Quasi-weekly oscillation of regional $PM_{2.5}$ transport over China driven by the synoptic-scale disturbance of East Asian Winter Monsoon circulation

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Abstract: The regional $PM_{2.5}$ transport is one of the important causes for atmospheric environment change. However, the variations of regional $PM_{2.5}$ transport in synoptic scale with meteorological drivers have been incomprehensively understood. Therefore, this study is targeted at the quasi-weekly oscillation (QWO) of regional $PM_{2.5}$ transport over central and eastern China (CEC) with the influence of synoptic-scale disturbance of the East Asian Winter Monsoon (EAWM) circulation. By constructing the data of daily $PM_{2.5}$ transport flux in CEC in the winters of 2015-2019, we utilize the extended empirical orthogonal function (EEOF) decomposition and other statistical methods to extract the moving spatial distribution of regional $PM_{2.5}$ transport over CEC, recognizing the QWO in regional $PM_{2.5}$ transport with the spatial-temporal variations over CEC. The source-acceptor relationship in regional transport of $PM_{2.5}$ is identified with the 2-d lag effect of the North China Plain, as the upwind source region, on the $PM_{2.5}$ pollution change in the Twain-Hu Basin, as the downwind receptor region in central China. The QWO of regional $PM_{2.5}$ transport over CEC is regulated by the synoptic-scale disturbance of the EAWM circulation with the periodic activities of Siberian high. These findings could provide new insight into the

understanding of regional $PM_{2.5}$ transport with source-receptor relationship and the meteorological mechanism in atmospheric environment change.

Key words: regional $PM_{2.5}$ transport, quasi-weekly oscillation, source-receptor relationship, extended empirical orthogonal function (EEOF)

1 Introduction

$PM_{2.5}$ pollution has attracted worldwide attention due to its adverse impact on the environment and human health (Fan et al., 2016; Geng et al., 2021; Lin et al., 2018). The $PM_{2.5}$ pollution in the cold season has become one of the major atmospheric environmental problems in China (An et al, 2019; ~~X.~~ Huang et al, 2020b). The high-concentration $PM_{2.5}$ tends to occur with extensive spatiotemporal coverage (Tao et al, 2016; Zhang et al, 2019), and synthetic physical-chemical processes caused such heavy $PM_{2.5}$ pollution events (Ding et al, 2017; Quan et al., 2020), including emissions (Liu et al, 2016; Zheng et al, 2018a), chemical formation (Huang et al, 2014; Nie et al, 2014), atmospheric boundary layer processes (Huang et al, 2018; Zhong et al, 2019), localized circulation (Miao et al, 2015; Shu et al, 2021; Zheng et al, 2018b), as well as weather and climate (Cai et al, 2017; Wu et al, 2016). The interactions among these physical and chemical processes make it more challenging to comprehend the severe haze formation, which serves as one of the major difficulties in forecasting and controlling atmospheric environment change and heavy air pollution (Zhang et al., 2012; Zhang et al., 2019).

$PM_{2.5}$ is featured with complex spatiotemporal changes on multiscale (Georgoulias and Kourtidis, 2012; Wu et al, 2021). $PM_{2.5}$ oscillates periodically at multi-time scales, and the periodic oscillation of atmospheric circulation is the leading cause of the cyclical variations of $PM_{2.5}$ (Chen et al, 2020; Dong et al, 2021; Fu et al, 2020; Perrone et al, 2018). To be specific, the 1-d periodic change or diurnal variation of near-surface $PM_{2.5}$ concentrations is mainly attributed to the atmospheric boundary layer process and localized circulation (Miao et al, 2019); the periodic change of around 7 days may be controlled by the fluctuation of the long-wave trough in middle and high latitudes (Guo et al, 2014); the oscillating cycle of about 14 days is closely related to the quasi-biweekly oscillation of the synoptic circulation (Gao et al, 2020; Zhao et al, 2019); and the 30-60-d intra-seasonal oscillation is mainly caused by the impact of monsoon circulation change (Xu et al, 2014; Zhang et al, 2019). Comprehensively revealing the interaction between $PM_{2.5}$ and meteorology at different time scales is essential for solving air pollution problems more effectively (Bäumer and Vogel, 2007; Wang et al, 2020). Previous studies mainly focused on the multiscale periodic variation of atmospheric pollutants in a certain region or local area, have not yet found on the $PM_{2.5}$ trans-regional and periodic oscillation in the large area of central and eastern China (CEC).

