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Key Points:
- On the long-term timescale, the haze pollution in FWP had an overall upward trend and became more serious after 2000.
- On the interannual timescale, EU pattern had the most obvious influence on haze pollution among several atmospheric circulations.
- The impact of EU pattern on visibility through the meteorological conditions mainly caused by two possible pathways.

Supporting Information:
- Supporting Information S1

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Abstract During the past few years, air pollution in the Fenwei Plain (FWP) region had obviously rebounded. In this study, we used quantitative analysis, difference analysis, and correlation analysis methods to analyze the temporal and spatial distribution and the influence of the meteorological and climatic factors on haze pollution in FWP. The results showed that on the long-term timescale, the haze pollution had an overall upward trend during the winter of 1984–2017, and the pollution became more serious after 2000. In addition, the differences in meteorological parameters such as relative humidity, sea level pressure, temperature, vertical velocity, and wind fields near the surface between the regional haze days and the regional clean days were remarkable, indicating that the changes in these meteorological parameters had a distinct impact on haze pollution. Among several atmospheric circulations in the Northern Hemisphere mid-high latitudes, Eurasian (EU) pattern had the most obvious influence on haze pollution via two possible pathways: First, on the interannual timescale, the evolution of EU pattern affected the changes of Siberian high and Aleutian low pressure; second, changes in EU pattern could result in changes in wind speed at 850 hPa, boundary layer height and relative humidity in the lower troposphere. All these findings may provide some help for the government to take prevention measures for haze pollution in FWP.

1. Introductions

With the rapid development of society and economy, the problem of environmental pollution has become increasingly prominent (Sun et al., 2016). In January 2013, more than 8 million population in eastern China suffered a serious haze pollution event, which caused great adverse effects on human daily life and health (Wang et al., 2013, 2014; Zhang et al., 2014). Since then, the Chinese government has adopted a series of measures to prevention and control the air pollution to improve the air quality in Beijing-Tianjin-Hebei (BTH), the Pearl River Delta (PRD), and other regions (Chen & Wang, 2015; Jiang et al., 2018; Meng et al., 2018). However, air pollution in the Fenwei Plain (FWP) region has rebounded, and many pollution indicators have increased instead, especially in autumn and winter (Yang et al., 2018). Compared to the traditional four major polluted regions in China, that is, BTH, PRD, the Yangtze River Delta (YRD), and Sichuan Basin (SCB), where the NO2 column concentration had decreased since 2011, the SO2 column concentration had increased from 2013 to 2016 in FWP instead. Moreover, the SO2 column concentration in FWP has surpassed the above four areas after 2014 (Wei et al., 2018). The PM2.5 concentration in FWP increased year by year from 2015 to 2017, especially during the annual heating period (November–March of the next year), the increase of PM2.5 concentration was the most evident (Huang et al., 2019). In 2017, the average annual concentration of PM2.5 has reached 68 μg m−3, making FWP one of the most polluted areas in China (Yang et al., 2018). In addition, the tropospheric NO2 column concentrations of most urban in FWP reached the maximum in 2017 (Zhang et al., 2019). At the National Environmental Protection Work Conference in 2018, the PRD was withdrew from the key prevention and control regions due to three consecutive years of air quality compliance and FWP replaced the PRD for the first time in the national air pollution prevention and control key regions, and the problem of haze pollution control in FWP was first put on the agenda (Yang et al., 2018). FWP is located at the junction of Shaanxi, Shanxi, and Henan provinces, northwest of China, mainly including the Fenhe Plain, the Weihe Plain, and its surrounding terraces in the Yellow River Basin. FWP has a long
and narrow terrain and many mountains, distributing in the northeast-southwest direction. It is the fourth largest plain in China and the largest alluvial plain in the middle reaches of the Yellow River. Figure 1 shows the region and topography of FWP, including 11 cities such as Xi’an, Taiyuan, Xianyang, Yuncheng, Weinan, Linfen, and Luoyang. Owing to its coal dominated energy structure, heavy highway transportation, and large population density, the pollutant emissions in FWP are large. In addition, its special topographic conditions are not conducive to the spread and diffusion of pollutants (Li et al., 2019). All above are important contributors affecting the haze pollution in FWP.

