



## Contrasting impacts of two types of El Niño events on winter haze days in China's Jing-Jin-Ji region

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**Abstract.** El Niño is a complex system with diverse distribution features and intensities. The regional climate anomalies caused by different types of El Niño event likely lead to various impacts on winter haze pollution in China. Based on long-term site observations of haze days in China from 1961 to 2013, this study explores the effects of Eastern Pacific (EP) and Central Pacific (CP) types of El Niño event on winter haze days (WHD) in China's Jing-Jin-Ji (JJJ) region and the physical mechanisms underlying WHD changes. The results show statistically significant positive and negative correlations, respectively, between WHD in the JJJ region and EP and CP El Niño events. At most sites in the JJJ region, the average WHD are increased in all EP El Niño years, with the maximum change exceeding 2.0 days. Meanwhile the average WHD are decreased at almost all stations over this region in all CP El Niño years, with the largest change being more than -2.0 days. The changes in large-scale circulations indicate obviously positive surface air temperature (SAT) anomalies and negative sea level pressure (SLP) anomalies over North China, and southerly wind anomalies at the mid-low troposphere over eastern China in the winters of EP El Niño years. These anomalies are conducive to increases in WHD in the JJJ region. However, there are significant northerly and northwesterly wind anomalies at the mid-low troposphere over eastern China, and stronger and wider precipitation anomalies in the winters of CP El Niño years, which contribute to decreased WHD over the JJJ region. Changes in local synoptic conditions indicate negative SLP anomalies, positive SAT anomalies, and weakened northerly winds over the JJJ region in the winters of EP El Niño years. The occurrence frequency of circulation types conducive to the accumulation (diffusion) of aerosol pollutants is increased (decreased) by 0.4% (0.37%) in those winters. However, the corresponding frequency is decreased (increased) by 0.54% (0.56%) in the winters of CP El Niño years. Our study highlights the importance of distinguishing the impacts of two types of El Niño events on winter haze pollution in China's JJJ region.

### 1 Introduction

North China, with the Jing-Jin-Ji region at the core, has encountered continuous severe haze pollution in recent winters. These atmospheric calamities have seriously harmed traffic, economic development, and resident health in this region (Gao et al., 2017; Liu et al., 2017; Zhang et al., 2019a). Increased anthropogenic emissions are considered as the crucial reason for the increased frequency and intensity of haze pollution. However, many studies have verified the modulation of worsening local weather conditions caused by large-scale climatic anomalies to severe haze events (Li et al., 2016; Cai et al., 2017; Li et al., 2018; Yin and Wang, 2018). Anomalous meteorological conditions have significant influences on the development and maintenance of haze events, and especially the explosive increase of local air pollutants is always accompanied by anomalous atmospheric circulation conditions (He et al., 2018; Zhang et al., 2018; Zhong et al., 2018). Hence, identifying the mechanism underlying the response of haze events to worsening weather conditions caused by interannual climate changes has implications for effectively controlling haze pollution and improving air quality.



As a strongest signal of interannual climate variation (Wyrski, 1975; Cane, 2005), El Niño has an important influence on the maintenance and diffusion of air pollutants via affecting large-scale atmospheric circulation and precipitation (Feng et al., 2016a, 2016b; Zhao et al., 2018), and consequently modulates the interannual variation of winter haze days (WHD) in China (Gao and Li, 2015; Sun et al., 2018; He et al., 2019). Several studies have reported that an anomalous anticyclone develops over the Northwest Pacific during the maturation of El Niño, resulting in increased precipitation and decreased WHD in southern China (Li et al., 2017; Zhao et al., 2018; He et al., 2019). Moreover, atmospheric circulation anomalies caused by El Niño can exacerbate the northward transport of aerosols in South and Southeast Asia, thereby increasing winter mean aerosol concentrations (Feng et al., 2016a) and intraseasonal severe haze days in eastern China (Zhao et al., 2018; Yu et al., 2019). Recent studies have indicated that there is a significant negative correlation of El Niño with WHD in southern China (Li et al., 2017; Zhao et al., 2018; He et al., 2019). However, the impacts of El Niño on WHD in northern China remain controversial. For example, Sun et al. (2018) showed that El Niño led to increased WHD in North China by suppressing the activity of the East Asian winter monsoon (EAWM). However, based on statistical analyses of long-term site observations of WHD in China, several studies found that there was no statistically significant correlation between El Niño indices and WHD in North China (Li et al., 2017; Zhao et al., 2018; He et al., 2019).

The above studies mostly focused on analyzing the impacts of integral El Niño events on WHD in China. Their results indicated that the modulation of El Niño events on air pollutants in northern China was much weaker than that in southern China (Li et al., 2017; Zhao et al., 2018; He et al., 2019). However, El Niño is a complex system with two dominant modes of quasi-quadrennial and quasi-biennial oscillations (Rayner et al., 2003; Timmermann et al., 2018), which can be classified into the Eastern Pacific (EP) and Central Pacific (CP) El Niño according to the anomalous sea surface temperature (SST) patterns (Ashok et al., 2007; Bejarano et al., 2008; Levine et al., 2010; Roberts et al., 2016). Because of the significantly distinct SST anomaly patterns in the equatorial Pacific, two types of El Niño events have different influences on the Walker circulation, which further stimulate global circulation wave trains and result in contrasting temperature and precipitation anomaly patterns in East Asia (Larkin et al., 2005; Yuan et al., 2012; Cai et al., 2018). Above anomalies of regional climate caused by two types of El Niño events may have different influences on winter atmospheric pollutants in China. For example, using the tropospheric chemical model GEOS-Chem, Feng et al. (2016a) showed that CP El Niño played an important role in redistributing seasonal mean PM<sub>2.5</sub> (particulate matter with a diameter  $\leq 2.5 \mu\text{m}$ ) concentrations in China. Recently, Yu et al. (2019) also found significantly opposite changes in winter mean aerosol concentrations and severe haze days in North China in the responses to different types of El Niño events by using a global aerosol-climate model. Nevertheless, the observation-based studies on the effects of two types of El Niño events on haze pollutants in China are still insufficient. The Jing-Jin-Ji (JJJ) region is one of the most densely populated areas in China and a typical region of severe air pollution (Cai et al., 2017; Miao et al., 2017; Zhong et al., 2018). Therefore, it is significant to understand the different responses of WHD in this region to two types of El Niño events in greater depth.

This study first classifies different types of El Niño events according to the latest national standard of the People's Republic of China (PRC) "Identification method for El Niño/La Niña events" issued by the China Meteorological Administration (CMA) (Ren et al., 2017). Then, we explore the impacts of two types of El Niño events on WHD in China's JJJ region (37°N–42°N, 113°E–120°E) from the perspectives of large-scale circulation and local synoptic condition anomalies using long-term site observations and reanalysis datasets, combined with commonly used circulation types classification methods. The datasets and methods used in this study are presented in Sect. 2. The impacts of two types of El Niño events on WHD in China's JJJ region and the potential physical mechanisms are analyzed in Sect. 3. The discussion and conclusions are presented in Sect. 4.