East Asian Winter Monsoon (EAWM) is one of the most active atmospheric circulation system in the cold season over the Northern Hemisphere (Ding et al, 2017; Wu and Wang, 2002), which is also a critical leading factor for the variation of wintertime air pollution in CEC (Chin, 2012; Li et al, 2016). Being the major circulation system of EAWM, the Siberian High dominates the cold seasons, acting as a particular driver of cold airflows, so having an important impact on the wintertime atmospheric environment in CEC (An et al, 2019; Shen et al, 2021, 2022; Wu et al, 2016). The rapid southward advance of cold air with strong Siberian High can effectively drive the regional transport of air pollutants with less accumulations across CEC, while the weak Siberian High with the slow southward movement of cold air can particularly favorable for the transport of air pollutants from the northern source regions to southern receptor region over CEC (Hou et al., 2020; Zhang et al., 2016). When the position of Siberian High is more eastern than normal, the transport of air pollutants from northern China to the south is weakened, and the aggravation of pollution is enhanced in northern China (Jia et al., 2015). Regional pollutant transport driven by the southward movement of a cold front with the Siberian High would exacerbate the air quality in the corresponding receptor regions (Kang et al., 2019; Hu et al., 2021; Shen et al, 2022). The characteristics of atmospheric circulation anomalies favoring heavy haze pollution in China have changed in recent years, and the leading formation mechanism of severe haze has been shifting from local accumulation to regional transport processes in eastern China (Y. Yang et al, 2021b). Therefore, studying the influence of EAWM circulation system on regional pollutant transport over CEC is an important issue in atmospheric environment changes (Bai et al, 2021, 2022; Ge et al, 2018; Merrill and Kim, 2004; Tan et al, 2021; W. Yang, et al, 2021a).

Previous studies have primarily focused on the relationship between atmospheric intraseasonal oscillations in the mid-to-high latitudes of the Eurasian region and the persistent $PM_{2.5}$ pollution (An et al., 2022; Gao et al., 2020; Li et al., 2021; Liu et al., 2022; Wu et al., 2023;

Yang et al., 2024b). $PM_{2.5}$ concentration anomalies in North China exhibit significant lifetimes of 10–30 days, with anticyclonic anomalies and related meteorological conditions (e.g., surface air temperature, boundary layer height) in Northeast Asia influencing local $PM_{2.5}$ accumulation and hygroscopic growth (An et al., 2022; Yang et al., 2024b). These studies have investigated the quasi-biweekly lifecycle of persistent $PM_{2.5}$ pollution events in North China through phase synthesis methods (Gao et al., 2020; Wu et al., 2023; Yang et al., 2024b). However, there remains a lack of systematic studies on the synoptic-scale oscillation of regional $PM_{2.5}$ transport.

The “harbor” effect on the eastern lee of the Tibetan Plateau’s large topography on the westerlies is possibly an important factor influencing the regional distribution of $PM_{2.5}$ pollution in CEC with weak horizontal winds and sinking motion in the lower troposphere, which exacerbates the environmental impacts of local air pollutant emissions establishing a "susceptibility zone" in this region (Xu et al., 2016; Zhu et al, 2018). Anticyclones and cyclones alternatively affect the region on a time scale of 3-7 days, resulting in periodic air pollution in cities (Guo et al., 2014). Thus, the weather system in the CEC is basically characterized by periodic changes and the cold air in winter with EAWM oscillates in quasi-weekly periods (Wu and Wang, 2002; Wu et al., 2016). However, the influence of the synoptic-scale disturbance of the EAWM on regional $PM_{2.5}$ transport over CEC is not yet clear. Responding to this problem, this study aims to reveal from a new perspective the quasi-weekly oscillation (QWO) of regional $PM_{2.5}$ transport over CEC affected by EAWM and its underlying mechanism with the synoptic-scale oscillation of the EAWM circulation. This study could ~~be beneficial to~~ deepen the understanding of regional $PM_{2.5}$ transport, its source-receptor relationship and meteorological mechanism in the atmospheric environment changes, and provide scientific evidence for air pollution forecast, early warning and coordinated control.

2 Data and methods

2.1 Environmental and meteorological data

The daily dataset of $PM_{2.5}$ concentrations selected for this study was from China National Environmental Monitoring Center (http://datacenter.mee.gov.cn/), including daily $PM_{2.5}$ concentrations from 1079 air quality monitoring stations in CEC during the winters

(December-February) of 2015-2019.

Meteorological data were selected out of the NCEP/NCAR global reanalysis daily data (https://psl.noaa.gov/data/gridded/tables/daily.html) with a grid resolution of 2.5 °×2.5 ° for the large-scale circulation analysis. It is composed of the daily sea level pressure (SLP), air temperature at 1000 hPa, and the U- and V-components of wind at 1000 hPa during the winters of 2015–2019.

In addition, the ERA5-land high-resolution reanalysis hourly dataset (https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-land?tab=form) with spatial resolution of 0.1 °×0.1 ° was selected for the calculation of transport flux (TF) of $PM_{2.5}$ in CEC. The U- and V-components of the 10-m wind over CEC were obtained at 00, 06, 12, and 18 UTC daily during the winter (December-February) of 2015-2019. In order to match the resolution of $PM_{2.5}$ daily data, the ERA5-Land high-resolution 10-m wind was processed into daily average data.

2.2 $PM_{2.5}$ TF and its divergence

In order to quantitatively characterize the horizontal transport direction and intensity of $PM_{2.5}$ as well as convergence or divergence during regional $PM_{2.5}$ transport, we introduced the concepts of $PM_{2.5}$ TF and divergence of $PM_{2.5}$ TF. Generally, there are two types of TF: horizontal and vertical. This study only addresses the near-surface horizontal $PM_{2.5}$ TF. The horizontal $PM_{2.5}$ TF is defined as the $PM_{2.5}$ mass ~~concentrations~~ passing through the unit area in unit time (unit: μg m^{-2} s^{-1}), expressed as the product of wind vector and $PM_{2.5}$ concentration (Liu et al., 2019; Ma et al., 2021), and its vector points to the same direction as the horizontal wind. The zonal component (F_u) and meridional component (F_v) of $PM_{2.5}$ TF vector (TFV) and the magnitude (TFM) are calculated as follows:

$$F_u = C\,u \tag{1}$$

$$F_v = C\,v \tag{2}$$

$$TFV = F_u\,i + F_v\,j \tag{3}$$

$$TFM = \sqrt{F_u^2 + F_v^2} \tag{4}$$

where C is the surface $PM_{2.5}$ concentration, u and v are the zonal and meridional components of the 10-m wind speed, respectively.

