is incapable of diffusing amassed pollutants and water vapor in the horizontal and vertical directions effectively, thus inducing favorable environmental conditions for the formation of wintertime haze over North China. As a matter of fact, the emergence of DJF NEAACA corresponds to a weakened EAWM. Although the number of AHDs and WHDs are both regulated by the NEAACA, the EFFs and associated processes/mechanisms responsible for development, strengthening and maintenance of the SON and DJF NEAACA are different. The DJF NEAACA is modulated by multiple remote EFFs like SSTs, ASI and ESC in autumn through complex air–sea, air–ice and air–land interactions, showing their lagged impacts; whereas the SON NEAACA is regulated by remote autumnal SSTs in the SNA and WNP sectors, suggesting their simultaneous influences. In effect, those EFFs' indirect and remote modulation effects are the important reasons for a higher AHDs/WHDs in North China, and the NEAACA plays a key bridging role. However, whether or not the SON NEAACA can be modulated by other climatic factors such as ASI is an open question meriting further exploration.

Researches into the interdecadal variability of haze over North China mainly concentrated on the winter season. The greater number of WHDs since the mid-1980s was closely tied to the interdecadal weakening of the EAWM and the enhancing of global warming. Besides, the decadal weakening of EAWM was associated with the anomalies of EFFs. The positive wintertime thermal anomalies on TP and the warm phases of PDO and AMO could remotely and jointly regulate the climate variability in EAWM (or NEAACA) and atmospheric static stability over North China on the interdecadal timescale, leading to the weakening of EAWM and the enhancing of localized air static stability. These atmospheric conditions were not conducive to the dispersion of atmospheric aerosols, leading to a higher epochal WHDs in North China.

However, there are two caveats concerning those discussed climatic factors. First, any EFFs can be regarded as drivers for the winter haze variability if they can affect the EAWM. A case in point is the TP. Xu et al. (2016) identified that the wintertime TP warming can lead to a weakened EAWM on the interannual timescale. Additionally, the TP snow cover (TPSC), which is viewed as an integral part of ESC, has profound impacts on DJF climate in downstream Northeast Asia (e.g., Lin and Wu, 2012). In fact, when the previous SON TPSC shows significant negative anomalies, the intensity of the EAWM in winter is much weaker, featuring a suppressed EAT; and northern China is controlled by a huge NEAACA with two anomalous centers **(Figure S1)**. Therefore, TPSC may pose indirectly impacts on the variability of WHDs in North China. Second, the connection between EFFs and EAWM intensity could be unstable, posing difficulties for haze prediction. For instance, Wu et al. (2011) found that the autumn sea ice loss does not always correspond to a strengthened EAWM. As reviewed, the SON ASI can affect the ensuing winter haze frequency in North China via regulating the EAWM (e.g., Yin et al., 2017). Because of their variable relationships, an unsatisfactory result might be obtained when one only uses ASI to predict DJF haze variability. So, a deep understanding of mechanisms/processes on how EFFs affect the EAWM variability might guarantee better EFFs usage for haze prediction in winter, which warrants further investigation.

Furthermore, a dramatic increase in the summertime surface ozone pollution over North China Plain during the period 2013-2017 has attracted considerable attention (e.g., Lu et al., 2018; Silver et al., 2018; Shen et al., 2019). Multiple observations and sensitivity model simulations suggested that such phenomenon can be attributed to the sharp decrease in the in situ surface $PM_{2.5}$ concentrations (Li et al., 2019a, 2019b). Again, other new findings unveiled that the year-to-year summer ozone variability can be modulated by climate anomalies, such as specific concurrent anomalous circulation patterns (Yin et al., 2019d) and prior May ASI anomalies (Yin et al., 2019e, 2019f). Surface ozone pollution can also pose a threat to the public health (Liu et al., 2018). It is believed that these new results would help the government to draw up guidelines on the treatment of this issue, which is conducive to the improvement on the in situ air quality. In addition, whether or not the summer ozone variability can be regulated by SSTA is a meaningful work deserving further studies.

7. Future directions

The haze variability in North China is closely associated with copious climatic factors as well as human activity. To further improve the forecasting skill with respect to SON/DJF haze variations in North China, future studies could focus on the following aspects.