## 2 Methodology

### 80 2.1 Data

The datasets used in this study were as follows. (1) The monthly haze days dataset from the National Meteorological Information Center of the CMA. The time span of the dataset is from March 1961 to February 2013. According to a comprehensive judgment method widely used in previous studies, a haze day is identified when the daily mean visibility is less than 10 km, and the daily mean relative humidity is less than 90% (Schichtel et al., 2001; Doyle et al., 2002; Wu et al., 85 2010). (2) The monthly Niño3 index (SST anomaly averaged over the Niño3 domain (150°W–90°W, 5°S–5°N),  $I_{Niño3}$ ), Niño4 index (same as the Niño3 index, but over the Niño4 domain (160°E–150°W, 5°S–5°N),  $I_{Niño4}$ ), and Niño3.4 index (same as the Niño3 index, but over the Niño3.4 domain (170°W–120°W, 5°S–5°N),  $I_{Niño3.4}$ ) from March 1961 to February 2013, provided by the National Climate Center of the CMA. All Niño indices are calculated using the Hadley Centre Sea Ice and Sea Surface Temperature Data (HadISST) from March 1961 to December 1981 and the National Oceanic and 90 Atmospheric Administration (NOAA) daily optimum interpolation (OI.v2) SST dataset from January 1982 to February 2013 (Ren et al., 2017). (3) Daily and monthly ERA-40 and ERA-Interim reanalysis data from the European Centre for Medium-range Weather Forecasts (ECMWF), including sea level pressure (SLP), air temperature at 2 m, wind at 10 m, geopotential height at 500 hPa, and wind from 1000 to 850 hPa (contain seven pressure levels at 850 hPa, 875 hPa, 900 hPa, 925 hPa, 950 hPa, 975 hPa, and 1000 hPa). The horizontal resolution is  $0.25^\circ \times 0.25^\circ$  and the time span is from March 1961 to February 95 2013 for both daily and monthly reanalysis data. The data from March 1961 to December 1978 are derived from the ERA-40 reanalysis data and the data from January 1979 to February 2013 are derived from the ERA-Interim reanalysis data. (4) The global land surface precipitation data were provided by the Global Precipitation Climatology Centre (GPCC), with a horizontal resolution of  $0.5^\circ \times 0.5^\circ$ , covering March 1961 to February 2013 (Schneider et al., 2014).

### 2.2 Identification for two types of El Niño events and calculation of their indices

100 Similar to Yu et al. (2019), we classified different types of El Niño events referring to the national standard of the PRC mentioned in Sect. 1. This method identifies El Niño events based on the widely used  $I_{Niño3.4}$  and employs  $I_{Niño3}$  and  $I_{Niño4}$  to distinguish the different characteristics of two types of El Niño events.  $I_{Niño3}$  and  $I_{Niño4}$  are highly sensitive to EP and CP El Niño events, respectively. This identification method has been applied to the climate operations of the CMA, and has been widely used in research on the effects of El Niño events (e.g., Mu et al., 2017; Yu et al., 2019). We first selected all El Niño 105 events from 1961 to 2013. An El Niño event is identified when the absolute value of the 3-month smoothing average of  $I_{Niño3.4}$  reaches or exceeds  $0.5^\circ\text{C}$  for at least 5 months. All El Niño events were classified referring to the EP El Niño index ( $I_{ep}$ ) and the CP El Niño index ( $I_{cp}$ ).  $I_{ep}$  and  $I_{cp}$  were calculated as follows:

$$I_{ep} = I_{Niño3} - (\alpha \times I_{Niño4}), \quad (1)$$

$$I_{cp} = I_{Niño4} - (\alpha \times I_{Niño3}). \quad (2)$$

110 According to an empirical formula, the constant  $\alpha$  is 0.4 if  $I_{Niño3} \times I_{Niño4} > 0$ , but  $\alpha$  is 0 if  $I_{Niño3} \times I_{Niño4} \leq 0$ . An event is defined as an EP (CP) El Niño event if the absolute value of  $I_{ep}$  ( $I_{cp}$ ) reaches or exceeds  $0.5^\circ\text{C}$  for at least 3 months. Table 1 shows the specific classifications of two types of El Niño events obtained by the above method.

### 2.3 Circulation types classification methods

115 An aim of employing circulation types classification is to identify the most frequently occurring subset of the meteorological data, thereby considering the numerous interrelated meteorological variables within an integrated framework and exploring the physical mechanisms underlying aerosol pollution in the JJJ region in the classification process (Richman et al., 1981; Miao et al., 2017). Among the multitudinous circulation classification techniques, the T-mode principal component analysis (PCA) combined with the K-mean cluster used in this study is the most effective identification approach because of its



reproduction of predefined types, temporal and spatial stability, and low dependence on pre-set parameter (Huth et al., 1996; Zhang et al., 2012). This method has been widely used to identify the circulation types associated with air pollution (He et al., 2017a, 2017b, 2018). Similar to He et al. (2018), the daily SLP data from March 1961 to February 2013 in the JJJ region were taken as the samples for circulation types classification. First, we reshaped three-dimensional daily SLP data, including time, latitude, and longitude, into two-dimensional data (time  $\times$  grid) and normalized the two-dimensional data for time series. Second, the normalized SLP data performed the T-mode PCA and its main components were obtained according to the cumulative variance contribution of 95%. Third, we clustered the main components using the K-means cluster and identified the optimal number of clusters referring to the criterion function (Liu and Gao, 2011). In this study, the inflection of the criterion function, which represents the optimal number of clusters, was eight. Finally, the daily SLP data were assigned to eight synoptic-scale circulation types base on cluster result, and the other reanalysis data (e.g. temperature at 2 meter and wind at 10 meter) were classified in the same way as the SLP data. Each pattern of synoptic-scale circulation was determined.

## 2.4 Correlation analysis

The correlation coefficients of site-observed WHD in eastern China (east of 110°E) with the different types of El Niño indices, i.e.,  $I_{\text{Nino}3.4}$ ,  $I_{\text{ep}}$ , and  $I_{\text{cp}}$ , were calculated in this study. The sites without WHD at least consecutive 25 years were eliminated before the correlation analysis, since the time series of WHD at these sites lack interannual and interdecadal fluctuations, and their responses to anomalous synoptic conditions caused by climate change are weak. In addition, a band-pass filtering of 2-10 years was performed for the WHD data to remove signal interference from changes in local aerosol emissions and interdecadal climate variability following Zhao et al. (2018) and He et al. (2019). The final results more intuitively reflect the correlation between El Niño events and WHD.