Many studies have shown that haze pollution is closely related to changes in atmospheric pollutant concentrations, which are not only directly affected by emissions (Dang & Liao, 2019; Fu et al., 2013) but also by local meteorological conditions (Chen et al., 2019; Wang H. et al., 2019; Wu, 2012; Zhang et al., 2015). For example, temperature, relative humidity, and boundary layer height can affect the generation and conversion of aerosols and PM$_{2.5}$ (Li et al., 2014, 2017; Liu et al., 2019). Wind, sea level pressure, and other conditions, such as the synoptic flow patterns and boundary layer process, can affect the dilution, transmission, and diffusion of pollutants (Li et al., 2016; Ye et al., 2016), and large-scale circulation and local circulation are also important for the transportation of pollutants (Hao et al., 2018; Silcox et al., 2012). However, we are not sure which atmospheric circulation or teleconnection in the Northern Hemisphere mid-high latitudes affect FWP haze pollution and how local meteorological conditions affect haze pollution are not well explained to our limited knowledge.

The purpose of study concludes three aspects: first, characterizing the haze pollution of FWP by quantitative analysis; second, exploring the influence on haze pollution of local meteorological conditions by the difference analysis between the regional haze days and the regional clean days; and third, examining the relationship between the possible atmospheric circulation and winter haze pollution by the correlation analysis and studying possible physical mechanisms to illustrate the impact of atmospheric circulation on the haze pollution of FWP. Generally, this study may provide some help for the prediction of haze pollution in FWP and provide some scientific reference and decision support for the specific prevention measures required by the government to “Three-year plan of action for winning the war to protect blue skies.”

2. Data and Methods

2.1. Observation Data

The daily observation data are the gauge data from the Global Summary of Day (GSOD) from the National Climatic Data Center (NCDC). This data set includes daily mean visibility (VIS), sea level pressure (SLP), temperature (TEMP), dew-point temperature (DEWP), wind speed (WS), and other meteorological...
phenomena as well as fog, rain or drizzle, snow or ice pellets, hail, and other extreme weather. We calculated the surface relative humidity (RH) based on TEMP and DEWP according to the following formula (Bolton, 1980):

\[ RH = \frac{e}{E} \times 100\% \quad (1) \]

where \( E \) is the saturated vapor pressure in hPa and \( e \) is the actual vapor pressure in hPa; they are calculated as follows:

\[ e = E_0 \exp \left( \frac{a_T D}{T + b} \right) \quad (2) \]

\[ E = E_0 \exp \left( \frac{a_T}{T + b} \right) \quad (3) \]

where \( E_0 = 6.112 \), \( a = 17.67 \), \( b = 243.5 \), \( T \) is TEMP, and \( T_D \) is DEWP.

In order to ensure the integrity of the data during the wintertime for 1984–2017, 334 ground surface gauge stations are selected in China, including six effective stations in FWP (supporting information Table S1).

In this study, the haze day (HD) is defined as VIS < 10 km and RH < 90%, which excludes the extreme weather such as fog, rain, snow, and hail (Wu et al., 2014). The mean number of haze days (\( \text{NHD} \)) of each winter in FWP can be calculated by the following formula:

\[ \text{NHD} = \frac{1}{n} \sum_{i=1}^{n} N_i \quad (4) \]

where \( n \) is the number of stations (\( n = 6 \)); \( N \) is the number of haze days in a station in each winter. The mean visibility (\( \text{VIS} \)) of each winter in FWP can be calculated by

\[ \text{VIS} = \frac{1}{n} \sum_{i=1}^{n} \left( \frac{1}{m} \sum_{j=1}^{m} V_{ij} \right) \quad (5) \]

where \( n \) is the number of stations (\( n = 6 \)), \( m \) is the number of valid days in each winter.

During 1984–2017, the relative larger number of haze days occurs in January, February, November, and December in FWP (Figure S1); therefore, we define the wintertime in our study as November, December, and the following year’s January and February. For example, the winter consists of November and December in 1990, and January and February in 1991.

2.2. Reanalysis Data

2.3. NCEP/NCAR Reanalysis Data

The global NCEP/NCAR reanalysis data of monthly SLP, zonal and meridional winds at 850 hPa (UV850), and geopotential height field at 500 hPa (H500) from November 1984 to February 2018 are used to discuss the high-frequency correlation between visibility and atmospheric circulation index as well as meteorological parameters. Moreover, the daily SLP, vertical velocity (\( \Omega \)), RH, H500, and surface temperature (\( T_s \)) are used to discuss the differences between the regional haze days and the regional clean days in FWP. The spatial resolution of NCEP/NCAR reanalysis data is 2.5° × 2.5° (Kalnay et al., 1996).