7.1 Construction of a multi-scale haze prediction system

The existing research developments suggest that, the interannual predictability of climatic factors is relatively high, such as the forecasting of ENSO (Tang et al., 2018). As such, Yan et al. (2018) proposed that, via employing the relevant large-scale factors such as ASI, oceanic oscillations and atmospheric teleconnections that are produced by existing climate dynamical models, we could carry out climate predictions of haze variability effectively. Besides, the statistical forecast methods could be a supplement to the numerical prediction of haze. For example, based on multiple linear regression and generalized additive models and distinct leading and significant atmospheric/oceanic predictors in the preceding autumn, Yin and coauthors (Yin and Wang 2016a, 2017; Yin et al., 2019c) established different statistical prediction models to conduct seasonal prediction of WHDs in North China. These models can well capture the trends, turning points and the extreme values of the time series of WHDs. It is expected that if these statistical equations are embedded in the numerical climate models, their performance in the seasonal haze forecast in North China could be improved.

Nevertheless, climate prediction on the interdecadal timescale (also termed short-term climate change prediction) is currently in the research and prediction testing stage. The interdecadal climate prediction centers around climate change on 10–30 years in the future. Due to many uncertainties such as the predictability theories (Zhou and Wu, 2017) and the anthropogenic emissions, it is very difficult to improve the haze prediction accuracy on this timescale. In this regard, in the future, it will be essential to construct a so-called global-to-regional multi-scale haze prediction system based on high-resolution complex climate system models and climate change models. Such system could provide scientific support for haze prediction over North China and other polluted regions in China on multiple timescales.

Furthermore, since the climate variability can affect the aerosols and the aerosols in turn influence the climate variability (e.g., Charlson et al., 1992; Jacob and Winner, 2009), delving more deeply into their interplay mechanisms is imperative. These studies could improve outputs of the above haze prediction system through embedding new findings in the corresponding model modules. Again, a comparative analysis of the similarities and disparities between haze over northern and southern China from the meteorological, microphysical and chemical perspectives would advance our understanding of the nexus between climate and haze variability. As such, interrelationships among aerosol, cloud, radiation and precipitation over China should be an important issue for future investigations (e.g., Wu et al., 2016a), and it is hoped that the novel answers for this issue would also ameliorate the system's prediction performance.

7.2 Detection and attribution of changes in climatic factors tied to haze variability

The climate variability in climatic factors connected to the haze variability is significantly impacted by both human activity and natural forcing, which, in turn, could affect the haze variability in North China. Here, we take the air temperature as an example. According to the CAM5.1-1degree model simulations from the C20C+D&A (Climate of the 20th Century plus Detection and Attribution) project, it can be detected that the gradually increased temperature in the mid-troposphere over the BTH region in winter should be primarily influenced by human activity compared to natural forcing **(Figure 8)**. More specifically, especially since the middle and latter period of the 1990s, the temperature increase has been considerably enhanced **(Figure**

8a). Under such circumstances, an inversion layer in the lower troposphere could be easily established, which would not be conducive to the dispersion of pollutants. However, under the natural forcing only (except years before the 1970s), the whole atmosphere does not show noticeable warming **(Figure 8b)**, which implies the crucial role of human activity accordingly.

At present, when it comes to studies regarding the uses of global climate model simulations in haze variability [e.g., Coupled Model Intercomparison Project phase 5 (CMIP5) models' projections (Taylor et al., 2012)], more work concentrated on evaluating models' ability to emulate meteorological conditions responsible for haze formation and projecting the trend in haze frequency in the future (e.g., Cai et al., 2017; Han et al., 2017; Wu et al., 2017b). Nonetheless, in-depth studies into the degree to which human activity and natural forcing affect the changes in climatic factors responsible for haze variability are relatively rare. Such detection and attribution work based on multi-model projections could expand knowledge of their quantitative effects on climatic factors tied to haze variability in North China and even much larger areas of China. Note that **Figure 8** only delineates a quite preliminary study about this detection and attribution work. Detection and attribution of changes in other meteorological parameters (e.g., winds and precipitation) as well as atmospheric circulations and EFFs tied to haze variability still merit substantial investigations in the future.