## 3 Results

### 3.1 Impacts of two types of El Niño events on WHD in China's JJJ region

Figure S1 shows the correlation coefficients between the time series of site-observed WHD in eastern China and  $I_{\text{Nino}3.4}$ ,  $I_{\text{ep}}$  and  $I_{\text{cp}}$  indices. Whether for EP or CP El Niño events, their indices are featured by the uniformly negative correlation with WHD at most of the stations in southern China. This result is in agreement with previous studies (e.g., Li et al., 2017; Zhao et al., 2018; He et al., 2019), which reported that the increase in precipitation over southern China due to the anomalous anticyclone over the West Pacific during the mature phase of El Niño events significantly reduced WHD in this region. However, the sign of the correlation coefficient between EP El Niño and WHD is completely opposite that between CP El Niño and WHD for the majority of sites in the JJJ region. At most sites, WHD is positively correlated with the  $I_{\text{ep}}$  indices, but negatively correlated with the  $I_{\text{cp}}$  indices. As seen in Fig. 1, the absolute values of the correlation coefficients at some stations exceed 0.4. There are statistically significant correlations between the site-averaged WHD in the JJJ region and  $I_{\text{ep}}$  and  $I_{\text{cp}}$  indices ( $p \leq 0.05$ ), though the correlation coefficient of 0.16 and -0.2 are low (Table 2). Moreover, the corresponding correlation coefficients reach 0.31 and -0.43, respectively, with a confidence level of 99%, when only selecting the stations at which the correlations pass a significance level of 90% (Fig. 1).

Figure 2 shows the composite anomalies of WHD at all sites over the JJJ region in different types of El Niño years relative to the 1961-2013 mean WHD. For the majority of stations in the JJJ region, the WHD is increased in EP El Niño years, with the maximum change exceeding 2.0 days. However, the WHD are reduced at almost all stations over this region in CP El Niño years, with the maximum change exceeding -2.0 days. For instance, in EP El Niño years, there are significant positive WHD anomalies surrounding Beijing and Tianjin in which the positive values generally exceed 1.2 days. In CP El Niño years, the



comparable negative WHD anomalies can be seen in the same region. The opposite differences in the WHD corresponding to two types of El Niño are also apparent in the northwestern and northeastern parts of the JJJ region. The spatial correlation coefficient between the anomalous WHD in the JJJ region in both types of El Niño years reaches -0.71, which is significant at the 99% level.

The detailed statistics of WHD anomalies at all sites over the JJJ region in each El Niño year are shown by the box-and-whisker plots in Fig. 3. As seen in Fig. 3a, the medians of WHD anomalies for all sites are below the zero line in all CP El Niño years, indicating a negative WHD anomaly for more than half of the sites. Although the medians of WHD anomalies fluctuate above and below the zero line in different EP El Niño years, the anomalies of WHD show obviously wider distributions in the positive range for all sites in each year, with the positive extremum exceeding 10 days in most EP El Niño years. In addition, the distributions of WHD anomalies in different types of El Niño years also display interdecadal variations. The quasi-quadrennial mode was significantly strong, and EP events occurred more frequently during 1980-1999, corresponding to a larger proportion and higher extremum of positive WHD anomalies for all sites in the JJJ region. After 2000, the frequency of CP El Niño events was increased corresponding to the dominant quasi-biennial mode in the tropical Pacific, which led to a larger proportion and higher extremum of negative WHD anomalies in the JJJ region. This phenomenon may be attributable to the interdecadal transformation of the relative activity or stability between two types of El Niño modes (Wang and Ren, 2017). Figure 3b also shows that the WHD anomalies are mainly located in the positive range in the EP El Niño years, but are obviously located in the negative range in the CP El Niño years.

In summary, the impacts of two type of El Niño events on WHD are clearly opposite over the JJJ region. The EP El Niño events lead to increases in WHD in the JJJ region, whereas the CP El Niño events decrease the WHD in this region. This is the reason why the correlation coefficient between the time series of WHD over North China and the El Niño indices was found to be statistically insignificant when taking the El Niño event as a whole in previous studies (e.g., Li et al., 2017; Zhao et al., 2018; He et al., 2019).

### 3.2 Anomalies of winter mean large-scale circulations for two types of El Niño

Next, we explore the physical mechanisms underlying the WHD changes in the JJJ region in response to EP and CP El Niño events, respectively, from the perspective of large-scale circulation anomalies (Fig. 4). Previous studies have found that the severe haze events over North China in boreal winter were always accompanied by a decrease in northerly wind speed in the lower troposphere and weakening of the East Asian trough in the middle troposphere (Chen and Wang, 2015). The formation of heavy haze pollution over Beijing and its surroundings is significantly facilitated by the weakened EAWM, high-pressure anomalies at 500 hPa, and enhanced atmospheric stability (Zhang et al., 2014; Zhong et al., 2018).

The surface air temperature (SAT) generally increases over East Asia in the winters of EP El Niño years, especially in northern China, northeastern China, and eastern Siberia, with the maximum increase reaching 2 K (Fig. 4a). The SLP generally drops over East Asia. In particular, the SLP is decreased more significantly north of 30°N, with the maximum reaching -4 hPa in eastern Siberia (Fig. 4b). On the one hand, the worsening meteorological conditions, including near-surface warming and low pressure, are not conducive to the southward movement of the Siberian high pressure system, thereby weakening the transport of the EAWM on aerosol pollutants over northern China. On the other hand, such conditions promote relatively stable circulation, which is conducive to the accumulation of aerosol pollutants. In addition, there is a significant positive anomaly of geopotential height at 500 hPa over the northwestern Pacific in the winters of EP El Niño years, with the maximum anomalies exceeding 20 gpm over southern Japan and the northwestern Pacific. These positive geopotential height anomalies also extend westward over northeastern and eastern China (Fig. 4c). At the same time, there is a negative geopotential height anomaly at 500 hPa over southwestern China. Consequently, such distribution of geopotential height anomalies results in an anomalous southerly wind in the middle and lower troposphere over northeastern and eastern China (Fig. 4d). The anomalous southerly wind weakens the seasonal prevailing northwesterly wind in the JJJ region, with



200 the maximum decrease exceeding  $0.5 \text{ m s}^{-1}$ . This type of large-scale circulation anomalies suppresses the outward transport of aerosol pollutants in this region. Similar circulation anomalies were also found during the 2015/2016 super-strong EP El Niño event in earlier study (Chang et al., 2016).