2.4. ERA-5 Reanalysis Data

In order to study the relationship between the boundary layer height (BLH), RH of the lower troposphere and the visibility, ERA-5 reanalysis data of the monthly RH from 1,000 to 500 hPa (16 pressure levels) and BLH are used. The spatial resolution of ERA-5 reanalysis data is 0.25° × 0.25° (Copernicus Climate Change Service, 2017).

2.5. Atmospheric Circulation Index Data

In this study, the data of the Northern Hemisphere teleconnection patterns, including Arctic Oscillation (AO) index, North Atlantic Oscillation (NAO) index, East Atlantic pattern (EA) index, East
Atlantic-Western Russia pattern (EAWR) index, East Pacific-North Pacific pattern (EPNP) index, and Polar-Eurasian pattern (PEU) index are collected from the Climate Prediction Center of the National Oceanic and Atmospheric Administration (NOAA). The Eurasian pattern (EU) index is calculated by the following formula (Wallace & Gutzler, 1981):

$$I_{EU} = -\frac{1}{4}Z^* (55°N, 20°E) + \frac{1}{2}Z^* (55°N, 75°E) - \frac{1}{4}Z^* (40°N, 145°E)$$

where $Z^*$ represented the normalized monthly mean H500.

2.6. Analysis Method

Some common statistical methods are used in this study, including composite analysis, Pearson correlation analysis with two-tailed Student’s t test. In addition, in order to examine the stability of two time series on an interannual variation timescale, we need to remove the effects of long-term trends, which are affected by anthropogenic emissions, global warming, and so on. Here we use high-pass filtered method (Gong & Luterbacher, 2008) to obtain the high-frequency (<10 years) correlation of two time series, representing the interannual correlation (Zhang et al., 2016).

3. Results and Discussions

3.1. The Temporal and Spatial Distribution Characteristics of Winter Haze Pollution in FWP

The spatial distribution of winter mean visibility in 1984–2017 was shown in Figure 1a. During the past 34 years, the stations with lower visibility were mainly concentrated in central and eastern China, northern China, southern China, and northeastern China. FWP was marked with shadow, and its mean visibility (10.8 km) was significantly lower than the national mean (17.9 km), indicating that the haze pollution in FWP was severe. The mean visibility over the areas to the northwest of FWP (northern Shaanxi, Ningxia, Gansu, and western Inner Mongolia) was significantly higher than the southeast counterpart (southern Henan, Hubei, and Anhui). In general, the mean visibility in central China was gradually increasing in the southeast-northwest direction (Figure 1a). However, over FWP the mean visibility of the northwestern stations (Wusu, Jixiu, and Xianyang) was lower than that of southeastern counterpart (Yuncheng, Mengjin, and Lushi), which was contrary to the distribution in central China. The reason of this phenomenon may be attributed to the topography around FWP.

FWP is surrounded by the Weihe Plain to the northeast, Taihang Mountain to the east, and the Lvliang Mountain to the west. Moreover, the Weihe Plain is bordered by the Loess Plateau to the north and the Qinling Mountains to the south (Figure 1b). This special topography makes Wusu, Jixiu, Xianyang, and Yuncheng locate in a closed and narrow basin, coupled with the large consumption of coal and the large amount of transportation, causing the pollutants in these areas not only more but also difficult to spread. However, Lushi and Mengjin are located at the junction of the North China Plain and FWP, the pollutants of this area are easier to spread, so the mean visibility is higher than the above four stations.