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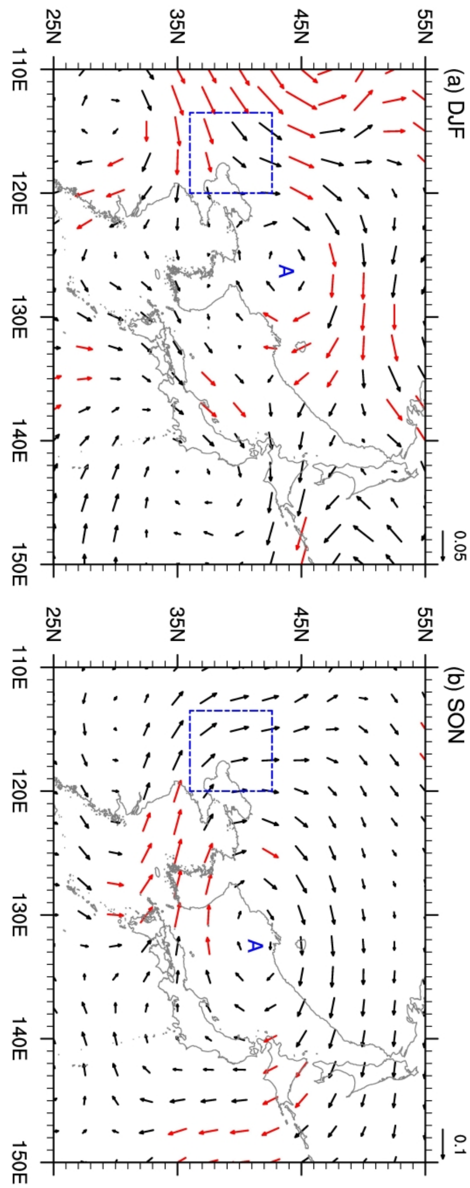

FIGURE 1 Regressed anomalies of 850 hPa winds (vectors; m s−1) with respect to (a) WHDs and (b) AHDs on the interannual timescale for 1960–2013. The letter A represents the center of the NEAACA. The blue box delineates the research domain of the BTH region. Red arrows represent the wind vectors with statistical significance above the 90% confidence level. The definition for a haze day is in concert with Chen and Wang (2015). The atmospheric variables were obtained from NCEP/NCAR reanalysis (https://www.esrl.noaa.gov/psd/data/gridded/data.ncep).

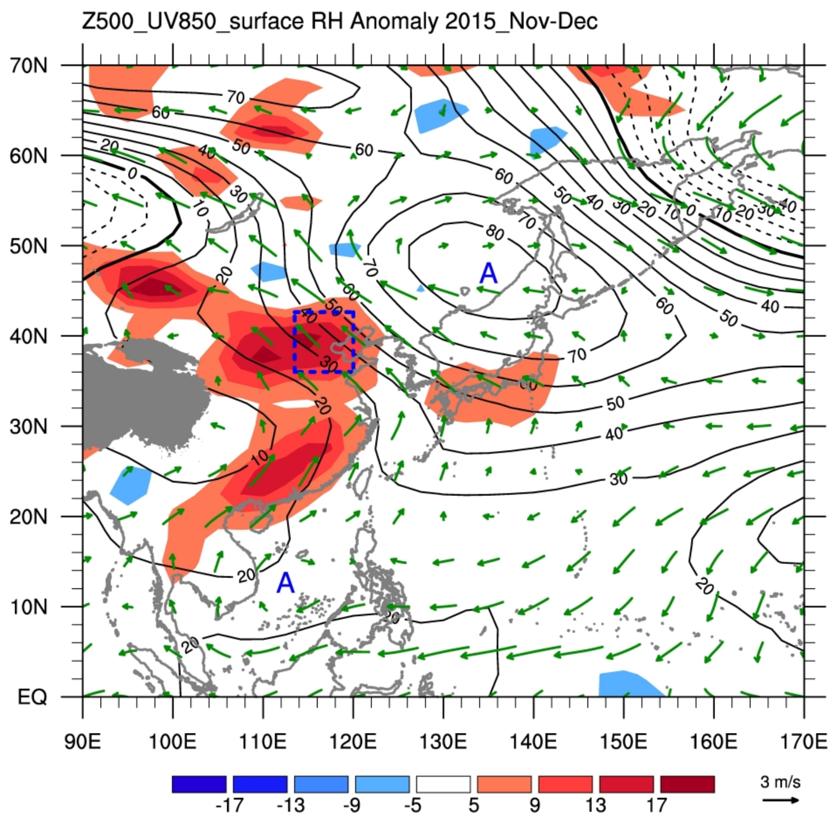

FIGURE 2 Anomalies of 500 hPa geopotential height (contours; gpm), 850 hPa winds (vectors; m s−1) and surface RH (shaded; %) averaged in November and December 2015. The base period is 1981–2010. The letter A represents the center of anticyclonic anomaly. The gray shaded area denotes the Tibetan Plateau. The blue box delineates the research domain of the BTH region. The atmospheric variables were obtained from NCEP/NCAR reanalysis (https://www.esrl.noaa.gov/psd/data/gridded/data.ncep).