Firstly, the U- and V-components of ERA5-Land high-resolution 10-m wind are interpolated to 1079 stations of environmental measurements in CEC for calculations of near-surface $PM_{2.5}$ TF in this study. Then, the daily $PM_{2.5}$ TF of the 1079 stations for the winters from 2015 to 2019 are calculated according to the calculation by Formulas (1)–(4).

The divergence of $PM_{2.5}$ TF can be an indicator for the $PM_{2.5}$ budget. When positive divergence occurs, the air pollutants were net outflow from the domain region, and vice versa (Wang et al., 2021). The divergence of horizontal $PM_{2.5}$ TF near the surface is calculated as follows (Wang et al., 2021):

$$D = \frac{\partial F_u}{\partial x} + \frac{\partial F_v}{\partial y} \quad (5)$$

where D is the horizontal $PM_{2.5}$ TF divergence, unit: μg m^{-3} s^{-1}. If D is positive (negative), it indicates divergence (convergence) of $PM_{2.5}$ TF.

In the i and j grids, the expression of Formula (5) for the differential calculation with grid spacing to be d is

$$D = \frac{Fu_{i+1,j} - Fu_{i-1,j} + Fv_{i,j+1} - Fv_{i,j-1}}{2d} \quad (6)$$

When calculating the horizontal divergence of transport $PM_{2.5}$ flux, it is necessary to interpolate the station data of zonal and meridional components (F_u, F_v) of $PM_{2.5}$ TFV to grid spacing with 0.25 by 0.25 degree in longitude and latitude in CEC and then calculate the divergence of $PM_{2.5}$ TF at each grid point according to Formula (6).

2.3 Butterworth filter

Atmospheric motion encompasses a variety of temporal and spatial scales. The sequences of meteorological variables often contain complex periodic components and exhibit multi-time-scale variations, including daily, weekly, seasonal, and interannual variations. Numerous observations have found QWO with periods of less than 10 days across various meteorological elements in the EAWM system (Compo et al., 1999; Murakami, 1979; Wu and Wang, 2002). Synoptic-scale atmospheric variations are closely related to atmospheric longwave adjustments, with QWO periods of 4-7 days observed in cold air activities of the EAWM (Bai et al., 2022; Wu and Wang, 2002). The synoptic-scale disturbance regulates the generation, transport, and removal of $PM_{2.5}$ in air pollution, which is a key mechanism behind the 4-7 day periodic changes in $PM_{2.5}$ in CEC during the periods of EAWM (Guo et al., 2014; Liu et al., 2018; Quan et al., 2014, 2020). Based on the research objectives, identifying the desired periodic components from the original observational sequences is referred to as sequence filtering. In this study, we employed a Butterworth filter to extract QWO from observational data.

The Butterworth filter is commonly used to separate atmospheric periodic variations across specific frequency bands. Due to its smooth amplitude response, linear phase characteristics, and ease of implementation, Butterworth filter has been widely applied in climate and meteorological studies (Gouirand et al., 2012; Yang et al., 2024a). The Butterworth filter can be configured as a low-pass, high-pass, or band-pass filter, depending on the specific requirements. A band-pass filtering only allows signals within a defined frequency range to pass through with attenuating signals outside the defined frequency range. It is often employed to extract and analyze signals within specific frequency bands, such as particular weather patterns and climate cycles. In this study, to investigate the QWO (8-d) of regional $PM_{2.5}$ transport over the CEC under the influence of EAWM circulations in the synoptic scale, we applied Butterworth band-pass filtering to the daily TFM of $PM_{2.5}$ change and daily SLP anomalies during the winters of 2015-2019 for identifying at the quasi-weekly (6-9 days) synoptic-scale component of regional transport of $PM_{2.5}$ over CEC.

2.4 Extended empirical orthogonal function (EEOF)

The Empirical Orthogonal Function (EOF) analysis is a widely-applied climate statistical method in atmospheric and oceanographic scientific studies (Kim et al., 2015; Li et al., 2019; Schepanski et al., 2016), also used to investigate the variability of atmospheric aerosols at different spatiotemporal scales (Bai et al., 2022; Feng et al., 2020). The mathematical process of EOF analysis is to decompose the variable field $X_{m\times n}$, which consists of observations at n times at m spatial points, into a linear combination of p spatial eigenvectors (modes) with corresponding time-weighting coefficients:

$$X_{m\times n} = V_{m\times p}\ T_{p\times n} \tag{7}$$

where V is the spatial eigenvector (load) and T represents the time coefficient. The main information of variable field $X_{m\times n}$ is represented by several eigenvectors. Since the method has been maturely applied, the detailed calculation steps of EOF decomposition are omitted here, and our focus is on how to construct the observation matrix.