Figure 2 presented the temporal variation of raw data and high-frequency filtered data of the winter $\nabla VIS$ and $\nabla NHD$ in FWP during the period of 1984–2017. The winter $\nabla VIS$ showed a downward trend ($−1.6$ km decade$^{-1}$) from 1984 to 2017, while $\nabla NHD$ showed an upward trend ($13.0$ day decade$^{-1}$) (Figure 2a). The correlation coefficient between winter $\nabla VIS$ and $\nabla NHD$ reached $−0.88$ ($p < 0.01$). Specifically, $\nabla VIS$ increased and $\nabla NHD$ decreased in 1985 compared to 1984. During the period of 1985–1989, the winter $\nabla VIS$ decreased significantly ($−9.4$ km decade$^{-1}$, $p < 0.01$) and $\nabla NHD$ increased significantly (16 day decade$^{-1}$, $p < 0.05$). However, there were no obvious changes in the 1990s. After 2000, $\nabla VIS$ decreased significantly ($−1.9$ km decade$^{-1}$, $p < 0.01$) and $\nabla NHD$ increased more significantly (22 day decade$^{-1}$, $p < 0.01$) compared to the period of 1985–1989. In summary, the winter haze pollution had been more aggravated with the rapid development of FWP. Compared to the period of 1984–1999, the haze pollution in the period of 2000–2017 winter was quite serious.

The fluctuations of $\nabla VIS$ and $\nabla NHD$ were intense on an interannual timescale, and they had a significant ($p < 0.01$) negative correlation with a high-frequency (<10 years) correlation coefficient of $−0.48$ (Figure 2b). Some studies have shown that the decline in visibility is mainly due to the increase of
atmospheric pollutants and changes in local meteorological parameters (Deng et al., 2011; Han et al., 2013; Xue et al., 2015). On the one hand, the increase of the atmospheric pollutants can increase aerosol optical thickness, which can enhance the scattering and absorption to sunlight resulting in decrease in visibility (Bäumer et al., 2008; Xu et al., 2017). On the other hand, changes in local meteorological parameters, such as WS, RH, and Ts, can affect the generation, transmission, and spread of pollutants and thus affect the visibility (Wang H. et al., 2019). Therefore, in the next section, we mainly analyze the differences in meteorological parameters between the regional haze days and the regional clean days in FWP.

3.2. Differences of the Meteorological Parameters Between the Regional Haze Days and Regional Clean Days in FWP

Table 1 presented the number of haze days for each station in different periods in FWP. During 1984–2017 (Period 1), there were three stations with an average number of winter haze day exceeding 40 (more than one third of total days). Therefore, we defined a regional haze day if there were more than three stations with haze day simultaneously in someday. Similarly, if there were more than three stations with visibility >10 km in someday, it was recorded as a regional clean day. Comparing the Period 2 (1984–1999) and Period 3 (2000–2017), we found that the average number of haze days of each station after 2000 was

| Station | Period 1 Mean | Period 1 Std | Period 2 Mean | Period 2 Std | Period 3 Mean | Period 3 Std | Difference |
|---------|--------------|--------------|--------------|--------------|--------------|--------------|------------|
| Wusu    | 59           | 16           | 46           | 10           | 71           | 11           | −25**      |
| Jiexiu  | 41           | 24           | 32           | 8            | 48           | 30           | −16**      |
| Yuncheng| 33           | 22           | 24           | 11           | 42           | 24           | −18**      |
| Xianyang| 57           | 25           | 38           | 12           | 74           | 20           | −36**      |
| Lushi   | 23           | 12           | 12           | 4            | 32           | 8            | −20**      |
| Mengjin | 18           | 9            | 12           | 6            | 24           | 7            | −12**      |

Note. Period 1: 1984–2017. Period 2: 1984–1999. Period 3: 2000–2017. Difference = Period 2 − Period 3. Significant at 95% confidence level. Significant at 99% confidence level.
significantly higher than that before 2000. In addition, the average number of haze days of Wusu, Jiexiu, Yuncheng, and Xianyang in the northwestern of FWP was higher than Lushi and Mengjin, which was consistent with the discussion of Section 3.1.

Based on the above definition of regional haze (clean) day, the winter regional haze (clean) days of FWP were obtained (Figure S2). It could be found that the regional haze days had an overall upward trend, which was significant ($p < 0.01$) especially after 2000. However, the regional clean days had an overall downward trend and fallen to zero after the winter of 2016. In order to examine whether there were significant differences in meteorological parameters between the regional haze days and the regional clean days, we should select the same number of the regional haze days and the regional clean days. Finally, 475 pairs of regional haze/clean days were selected in FWP during the wintertime of 1984–2017.