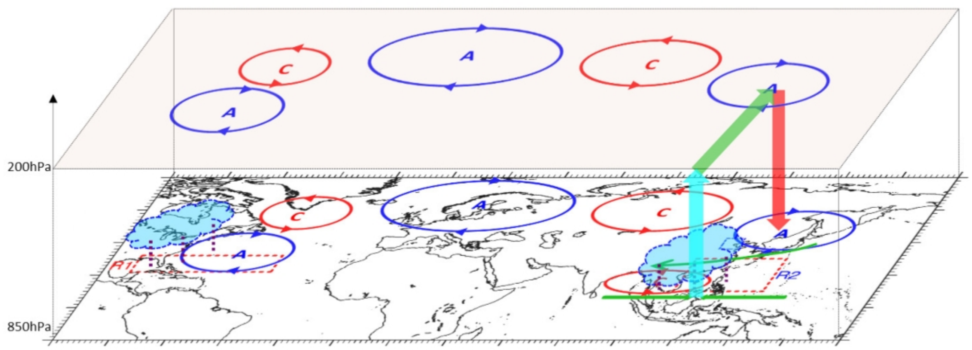

FIGURE 3 Schematic diagram encapsulating the SSTA-induced [warming in the SNA sector (R1) and WNP sector (R2)] physical mechanisms and pathways connected to above-normal years of AHDs in the BTH region. Anomalous quasi-barotropic anticyclones (A) and cyclones (C) are indicated by blue and red elliptical circles with arrows, respectively, denoting a large-scale Rossby wave train triggered by the heating to the north of R1. Green arrows depict the key horizontal low-level (850 hPa) airflows. The red, azure, and green arrows together exhibit the vertical overturning circulation tied to the SST warming in R2. The left-hand (right-hand) side of the pattern resembling a cloud, with violet short dashed lines, presents the significant anomalous precipitation induced by SSTA over R1 (R2). The blue dashed box delineates the research domain of the BTH region. Copied from Wang et al. (2019b).

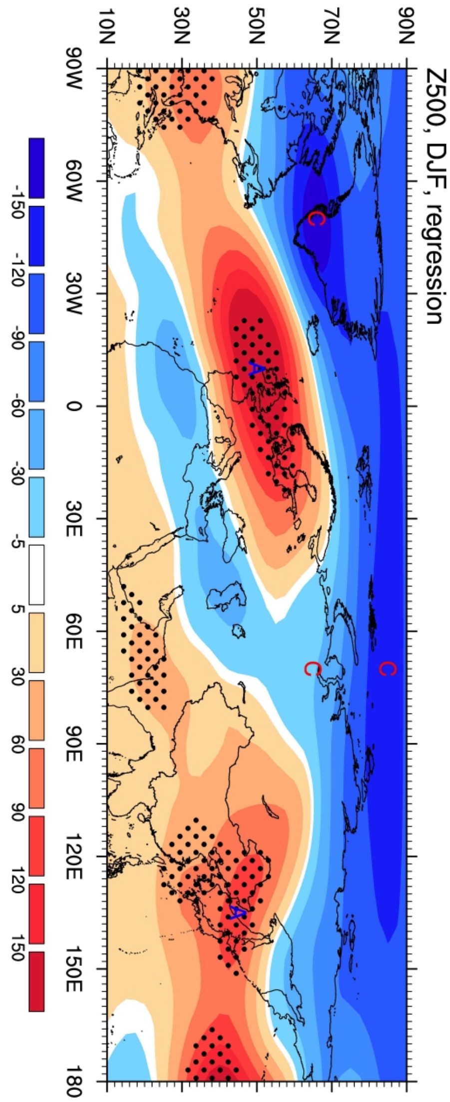

FIGURE 4 Regressed anomalies of DJF 500-hPa geopotential height (shaded; gpm) with respect to the prior detrended autumnal ASI zonal gradient index. The letters A and C represent the centers of anticyclonic and cyclonic anomalies, respectively. Regression coefficients that are significant at the 95% confidence level are stippled. The ASI zonal gradient index is defined as the SIC over the Barents–Kara–Laptev Sea (70°–80°N, 30°–140°E) minus that over the East Siberian Sea (70°–80°N, 150°E–180°). Revised based on Yin et al. (2017). ASI concentration data were from the Hadley Centre (http://www.metoffice.gov.uk/hadobs/hadisst/), and the height data were from NCEP/NCAR reanalysis (https://www.esrl.noaa.gov/psd/data/gridded/data.ncep).