Firstly, we decompose the daily $PM_{2.5}$ TFM anomalies of 1079 stations in CEC during the winters of 2015-2019 by EOF method. Thus, the following observation matrix can be obtained:

$$X = \begin{bmatrix} x_{11} \cdots x_{1n} \\ \vdots \\ x_{m1} \cdots x_{mn} \end{bmatrix} \tag{8}$$

where X represents the $PM_{2.5}$ TFM anomalies, m represents the spatial points for 1079 stations, and n represents the observation times of 450 days. Then, the variable field X is decomposed into the sum of the product of space and time functions according to Formula (7).

EOF decomposition of $PM_{2.5}$ TFV anomalies can be performed by employing the complex matrix, hence the following observation matrix is constructed:

$$X = \begin{bmatrix} u_{11} \cdots u_{1n} \\ \vdots \\ u_{m1} \cdots u_{mn} \\ v_{11} \cdots v_{1n} \\ \vdots \\ v_{m1} \cdots v_{mn} \end{bmatrix} \tag{9}$$

where X is the $PM_{2.5}$ TFV anomalies, and u and v refer to the zonal and meridional components of TFV anomalies.

With EOF analysis we can get the spatial distribution structure, which is in a fixed time pattern of climate variables, but we cannot get a temporally moving spatial distribution structure. EEOF is an extension of the EOF to analyze the autocorrelations of the variable field over time. By selecting a lag time, the original observational matrix is expanded into multiple continuous time matrices, diagnosing the temporal changes in the spatial structure of variable fields. This method has found widespread applications in the analysis and prediction of marine and atmospheric motions (Dey et al., 2018; Qian et al., 2019; H. Wang et al., 2019).

In this study, we utilized the EEOF analysis to reveal the evolution of $PM_{2.5}$ TF to reveal the spatiotemporal variations of regional $PM_{2.5}$ transport. On the basis of Formula (8), a new extension matrix of $PM_{2.5}$ TFM is constructed. Due to the study on the synoptic scale, 5 lag times are selected, and each lag time is 1 day in length. The constructed observation matrix is as follows:

$$X = \begin{bmatrix} X_{1,1} \cdots X_{1,n-5} \\ \vdots \\ X_{m,1} \cdots X_{m,n-5} \\ X_{1,2} \cdots X_{1,n-4} \\ \vdots \\ X_{m,2} \cdots X_{m,n-4} \\ X_{1,3} \cdots X_{1,n-3} \\ \vdots \\ X_{m,3} \cdots X_{m,n-3} \\ X_{1,4} \cdots X_{1,n-2} \\ \vdots \\ X_{m,4} \cdots X_{m,n-2} \\ X_{1,5} \cdots X_{1,n-1} \\ \vdots \\ X_{m,5} \cdots X_{m,n-1} \\ X_{1,6} \cdots X_{1,n} \\ \vdots \\ X_{m,6} \cdots X_{m,n} \end{bmatrix} \tag{10}$$

Seen from Formula (10), the new extended matrix is composed of $X_{6m,n-5}$, where X is the $PM_{2.5}$ TFM anomalies, m is the spatial points of observation station, and n is the observation times of 450 days. When EEOF decomposition is performed on $PM_{2.5}$ TFV, the complex matrix is still used for the extension, and the same lag scheme is adopted to construct a new extended matrix of $PM_{2.5}$ TFV based on Formula (9). After constructing the initial data matrix, the EEOF decomposition method is in line with the classical EOF decomposition method.

Additionally, existing studies have utilized wavelet analysis, power spectrum analysis, and band-pass filtering methods to extract intraseasonal oscillation sequences of regional $PM_{2.5}$ concentrations (An et al., 2022; Gao et al., 2020; Li et al., 2021; Liu et al., 2022; Wu et al., 2023; Yang et al., 2024b). Such approaches may serve as alternative methods to EEOF analysis for establishing the quasi-weekly lifecycle of regional $PM_{2.5}$ transport.

3 Results and discussion

3.1 QWO of regional $PM_{2.5}$ transport over CEC

The EOF decomposition is carried out on the daily anomalies of $PM_{2.5}$ TFM and TFV in the winters of 2015-2019 over CEC. The first two EOFs explain 26.6% and 14.2% (29.1% and 11.8%) of the total anomalous variations of $PM_{2.5}$ TFM (TFV), which is very helpful for better characterizing regional $PM_{2.5}$ transport variations.

Two principal modes govern the variations of $PM_{2.5}$ TF anomalies over CEC: the first leading mode of monopole (EOF1) and the second mode of meridional dipole (EOF2) (Fig. 1). EOF1 indicates the enhanced $PM_{2.5}$ TF over CEC (Fig. 1a). The large value center of TF mainly occurs in central China, and the transport vector direction is abnormally by north. The horizontal $PM_{2.5}$ transport is unusually strong in central China affected by the EAWM, presenting a typical channel for regional $PM_{2.5}$ transport over CEC (Yang ~~W.~~ et al., 2021a). The dipole mode of $PM_{2.5}$ TF anomalies displays a south–north out-of-phase pattern, with the flux large value centers located in the North China Plain (NCP) and the Twain-Hu Basin (THB) respectively, and the vector directions are opposite (Fig. 1b). This mode indicates that the air pollutants from NCP in the upwind are transported to THB in the downwind driven by the prevailing northerlies of EAWM (Hu et al., 2021; Shen et al., 2022), and the $PM_{2.5}$ flux in NCP decreases while that in THB increases in the regional $PM_{2.5}$ transport process.