The surface RH and Ts of the regional haze days in FWP were significantly higher than those of the regional clean day (Figures 3a and 3b). Higher RH and Ts were conducive to maintaining aerosols at higher levels (Xu et al., 2015). During the winter haze days in FWP, increase of RH contributed to the hygroscopic growth of aerosols, which could increase the extinction coefficient and result in decrease in visibility (Wei et al., 2014). On the other hand, the higher Ts contributed to enhance the secondary conversion of the aerosol, which could aggravate the haze pollution (Lin et al., 2009). Furthermore, the absorption of solar radiation by black carbon aerosols could further increase the temperature (Chen & Wang, 2015; Ding et al., 2018). In addition, during the regional haze days, SLP in FWP even over the entire Chinese mainland (except for northeastern China) decreased significantly (Figure 3c), indicating that the weakening of the continental high made the isobars sparse and resulted in a decrease in the pressure gradient force. Essentially, it illustrated the weakening of the difference between ocean and land heat and thus reduced winter surface WS in FWP (Figure 4b). The weakening of surface WS was not conducive to the transmission and diffusion of atmospheric pollutants, resulting in reduced visibility (Liu et al., 2018).

Figure 3d showed that $\Omega$ in FWP reduced significantly during the regional haze days, implying the weakening of atmospheric motion in the vertical direction. During the wintertime, the cold air activity in FWP was frequent, and the decrease of $\Omega$ indicated that the sinking motion of the cold air became weaker, weakening the air exchange capacity and leading to the high-altitude clean air difficult to reach the ground (Sun et al., 2017). We also found that there was a significant decrease in BLH in FWP (Figure S3), which might limit the diffusion of air pollutants in the vertical direction, associated with weaker turbulence (Wang L. et al., 2019). These conditions resulted in the accumulation of pollutants in FWP and worsened the visibility.

During the winter of 1984–2017, FWP was located at the center of the anticyclone and mainly controlled by high pressure. The northwest wind was dominated (Figure 4a). From Figure 4b, surface WS during the regional haze days in FWP was significantly lower than that in the regional clean days. In addition, the southeast wind bias during the regional haze days was related to the weakening of westerly winds and the enhancement of southerly winds by the latitudinal and meridional analysis (Figures 4c and 4d).

The haze pollution over regions to the southeastern of FWP (southern Henan, Hubei, and Anhui) was significantly higher than FWP (Figure 1a). Therefore, the abnormal southeast wind bias might lead pollutants from the southeastern of FWP to transport to FWP. In general, the weakening of the westerly winds made it difficult for pollutants dispersion, and the strengthening of the southerly winds could bring more pollutants, together making the haze pollution in FWP serious during the winter.

### 3.3. The Relationship Between Atmospheric Circulations and Haze Pollution in FWP

Table 2 showed the correlation coefficients between $\mathbf{VIS}$ and $\mathbf{NHD}$ and some common atmospheric teleconnection or oscillation indices of the Northern Hemisphere, including AO, NAO, EA pattern, EAWR pattern, EU pattern, EPNP pattern, and PEU pattern. According to the raw correlations ($R_1$), the relationships between the PEU pattern and $\mathbf{VIS}$ and $\mathbf{NHD}$ were closer. In addition, the $R_1$ between EAWR index and $\mathbf{NHD}$ was large but lower than that of PEU index. On the other hand, the high-frequency correlations ($R_2$) showed EU index and EAWR index were better in interannual correlation with $\mathbf{VIS}$ and $\mathbf{NHD}$, and the EPNP index only correlated well with $\mathbf{VIS}$. These better correlations were significant at 95% or 99% confidence level, indicating that these atmospheric circulations might have an impact on the haze pollution in FWP. The correlation of two time series might be affected by long-term variations. For example, the PEU pattern, which was mainly associated with above-average temperatures in eastern Siberia and
below-average temperatures in eastern China, could essentially exhibit strong low-frequency variability; thus, the R1 was significantly ($p < 0.01$) higher, and the R2 was lower between the PEU index and VIS and NHD.

It should be noted that the long-term changes in haze pollution are mainly controlled by pollutant emissions (Zhang et al., 2019); therefore, exploring the influence of climatic factors in long-term changes of haze pollution was complicated. In this study, we focused on the influence of climatic factors on haze pollution on an interannual timescale. The indicators of haze pollution included VIS and NHD, and only the atmospheric circulations significantly correlated with both indicators were considered, so the influence of EU pattern and EAWR pattern on haze pollution would be discussed later.