Compared to the EP El Niño years, there are larger increases in SAT and decreases in SLP over southern China in the winters of CP El Niño years, with the maximum changes reaching  $0.8 \text{ K}$  and  $-3 \text{ hPa}$  over the south of Yangtze River, respectively  
205 (Fig. 4f and g). However, the positive SAT anomalies and negative SLP anomalies over northern China in the winters of CP El Niño years are apparently weaker than the corresponding changes in the winters of EP El Niño years (Fig. 4f and g). The SAT is significantly decreased in northeastern China and Siberia, with the largest negative anomalies reaching  $-2 \text{ K}$ . Additionally, there are anomalous negative geopotential height at  $500 \text{ hPa}$  over west of Lake Baikal and the Aleutian region, but positive geopotential height at  $500 \text{ hPa}$  over southern Japan and the Korean peninsula in the winters of CP El Niño years  
210 (Fig. 4h). This leads to the westward shift of the East Asian trough (Jiang et al., 2017). As a result, there are northerly and northwesterly wind anomalies in the middle and lower troposphere north of  $30^\circ\text{N}$  in China, which significantly enhances the seasonal prevailing northerly wind (Fig. 4i). Such anomalous circulations are conducive to the outward transport of aerosol pollutants in the JJJ region. The monthly mean precipitation is significantly increased over eastern China in the winters of CP El Niño years, especially in the coastal regions of southeastern China, with the maximum changes exceeding  $20 \text{ mm}$ . The  
215 range of anomalous positive precipitation over the JJJ region is wider in CP El Niño years compared to that in EP El Niño years, although a comparable increase in precipitation over this region occurs with both types of El Niño years (Fig. 4e and j). Thus, the former is more conducive to enhancing the wet deposition of particulate matters.

### 3.3 Anomalies of intraseasonal local synoptic conditions in the winters of different types of El Niño years

In this section, we further explore the differentiated effects of two types of El Niño events on WHD in the JJJ region from  
220 the perspective of changes in intraseasonal local synoptic conditions. Using the T-mode PCA and K-means cluster analysis methods, eight circulation types were identified over the JJJ region in winter. The effects of two types of El Niño events on these circulation types were then compared. The changes in local synoptic conditions are defined as the differences between the results averaged in ten EP (six CP) El Niño years and the climatology.

Figures S2 and S3 show the climatological distributions of SLP, air temperature at  $2 \text{ m}$ , and wind at  $10 \text{ m}$  over the JJJ region  
225 in winter for the eight circulation types, respectively. A larger northwest-southeast SLP gradient (Fig. S2a, b, c and d) and a stronger northerly wind (Fig. S3a, b, c and d) can be seen over the JJJ region for the circulation types of Type 1, Type 2, Type 3, and Type 4. In particular, the high pressure system is stronger and broader (Fig. S2a and b), and the seasonal prevailing northerly and northwesterly winds are larger (Fig. S3a and b) over the northwestern part of the JJJ region for Types 1 and 2. This implies that the cold air is more active and the local aerosol pollutants are more easily transported outward under these  
230 circulation types. Conversely, there is an obviously smaller northwest-southeast SLP gradient (Fig. S2e, f, g and h) and weaker seasonal prevailing northwesterly and westerly winds (Fig. S3e, f, g and h) over the JJJ region for the circulation types of Type 5, Type 6, Type 7, and Type 8. Above all, there is a significant belt of low pressure in the JJJ region, and the seasonal prevailing wind becomes a southwesterly wind in the southeastern part of this region under the circulation types of Types 7 and 8. Such circulations with low pressure and weak wind not only suppress the southward movement of cold air but  
235 also promote atmospheric stability in the JJJ region. Consequently, the local aerosol pollutants are prone to accumulating. Therefore, the Types 1-4 are defined as the clean circulation types, and the Types 5-8 are defined as the pollution circulation types in this study.

Table 3 shows the occurrence frequency of clean and pollution circulation types in winter corresponding to the climatological means and two types of El Niño years, respectively. Compared to the climatological means, it is completely  
240 opposite for the changes in occurrence frequency of each circulation type between the two types of El Niño years. The occurrence frequency of clean circulation types is reduced by  $0.37\%$ , and that of pollution circulation types is increased by





0.4% in the winters of EP El Niño years. By contrast, the occurrence frequency of clean circulation types is increased by 0.56%, and that of pollution circulation types is decreased by 0.54% in the winters of CP El Niño years. These changes imply that the days conducive to the accumulation of local aerosol pollutants are increased in the winters of EP El Niño years, but the opposite occurs in the winters of CP El Niño years.

In the winters of EP El Niño years, there are negative SLP anomalies over the northwestern and northern parts of the JJJ region but obviously positive SLP anomalies over the southeastern and eastern parts of this region under most circulation types, except for Types 1 and 6 (Fig. 5). Hence, the gradients of SLP are apparently decreased over the JJJ region for each circulation type in the winters of EP El Niño years relative to the climatological means (Fig. S2). Affected by this, southerly wind anomalies occur at the near-surface layer over the JJJ region for both clean and pollution circulation types (Fig. 7c). In addition, the anomalies of SAT over the JJJ region under most circulation types, except for Types 1 and 5, are mainly distributed in the positive anomaly range, indicating that the SAT is generally increased in this region (Fig. 7a). The above analyses show that there are decreased SLP, reduced wind velocity, and increased SAT over the JJJ region under all circulation types in the winters of EP El Niño years, which lead to a stable synoptic situation. This means that the suppression effects of pollution circulation types on the outward transport of local aerosol pollutants are enhanced over the JJJ region. At the same time, these anomalous synoptic conditions are not conducive to the southward activity of cold air, weakening the diffusion effect of clean circulation types on the local aerosol pollutants in this region.

On the contrary, there are positive SLP anomalies over the northwestern and northern parts of the JJJ region but negative SLP anomalies over the southeastern or southern parts of this region under the clean circulation types in the winters of CP El Niño years, which increase the northwest-southeast SLP gradient (Fig. S2a~d and 6a~d). Correspondingly, the near-surface meridional wind anomalies over the JJJ region under the clean circulation types are mainly located in the negative anomaly range (Fig. 7d), which means that the seasonal prevailing wind is enhanced in this region. Moreover, the SAT anomalies are also distributed in the negative anomaly range under the clean circulation types (Fig. 7b), indicating a significant decrease in near-surface temperature over the JJJ region. These analyses show that the intensity of synoptic situations conducive to the outward transport of local aerosol pollutants is further enhanced over the JJJ region under the clean circulation types. This may be the reason for the reduction in WHD in this region.

In summary, there are significant differences between the impacts of two types of El Niño events on the intraseasonal local synoptic conditions. These differences lead to opposite WHD anomalies over the JJJ region in response to different types of El Niño events. In the winters of EP El Niño years, the increase in WHD over the JJJ region may be related to the increased days of pollution circulation types, the decreased days of clean circulation types, the enhanced suppression effect of pollution circulation types on aerosol pollutants, and the weakened diffusion effect of clean circulation types. In the winters of CP El Niño years, the reductions in WHD in the JJJ region are mainly attributable to the increased days and intensity of clean circulation types and the decreased days of pollution circulation types.

#### 4 Discussion and conclusions

Based on the long-term site observations of WHD from the CMA, the reanalysis datasets from the ECMWF, and the precipitation reanalysis data from the GPCC, this study explored the impacts of two types of El Niño events on WHD over China's JJJ region and the potential physical mechanisms underlying their differences. The conclusions and discussions are as follows.

The effects of two types of El Niño events on WHD over the JJJ region are significantly different. There are statistically significant positive (negative) correlation coefficients between WHD over the JJJ region and the Iep (Icp) indices. Correspondingly, WHD are increased (decreased) over the JJJ region in the winters of EP (CP) El Niño years. Our results are obviously different from those in previous studies without distinguishing two types of El Niño events (e.g., Li et al., 2017;



Sun et al., 2018; Zhao et al., 2018; He et al., 2019), which reported the statistically insignificant effect of El Niño on winter haze pollution in North China.