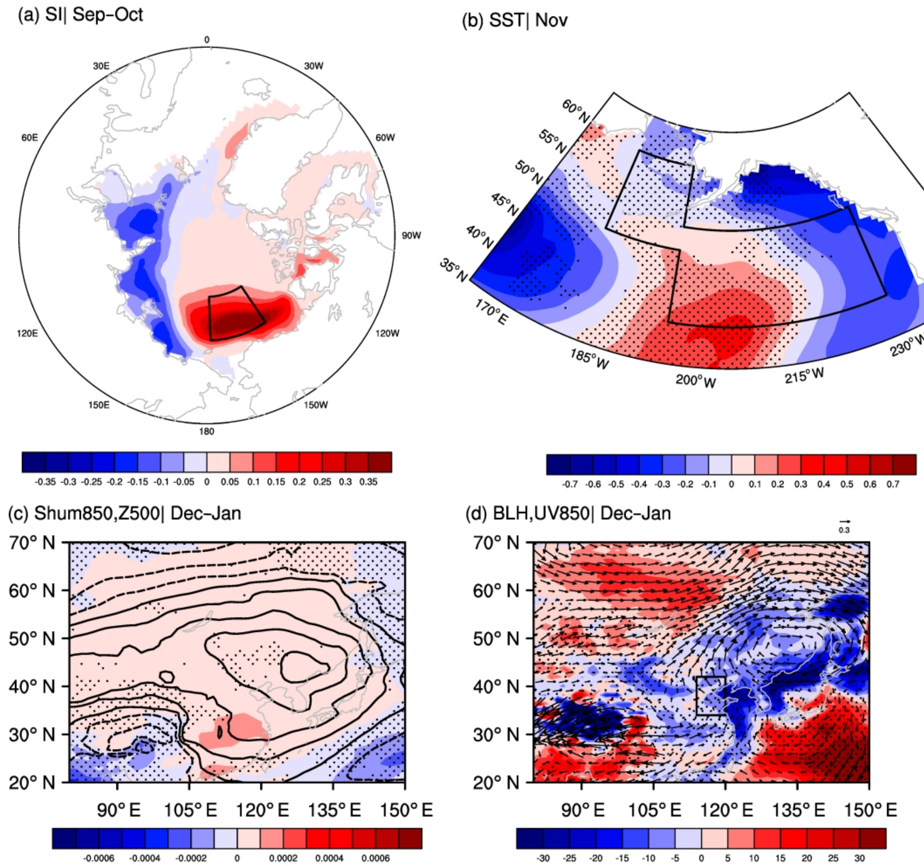

FIGURE 5 Composites of (a) September–October SIC (%), (b) SST in November (℃), (c) 500 hPa geopotential height (contours; gpm) and 850 hPa specific humidity (shaded; kg kg−1), and (d) PBLH (shaded; m) and 850 hPa winds (vectors; m s−1) in December–January. The black frame in panel (a) represents the location of the Bering Sea, and in panel (b) it represents the areas of the Bering Sea and Gulf of Alaska. Results are based on 35 ensembles of Community Earth System Model Large Ensemble simulations. The black dots indicate that the mathematical sign of the changes with shading from more than 50% of the members is consistent with the ensemble mean. Copied from Yin et al. (2019a).