Previous studies had shown that the traditional EU pattern, Scandinavian (SCAND) pattern (or Eurasia-1 pattern), and EAWR pattern (or Eurasia-2 pattern) were three important teleconnection patterns affecting the Eurasia (Gao et al., 2017). EAWR pattern was originally identified through an orthogonally rotated principal component analysis applied to the monthly mean geopotential height at 700 hPa and consisted of four main anomaly centers. The positive phase was associated with positive height anomalies located over Europe and northern China, and negative height anomalies located over the central North Atlantic and north of the Caspian Sea (Barnston & Livezey, 1987; Ionita, 2014). However, the traditional EU pattern, first identified by Wallace and Gutzler, was more dominant on winter mean field and could significantly impact the climate of Eurasia, especially in East Asia (Liu et al., 2014; Wallace & Gutzler, 1981).

The significant high-frequency correlations between VIS and EU index ($R = 0.70$) and the EAWR index ($R = -0.43$) indicated that the relationship between EU pattern and haze pollution in the interannual variability was closer than the EAWR pattern. As shown in Figure 5, compared with the interannual variation of the EAWR index, the interannual variation of EU index was more similar with visibility. Except for some

Figure 3. The difference of the surface (a) RH, (b) Ts, (c) SLP, and (d) absolute value of $\Omega$ between the regional haze days and the regional clean days in FWP. The shaded part is FWP, and areas significant at the 0.05 level are dotted. The data are from NCEP/NCAR reanalysis.
Figure 4. (a) The average surface wind fields in the wintertime for 1984–2017. The difference of the surface (b) wind speed (the wind vectors are compounded based on the difference of the meridional and zonal winds), (c) zonal wind speed, and (d) meridional wind speed between the regional haze days and the regional clean days in FWP. The shaded part is FWP, and areas significant at the 0.05 level are dotted. The data are from NCEP/NCAR reanalysis.

Table 2
Correlation Coefficients of Visibility and Haze Days and Circulation Indices

|       | AO   | NAO  | EA   | EAWR | EU   | EPNP | PEU  |
|-------|------|------|------|------|------|------|------|
| **VIS** |      |      |      |      |      |      |      |
| R1    | −0.11| −0.19| −0.21| 0.22 | 0.16 | 0.08 | 0.41 |
| R2    | −0.16| 0.03 | −0.19| −0.43*| 0.70*| 0.43 | 0.15 |
| **NHD** |      |      |      |      |      |      |      |
| R1    | 0.05 | 0.15 | 0.15 | −0.40| 0.10 | 0.03 | −0.47*|
| R2    | 0.19 | −0.13| 0.01 | 0.37 | −0.50| −0.07| 0.11 |

Note. VIS: the mean visibility; NHD: the number of haze days; R1: the raw correlations; R2: the high-frequency (<10 years) correlations. Significant at 95% confidence level. **Significant at 99% confidence level.
specific years (such as 1994 and 2011), the increase (decrease) of EU index was accompanied by an increase (decrease) of VIS, which showed that the haze pollution increased (decreased) in FWP in the negative phase (positive phase) of EU pattern, but the specific influence mechanism was needed to be further explored. In addition, because there was a strong negative correlation between VIS and NHD, we only analyzed the interannual relationship of EU pattern and VIS later.

3.4. The Impact Mechanism of EU on Haze Pollution in FWP

Figure 6a showed the difference in H500 field between the regional haze days and the regional clean day, which represented a significant increase of the H500 in the area from FWP to the northeastern Asia. It indicated that the weakening of the East Asian trough in the Northern Hemisphere mid-high latitudes was not conducive to the southward flow of cold air in high latitudes, leading to the weakening of the winter monsoon in FWP and resulting in anomalous southeast winds.

To explore the influence of the formation and development of EU pattern on the haze pollution in FWP, the distribution map of high-frequency correlation filed between H500 and VIS was shown in Figure 6b. Three anomalous centers were located the near Poland (55°N, 20°E), Siberia (55°N, 75°E), and Japan (40°N, 145°E). Obviously, there was a “− + −” wave train pattern from the eastern Europe through Siberia to the northern China-Korean Peninsula-Japan-Northwest Pacific (Zhang et al., 2016). Combined with the significant high-frequency positive correlation ($R = 0.70$) between EU index and VIS, this wave train pattern indicated that the increase in EU index, that is, H500 in Poland and Japan would increase, while H500 in Siberia would decrease. This could lead to the development and evolution of EU pattern, which eventually had an impact on haze pollution in FWP.