285 Figure 8 shows the physical mechanisms corresponding to the effects of EP and CP El Niño on WHD in the JJJ region, respectively. The changes in large-scale circulation at the near-surface and mid-low troposphere in East Asia are significantly different in response to two types of El Niño events, which consequently lead to the opposite effects on WHD over the JJJ region. There are increases in SAT and decreases in SLP over North China in the winters of EP El Niño years. Simultaneously, the seasonal prevailing wind is weakened due to a large range of southerly wind anomalies over the mid-low  
290 troposphere in this region. These anomalies suggest that the activity of the EAWM is significantly suppressed and the intensity of cold air is weakened, both of which are conducive to the concurrent increases in WHD over the JJJ region. In contrast, the meteorological conditions anomalies such as near-surface warming and low pressure are apparent over southern China in the winters of CP El Niño years. The westward shift of the East Asian trough at 500 hPa leads to northerly and northwesterly wind anomalies over the mid-low troposphere in eastern China, which significantly enhances the seasonal  
295 prevailing wind. This may result in the decrease in WHD over the JJJ region during the same period. Furthermore, the positive precipitation anomalies over eastern China are stronger in intensity and wider ranging in the winters of CP El Niño years, which also contribute to the reduction in WHD over the JJJ region.

Our results further indicate an increase in the occurrence frequency of pollution circulation types and a decrease in that of clean circulation types in the winters of EP El Niño years. These changes support the accumulation and maintenance of local  
300 aerosol pollutants in the JJJ region. In addition, there are obviously synoptic conditions anomalies, including the reduced SLP gradient, near-surface warming, and weakened northerly wind, over the JJJ region under all circulation types. These changes indicate the enhanced pollution circulation types and the weakened clean circulation types in the winters of EP El Niño years, which may be one reason for the increased WHD over the JJJ region. Conversely, the reductions in WHD over the JJJ region are mainly attributable to the increase (decrease) in occurrence frequency of clean (pollution) circulation types  
305 in the winters of CP El Niño years. These anomalous changes result in increased cold air days, and thereby facilitate the outward transport of local aerosol pollutants. Meanwhile, the intensity of cold air is enhanced due to the larger SLP gradient, negative temperature anomalies, and stronger near-surface northerly winds over the JJJ region under the clean circulation types. These anomalies likely contribute to the reduction in WHD in this region.

In recent years, the air quality improvement projects implemented by China's government have effectively controlled the  
310 emissions of PM<sub>2.5</sub> in most areas of China (Zheng et al., 2018; Ding et al., 2019; Gui et al., 2019; Zhang et al., 2019b). However, haze pollution events continue to occur (Zhang et al., 2019a). It is a greatly worth concern about the impacts of worsening meteorological conditions caused by annual climate change on haze pollution process. This study elucidates the potential physical mechanisms of WHD changes over the JJJ region in response to two types of El Niño events from the perspectives of large-scale circulation and local synoptic condition anomalies. As noted by Yu et al. (2019), we further  
315 emphasized the importance of distinguishing the effects of two types of El Niño events on winter haze pollution in North China. This study has certain implications to further understand the impact of climate changes on air pollution in China's typical regions. It is worth noticing that El Niño has the potential to change aerosol composition and size distribution via affecting aerosol transport, deposition, and chemical reactions, which are crucial to aerosol direct and indirect effects (Li et al., 2011; Shaheen et al., 2013; Rajeev et al., 2016; Jayarathne et al., 2018). Now, there are few long-term large-scale  
320 observations of aerosol composition, particle types, and size distribution in China, so we could not precisely characterize the overall process related to El Niño. More detailed analyses need to be solved by growing observations and performing some sensitive simulations in the future work. In addition, the winter haze pollution in China may also be affected by multiple-timescale climate change factors, including the EAWM (Kim et al., 2016), Arctic Oscillation (Chen et al., 2013), Arctic sea ice (Wang and Chen, 2016), Tibetan Plateau heat source (Xu et al., 2016), and interdecadal variation in snow cover (Yin et al., 2018). How to quantify the comprehensive contributions of different climate change factors on haze pollution in China  
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still needs be attended in future research.

#### Data availability

The monthly haze days dataset can be acquired from <http://data.cma.cn/data/cdcindex/cid/6d1b5efbdcfb9a58.html>. The monthly Niño3, Niño4, and Niño3.4 indices are available at [http://cmdp.ncc-cma.net/download/Monitoring/Index/M\\_Oce\\_Er.txt](http://cmdp.ncc-cma.net/download/Monitoring/Index/M_Oce_Er.txt). Daily and monthly ERA-40 and ERA-Interim reanalysis data are available at <https://www.ecmwf.int/en/forecasts/datasets/browse-reanalysis-datasets>. The global land surface precipitation data can be acquired from <https://climatedataguide.ucar.edu/climate-data>.

#### Author contributions

ZW conceived the study. XY, ZW, and HZ performed the analysis and led the manuscript writing. All authors provided comments and contributed to the text.

#### Competing interests

The authors declare that they have no conflict of interest.

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545 **Table 1: The classification of El Niño events**

Eastern Pacific (EP)	Central Pacific (CP)
1963/1964, 1965/1966, 1972/1973, 1976/1977, 1979/1980, 1982/1983, 1986/1988, 1991/1992, 1997/1998, 2006/2007	1968/1970, 1977/1978, 1994/1995, 2002/2003, 2004/2005, 2009/2010

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575 **Table 2: Correlation coefficients between the time series of site-averaged winter haze days in China's JJJ region and different types of El Niño indices. The values in parentheses indicate the correlation coefficients and confidence levels when only selecting the stations where the correlations pass a 90% significance level.**

	Nino3.4	Iep	Icp
Cor	0.04 (0.06)	0.16 (0.31)	-0.20 (-0.43)
P	0.65 (0.45)	0.05 (<0.01)	0.01 (<0.01)

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605 **Table 3: The occurrence frequencies of each circulation type in winter for climatology and two types of El Niño years (unit: %).**  
The values in parentheses represent changes relative to the climatological means.

	climatology	EP El Niño year	CP El Niño year
Clean circulation types	53.89%	53.52% (-0.37%)	54.45 % (+0.56%)
Pollution circulation types	46.1%	46.5% (+0.4%)	45.56 % (-0.54%)