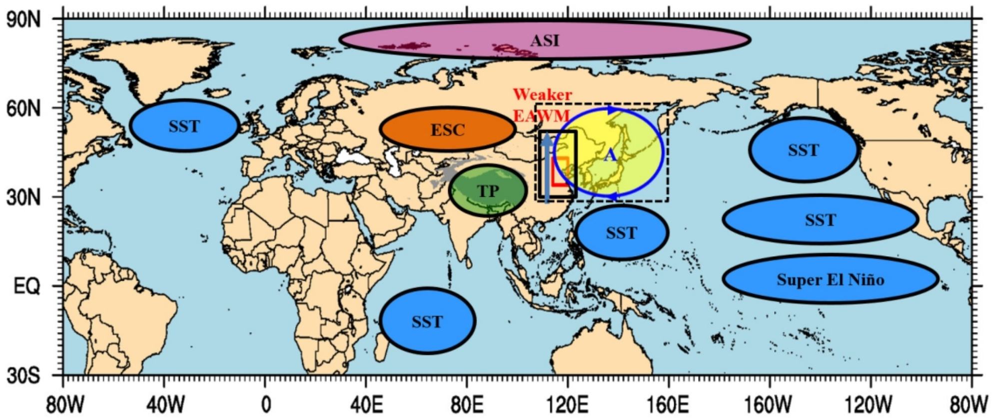

FIGURE 6 Sketch map of the principle climate factors associated with the number of WHDs in North China on the interannual timescale and their distributions. The black dashed frame denotes the crucial areas modulated by EFFs. The NEAACA is indicated by the blue elliptical cycle with arrows, with the letter A representing its center. The blue arrow denotes southerly wind anomalies on the western flank of the NEAACA, which corresponds to weakened EAWM activity (presented by the black solid rectangle). The gray shaded area denotes the TP, and the red box delineates the research domain of North China.

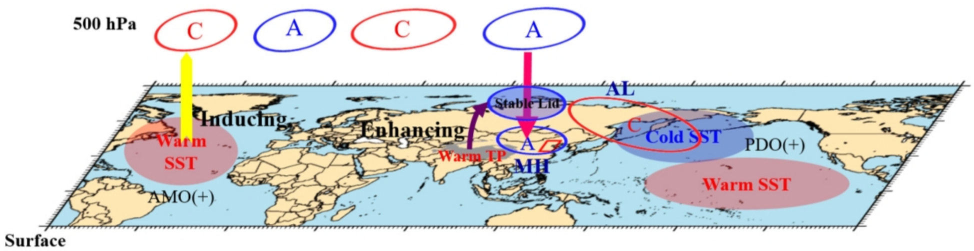

FIGURE 7 Schematic diagram encapsulating how climate anomalies trigger a higher number of WHDs in North China on the interdecadal timescale. Anomalous anticyclones (A) and cyclones (C) are indicated by blue and red elliptical circles. AMO(+)/PDO(+) means the warm phase of AMO/PDO. The pink arrow represents significant downward motions. The gray shaded area denotes the TP, and the red box delineates the research domain of North China. AL = Aleutian Low; MH = Mongolian High. Replotted based on Xiao et al. (2015), Xu et al. (2015) and Zhao et al. (2016).

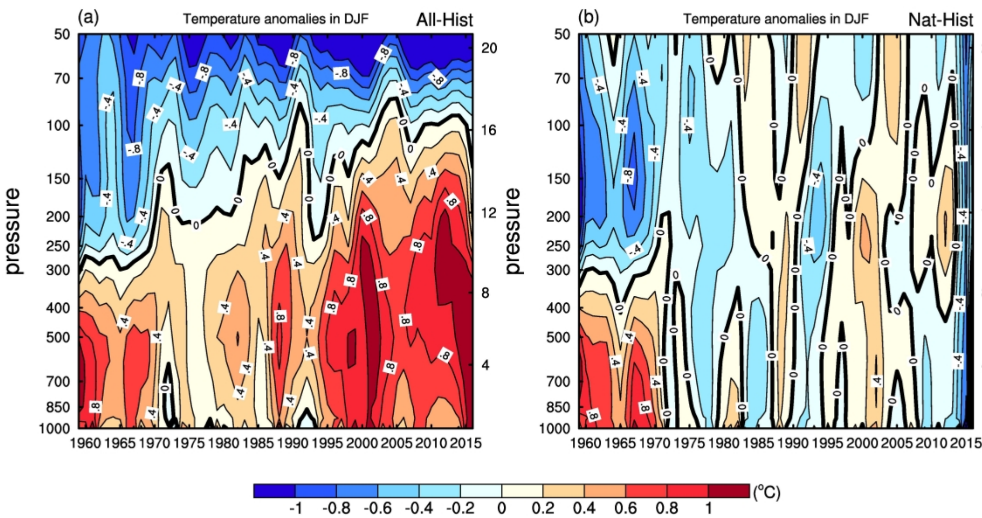

FIGURE 8 Longitude–time cross section of the DJF temperature anomalies (℃; relative to the reference period 1981–2010 of Nat-Hist) for (a) All-Hist and (b) Nat-Hist during 1959–2016 over the BTH region. The temperature data were from the CAM5.1-1degree model output (Stone et al., 2018). All-Hist indicates the factual scenario, and Nat-Hist indicates the counterfactual scenario.