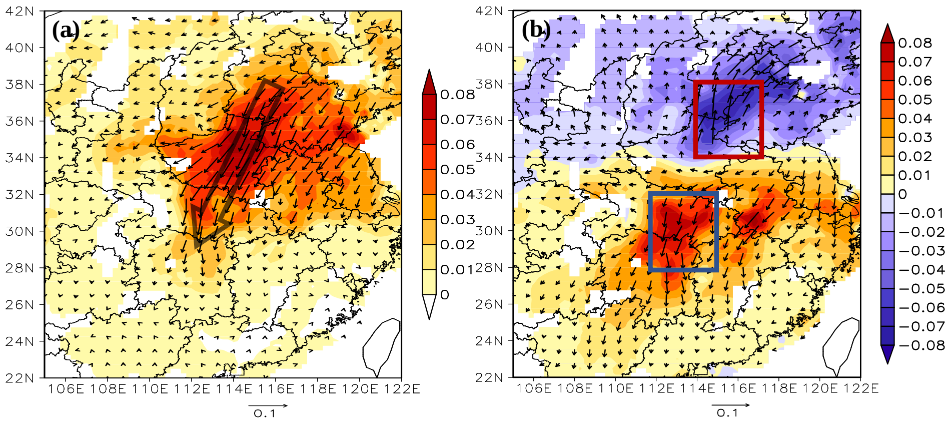


Figure 1. Spatial pattern of the (a) EOF1 and (b) EOF2 loads in the daily change of $PM_{2.5}$ TFV anomalies (vectors, unitless) and TFM anomalies (color contours, unitless) over CEC in the winters of 2015-2019. The red and blue boxes indicate NCP and THB, respectively. The grid cells in white represent "missing values".

Through EOF decomposition, the $PM_{2.5}$ TF could be understood from the perspective of a fixed time pattern of climate, but the temporal changes in the moving spatial structure of $PM_{2.5}$ TF over CEC failed to be obtained. However, EEOF decomposition can be used to analyze the continuous structural evolution of the main modes of regional $PM_{2.5}$ TF over CEC.

The EEOF decomposition was carried out for the daily variations of $PM_{2.5}$ TFM anomalies and TFV anomalies respectively over CEC during the winters of 2015-2019. Figure 2 and Figure S1 show the spatial distribution of different lag times for the main modes of EEOFs, which account for about 20% of the total variation. According to the analysis, the $PM_{2.5}$ TFM anomalies for EEOF2 and EEOF3, as well as TFV anomalies for EEOF1 and EEOF2, all show the structural evolutions in the different phases of regional $PM_{2.5}$ transport in one cycle. As it can be seen, Figures. 2a-d, S1a-d, and 2e-h respectively describe the evolution of the first and second four phases in a cycle and the first four phases in the next cycle (one phase represents 1day).

Figures 2a-d illustrate the positive anomalies of $PM_{2.5}$ TF shifting from NCP to THB in the first four phases under the effect of the EAWM, causing the upwind $PM_{2.5}$ TF to decrease and the downwind $PM_{2.5}$ TF to increase, which is in line with the spatial pattern of the EOF modes in Figure 1. The last four phases show the out-of-phase pattern of the first half cycle (Figs. S1a-d). It is noted that when anomalies of $PM_{2.5}$ TFV in the NCP turn to the northerly direction (Fig. S1d and Fig. 2e), it is a strong signal initiating the regional $PM_{2.5}$ transport. Then, the transport is repeated in the next periodic cycle (Figs. 2e-h). Therefore, the regional $PM_{2.5}$ transport over CEC enjoys a quasi-weekly (8-d) oscillation pattern.