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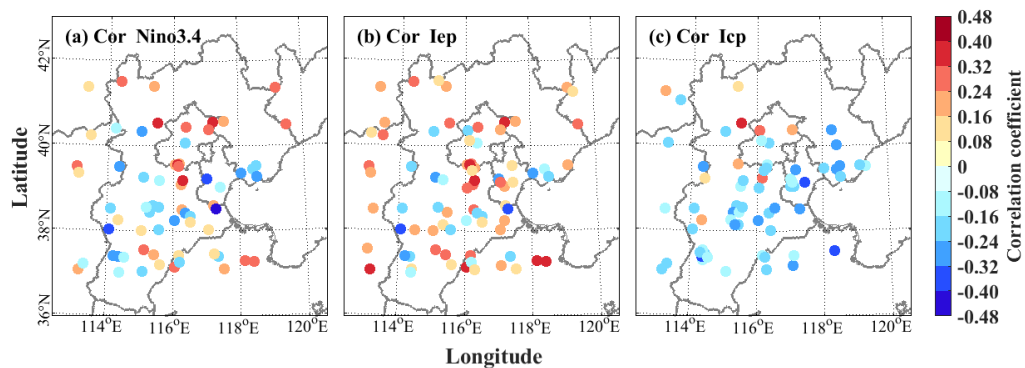


Figure 1: Correlation coefficients between the time series of site-observed winter haze days in JJJ region and (a)  $I_{Nino3.4}$ , (b)  $I_{ep}$ , and (c)  $I_{cp}$  indices. Only the sites where the correlations pass a 90% significance level are shown.

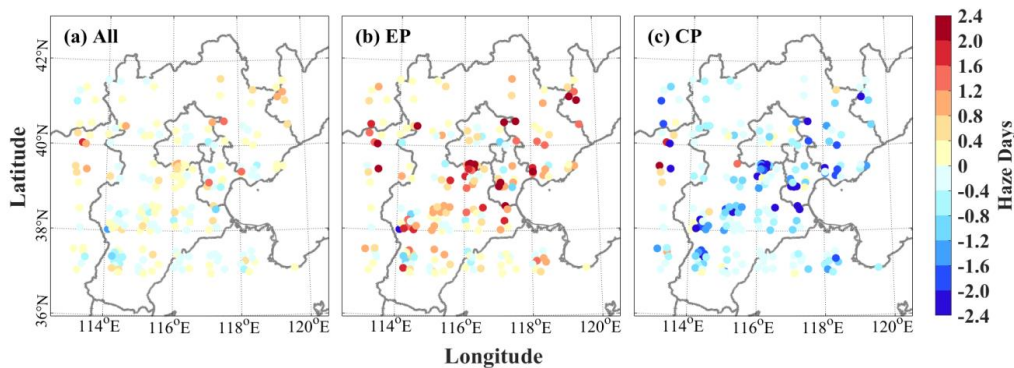
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**Figure 2: Composite changes of winter haze days at all sites over JJJ region in (a) all El Niño, (b) EP El Niño, and (c) CP El Niño years relative to the 1961-2013 mean winter haze days (unit: day).**

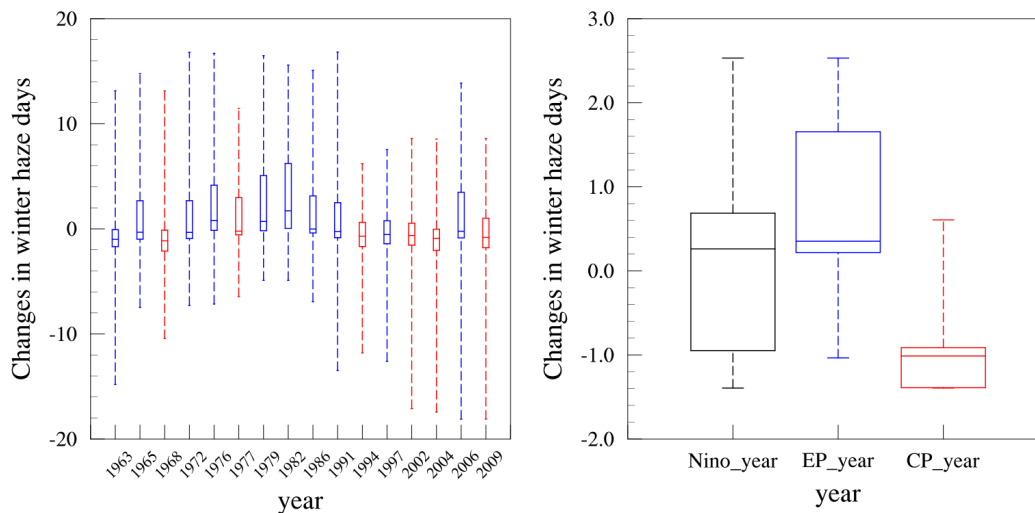
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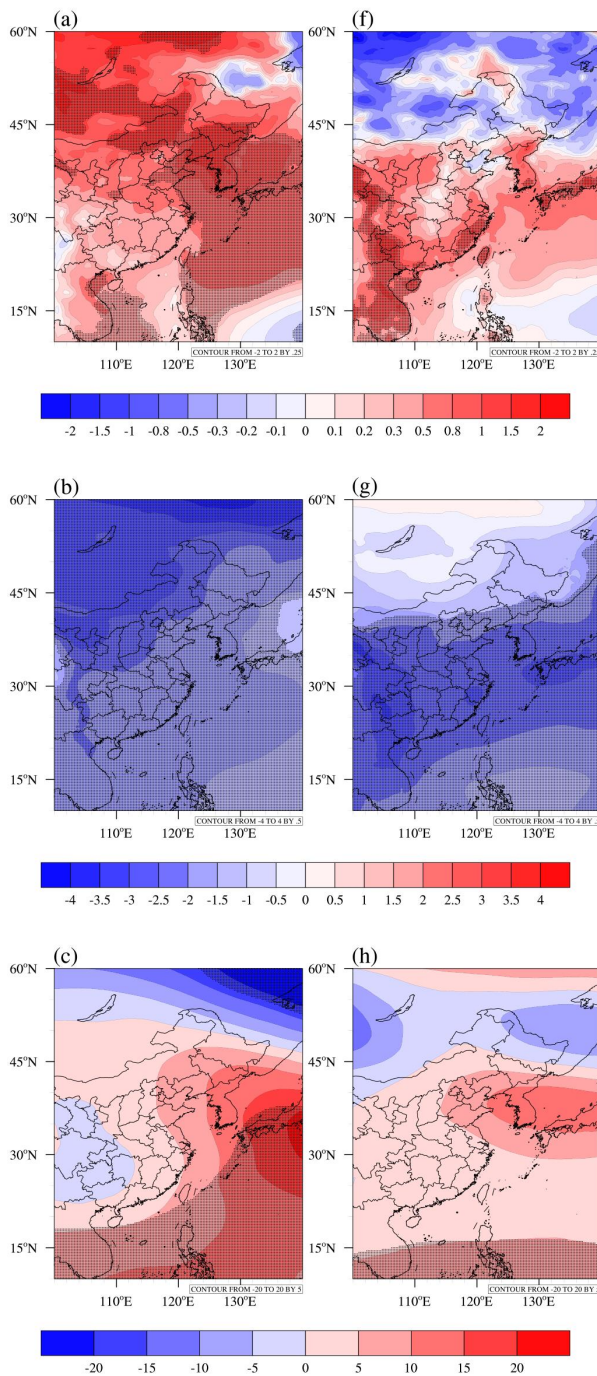