Correlation analysis was also applied to examine the specific influence mechanism of EU pattern on haze pollution in FWP. First, we examined the high-frequency correlations among SLP, VIS, and EU index. It could be found that the positive correlation center was principally located in the East Asian continent, while the negative correlation center was principally located in the northeastern of Asia and the northwestern
Paciﬁc (Figure 7a). The increase of SLP in East Asian continent and decrease in northeastern Asia and the northwestern Paciﬁc could increase visibility in FWP, which indicated that the difference in land-ocean thermal force on the lower troposphere in FWP could affect the changes of visibility. The increase of EU index could make the positive correlation center in the East Asian continent expanded and the negative correlation center in the northeastern Asia and the northwestern Paciﬁc contractible (Figure 7c), leading to an increase of the thermal dynamic of the land-ocean pattern in FWP and thus resulting in the visibility increased eventually.

Then, we examined the high-frequency correlations among UV850, VIS, and EU index and found that the lower troposphere in FWP and the northeastern China was dominated by anticyclone and northwest wind. In addition, there was a signiﬁcant positive correlation between winter WS at 850 hPa and VIS in FWP (Figure 7c). This indicated that the increase of WS at 850 hPa could accelerate the horizontal transmission and diffusion of pollutants, which was conducive to the increase of visibility. It could be seen in Figure 7d that EU index was also signiﬁcantly positively correlated with zonal and meridional WS at 850 hPa, indicating that the increase of EU index could enhance the northwest WS in the lower troposphere in FWP, resulting in an increase of visibility eventually.

Finally, we examined the high-frequency correlations among VIS, BLH, and RH of the lower troposphere. Figures 8a and 8b showed VIS of FWP was signiﬁcantly positively correlated with BLH and negatively correlated with the RH of lower troposphere in FWP. This indicated that the decrease of BLH in FWP and the increase of RH were not conducive to increase the visibility in the interannual variation. From Figures 8c and 8d, EU index was significantly positively correlated with the BLH and negatively correlated with the RH of lower troposphere in FWP, respectively. This indicated that the increase of EU index could increase the BLH and RH of the lower troposphere in FWP, which would affect the change in visibility. It was consistent with the signiﬁcantly positive correlation between EU index and VIS, which was obtained from the previous study.

Through the above analysis, we knew that with the change of H500 ﬁeld in Northern Hemisphere mid-high latitudes, the evolution of EU pattern would affect some meteorological factors on the surface or in the lower troposphere in FWP or Eurasia, and the haze pollution would be affected by the changes of these meteorological conditions through two possible pathways in FWP on the interannual timescale during the
wintertime of 1984–2017. One was the indirect influence of SLP, and the other one was the direct influence of UV850, BLH, and RH.

4. Conclusions

During the winter of 1984–2017, VIS and NHD in FWP integrally showed a downward trend and an upward trend, respectively. On the long-term timescale, the haze pollution had a decreasing tendency before 1990, and it was relatively stable in the 1990s. After 2000, the haze pollution had a significantly increasing trend. On the interannual timescale, the changes of the VIS and NHD were fiercely fluctuated.

Comparing with the regional clean days, there were obvious differences in SLP, Ts, RH, and Ω near the surface in FWP during the regional haze days. The reduction of SLP and Ω and the increase of Ts and RH had a certain impact on formation, transmission, and diffusion of atmospheric pollutants, which affected the haze pollution in FWP. In addition, during the regional haze days, the southeast wind anomaly could be seen in
the near ground. This phenomenon might indicate the pollutants in the areas of the southern Henan, Hubei, and Anhui, which are located to the southeast of FWP, could spread into FWP through anomaly southeast winds. Regional transportation could worsen haze pollution in FWP.

From the high-frequency correlation analysis, we found that EU pattern had a great impact on the haze pollution of FWP via two possible pathways in the interannual variations. First, EU pattern affected the changes of the SLP in the Siberian and the Aleutian, which indirectly affected the visibility of FWP through the difference in ocean-atmosphere thermal force in the lower troposphere. Second, the increase of EU index, which meant that the increase of the H500 in Poland and Japan and the decrease of the H500 in Siberia, might directly lead to the increase of the winter WS at 850 hPa and BLH and the decrease of the RH in the lower troposphere in FWP. Importantly, these findings could provide some help for the government to take prevention measures for haze pollution in FWP.

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