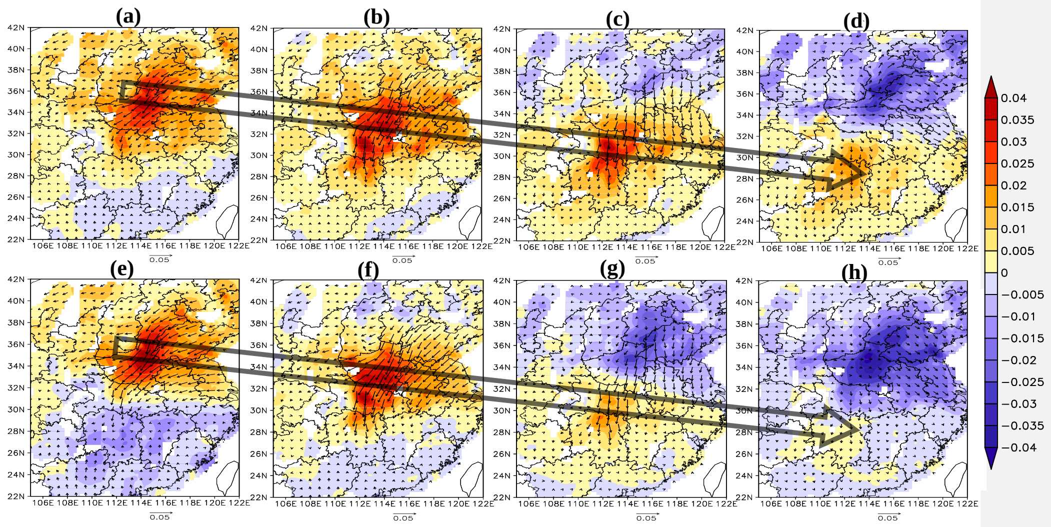


Figure 2. (a)-(d) The first four phases (days) of QWO (8-d) during the regional $PM_{2.5}$ transport over CEC; (e)-(h) the first four phases (days) of the next cycle. The Loads of $PM_{2.5}$ TFM anomalies (color contours, unitless) for EEOF2 and TFV anomalies (vectors, unitless) for EEOF1 with lag time (a) 0 d, (b)1 d, (c) 2 d and (d) 3 d, and loads of TFM anomalies (color contours, unitless) for EEOF3 and TFV anomalies (vectors, unitless) for EEOF2 with lag time (e) 2 d, (f) 3 d, (j) 4 d and (h) 5 d over CEC in the winters of 2015-2019.

To further study the variations of regional $PM_{2.5}$ transport over CEC, we have screened out 23 typical events with greater than 1.5 times standard deviations based on the standardized time coefficient of EEOF, and then used the 8 consecutive days of each event as the 8 phases of QWO in the composite analysis on the 23 typical events of regional $PM_{2.5}$ transport over CEC.

Figure 3 shows the composited $PM_{2.5}$ TF, divergence of $PM_{2.5}$ TF, and $PM_{2.5}$ concentration anomalies in the first four phases of QWO. The high fluxes of $PM_{2.5}$ transport from north to south persists for 3-4 days over CEC and decline in the THB (Fig. 3a-d). The regional $PM_{2.5}$ transport lifetime corresponding to synoptic systems is about 3-5 days (H. Huang et al., 2020a). Abnormal northerly winds drive the heavy $PM_{2.5}$ pollution from the upwind NCP to the downwind regions, aggravating $PM_{2.5}$ pollution in the downwind THB (Figs. 3e-h). Under the context of QWO, the average $PM_{2.5}$ TFM in NCP decreases from approximately 400 μg m^{-2} s^{-1} in the 1st and 2nd phases to 200 and 100 μg m^{-2} s^{-1} in the 3rd and 4th phases, respectively (Fig. S2a). Correspondingly, the $PM_{2.5}$ concentration anomalies decline from around 100 μg m^{-3} to approximately −50 μg m^{-3} (Fig. S2c). In the downwind THB, the average $PM_{2.5}$ TFM increases from about 200 μg m^{-2} s^{-1} in the

1st phase to approximately 300 μg m^{-2} s^{-1} in the 2nd and 3rd phases (Fig. S2b), with $PM_{2.5}$ concentration anomalies also rising to around 50 μg m^{-3} (Fig. S2d).

It is noteworthy that the regions $PM_{2.5}$ TF convergence zone (negative value of divergence) matches spatially the centers positive anomaly centers of $PM_{2.5}$ concentrations, which is confirmed with a significantly negative correlation of the $PM_{2.5}$ concentrations with divergences of $PM_{2.5}$ TF in the 23 typical events (Fig. ~~S2~~S3). The $PM_{2.5}$ transport is accompanied by flux convergence, which is beneficial to the $PM_{2.5}$ accumulation. In addition, the $PM_{2.5}$ TF in the upwind NCP changes from convergence to divergence, and the divergence of the $PM_{2.5}$ TF in the downwind THB alters to convergence in the meantime (Figs. 3i-l), indicating that the $PM_{2.5}$ over THB is transported from the upwind NCP. ~~The source-receptor relationship between NCP and THB during the regional $PM_{2.5}$ transport over CEC is discussed in detail in the next section.~~