685 **Figure 3: Box-and-whisker plots of (a) WHD anomalies at all sites over JJJ region in each El Niño year and (b) site-averaged WHD anomalies in different types of El Niño years (unit: day). Each site-averaged WHD anomaly was sampled from a single El Niño year and all these anomalies were divided into groups named as Nino year, EP year, and CP year. The blue, red, and black lines represent the EP, CP, and all El Niño years, respectively. Each box-and-whisker consists of the 25th quantile (the upper border of box), median (horizontal line in the middle of box), 75th quantile (the lower border of box) and extremums (the endpoints of whiskers).**

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**Figure 4:** Winter mean changes in (a, f) air temperature at 2 meter (unit: K), (b, g) sea level pressure (unit: hPa), (c, h) geopotential height at 500 hPa (unit: gpm), (d, i) wind averaged from 1000 hPa to 850 hPa (The arrows represent wind vectors and the contours represent wind velocities, unit:  $\text{m s}^{-1}$ ), and (e, j) precipitation (unit: mm) in responses to the two types of El Niño. The left (a-e) and right (f-j) panels represent the differences averaged in ten EP El Niño and six CP El Niño years relative to the 1961-2013 climatological means, respectively. The dots indicate significance at  $\geq 90\%$  confidence level from the t test.



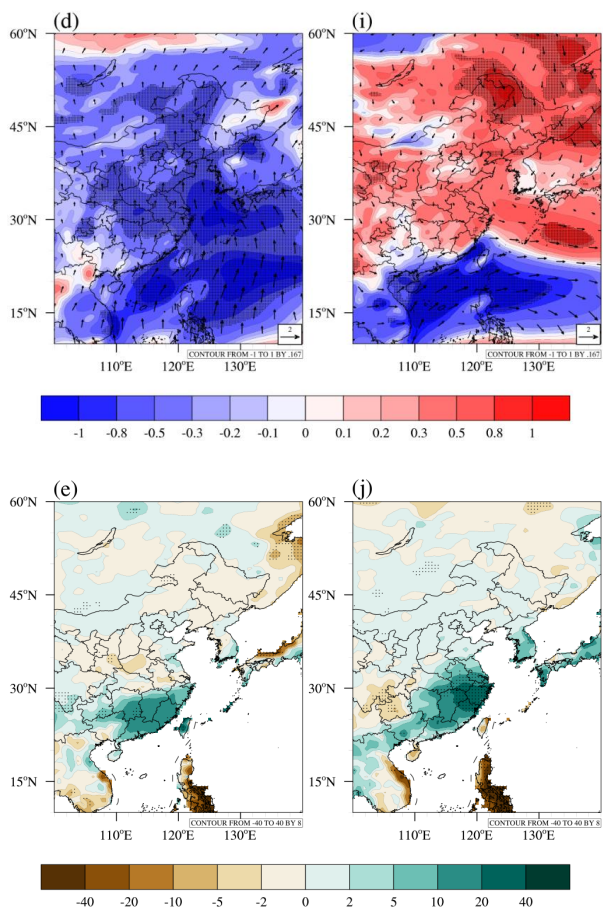


Figure 4: (Continued).

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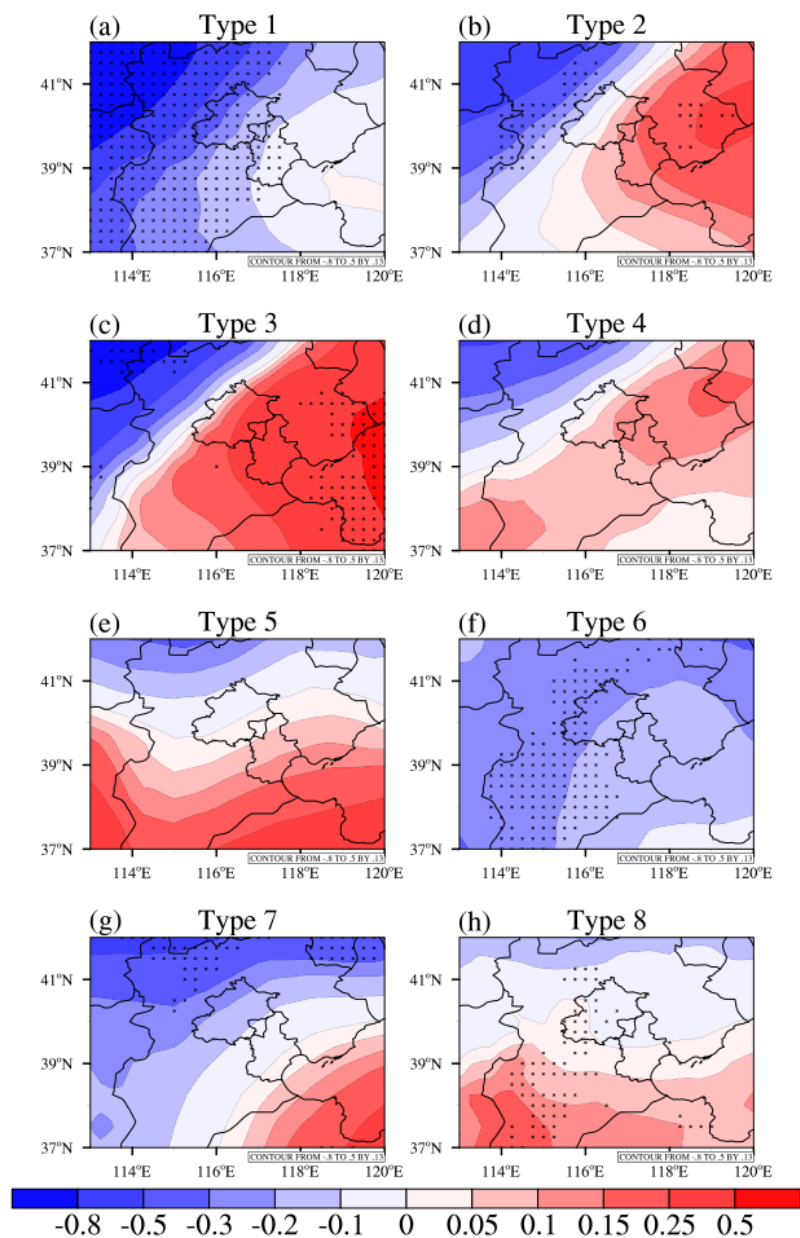


Figure 5: Changes in SLP over JJJ region under eight circulation types in the EP El Niño years relative to the climatological means (unit: hPa). The dots indicate that the differences between more than 60 % of ensemble member pairs have the same sign as the mean differences.