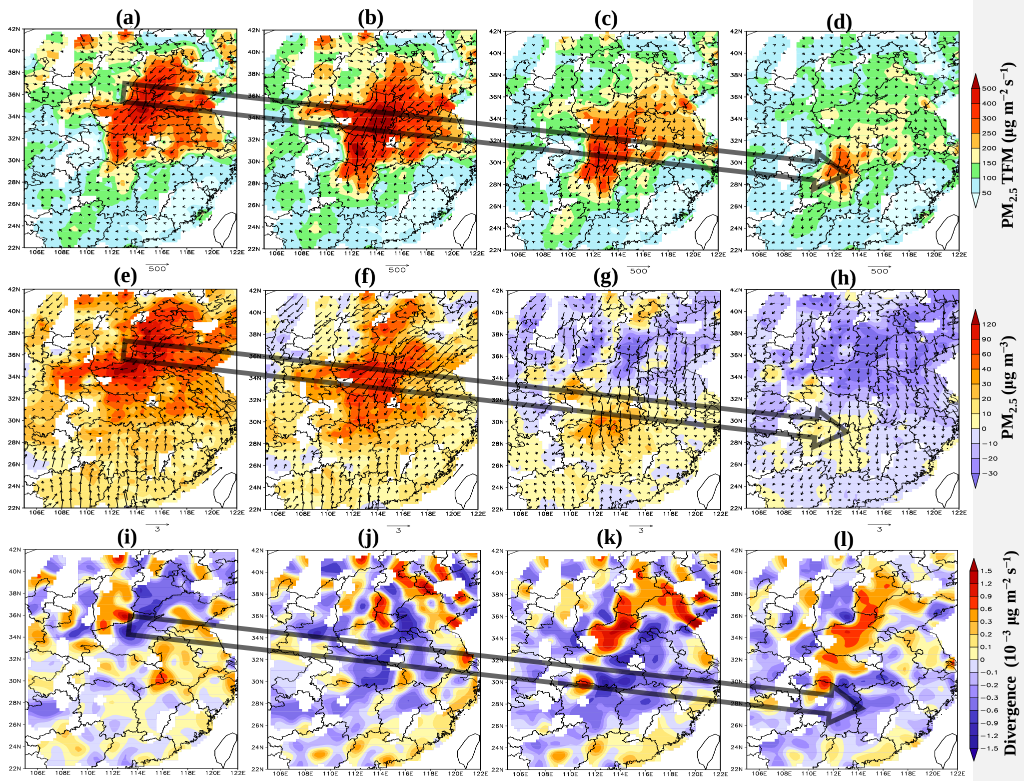


Figure 3. Spatial distributions of the composited (a-d) $PM_{2.5}$ TFM (color contours, unit: μg m^{-2} s^{-1}) and TFV (vectors, unit: μg m^{-2} s^{-1}), (e-h) anomalies of $PM_{2.5}$ concentrations (color contours, unit: μg m^{-3}) and 10-m wind vectors (unit: m s^{-1}), (i-l) divergence of $PM_{2.5}$ flux (color contours, unit: 10^{-3} μg m^{-3} s^{-1}) in the first four phases of

QWO during the 23 typical events of regional $PM_{2.5}$ transport over CEC.

3.2 Source-receptor relationship in regional $PM_{2.5}$ transport from NCP to THB

The regional pollutant transport governed by emissions and meteorology leads to a complex source–receptor relationship of air pollution changes (Yu et al., 2020). Band-pass filtering is performed on the daily $PM_{2.5}$ TFM anomalies at a quasi-weekly (6-9 days) synoptic scale in the winters of 2015-2019. In Figure 4a, we composite the filter components of $PM_{2.5}$ TFM in the 8 phases of QWO during the 23 typical events of regional $PM_{2.5}$ transport over the NCP and THB, respectively. The $PM_{2.5}$ TF exhibits an obvious QWO on the synoptic scale (Fig. 4a). The $PM_{2.5}$ TF over the NCP continues to decline in the first four phases, while that of THB first rises and then falls in the last four phases, the $PM_{2.5}$ TF over the NCP increases continuously, while that of THB falls first and then rises. We can see that the QWO of $PM_{2.5}$ TF over THB lags behind the NCP by 2 phases (Fig. 4a). The high TFM of $PM_{2.5}$ from NCP in the first phase spread to THB, resulting in the peak of $PM_{2.5}$ TF over THB in the third phase.

In addition, the distribution of the differences in $PM_{2.5}$ TF and the vectors between phase 3 and phase 1 of the QWO, and the $PM_{2.5}$ TF decrease and increase from phase 1 to phase 3 respectively over the upwind NCP and the downwind THB, which is in accordance with the spatial pattern of the EOF mode (Figs.1b and 4b), indicating that the source-receptor relationship over CEC exist the regions NCP and THB of regional $PM_{2.5}$ transport over CEC.