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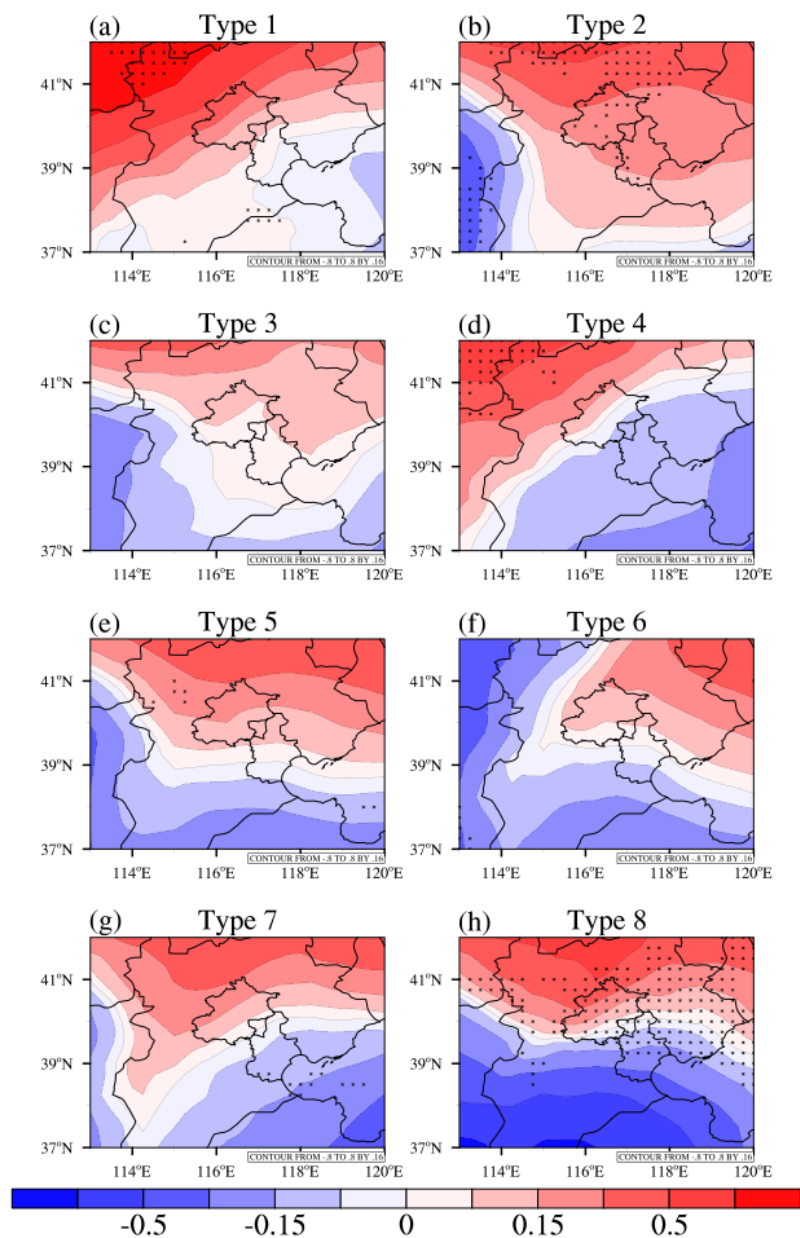
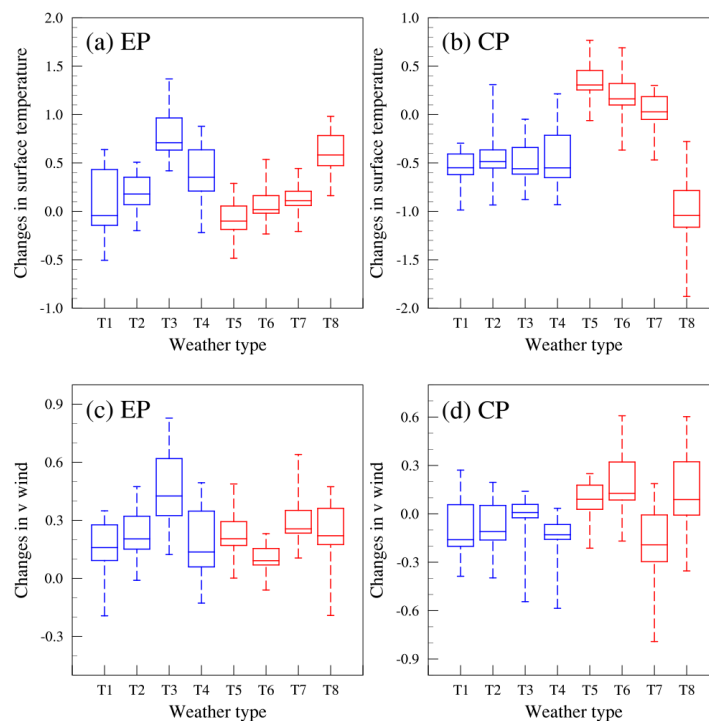


Figure 6: Changes in SLP over JJJ region under eight circulation types in the CP El Niño years relative to the climatological means (unit: hPa). The dots indicate that the differences between more than 60 % of ensemble member pairs have the same sign as the mean differences.



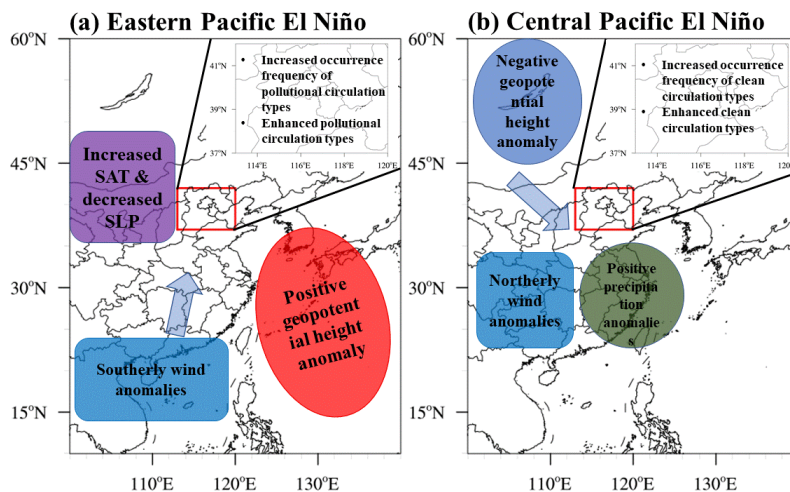
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**Figure 7:** Box-and-whisker plots of anomalies of (a, b) temperature at 2 meter (unit: K) and (c, d) meridional wind at 10 meter (unit:  $\text{m s}^{-1}$ ) over JJJ region under eight circulation types for different types of El Niño years. The blue and red lines represent the clean and pollution circulation types, respectively. Each box-and-whisker consists of the 25th quantile (the upper border of box), median (horizontal line in the middle of box), 75th quantile (the lower border of box) and extremums (the endpoints of whiskers).

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755 **Figure 8:** Schematic diagrams showing the physical mechanisms of effects of (a) Eastern Pacific and (b) Central Pacific El Niño on WHD in JJJ region.