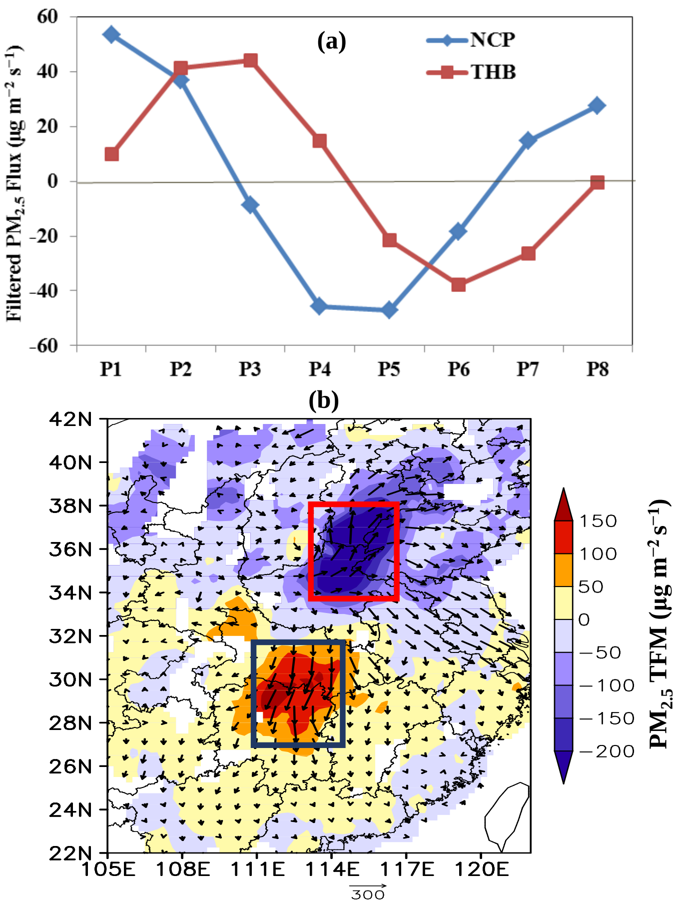


Figure 4. (a) The 8 phases (P1-P8) of QWO during the 23 typical events of regional $PM_{2.5}$ transport over the NCP and THB with composited 6-9 d band-pass filtering of $PM_{2.5}$ TFM; (b) spatial distribution of the differences in $PM_{2.5}$ TFM (color contours, unit: μg m^{-2} s^{-1}) and TFV (vectors, unit: μg m^{-2} s^{-1}) between the 3rd phase and the 1st phase of QWO. The red and black boxes represent NCP and THB.

The statistical analysis based on long-term observation also shows that there is a significant 2-day lag relationship of positive correlation between NCP and THB in $PM_{2.5}$ TF in the QWO (Fig. 5a). This discloses that the air pollutants are transported from the upwind NCP to the downwind THB in 2 days, confirming a quasi-2-d lag in the regional $PM_{2.5}$ transport from NCP to THB (Hu et al., 2021; Shen et al., 2021). Additionally, in the long-term change of air pollution, the divergences of $PM_{2.5}$ TF in the NCP are significantly negatively correlated to that of THB (Fig. 5b), that is, the $PM_{2.5}$ TF convergences in the downwind THB fits well with the $PM_{2.5}$ TF divergence in the upwind NCP. It can be reflected that the changes in the synoptic scale of EAWM atmospheric circulation impel the regional $PM_{2.5}$ transport to build the source-receptor relationship of atmospheric pollutants between the NCP and THB.

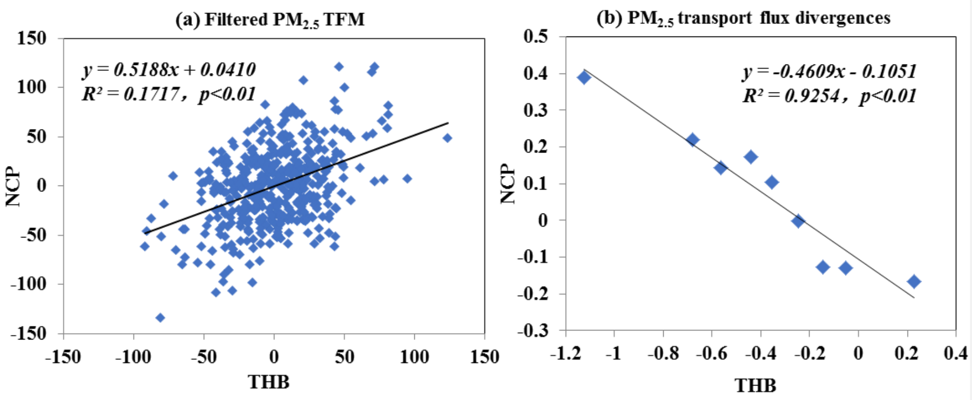


Figure 5. (a) Scatter plot of 6-9-d filtering components of $PM_{2.5}$ TFM (10^{-3} μg m^{-2} s^{-1}) over THB in 2-day lag and NCP during the winters of 2015-2019; (b) scatter plot of $PM_{2.5}$ TF divergences (10^{-3} μg m^{-3} s^{-1}) between THB and NCP, and the $PM_{2.5}$ TF divergences are averaged over the value interval of 0.1.

Driven by prevailing winds of EAWM, the THB became the main receptor for regional transport of air pollutants over CEC (Bai et al., 2022; Shen et al., 2021). During 2015–2019, approximately 65.2% of the total $PM_{2.5}$ heavy pollution events in the THB were triggered by regional transport of air pollutants over CEC (Hu et al., 2022; Shen et al., 2021). Such $PM_{2.5}$ transport from upstream source regions in CEC contributes 51%-85.7% of the $PM_{2.5}$ pollution over the THB receptor region (Hu et al., 2021; Lu et al., 2017; Shen et al., 2022; Yu et al., 2020), revealing the dominance of regional transport of air pollutants from CEC to the THB with the meteorological drivers. Our research emphasizes the QWO of regional $PM_{2.5}$ transport over CEC with the driver of the synoptic-scale disturbances of EAWM circulation, confirming the source-receptor relationships with their 2-day lagging effects in the regional $PM_{2.5}$ transport between the upstream NCP source region and the THB receptor region.

3.3 Effect of synoptic-scale disturbance of EAWM circulation on QWO of regional $PM_{2.5}$ transport over CEC

Meteorological change is the essential factor in regulating the occurrence and development of

$PM_{2.5}$ pollution on synoptic scales. To investigate the QWO of EAWM circulation in the synoptic scale disturbance, this study performs the 6-9-d band-pass filtering of the daily SLP anomalies (denoted as SLP_{QWO}) in East Asia during the winters of 2015-2019. The SLP and SLP_{QWO} fields (Figs. 6 and 7) as well as $PM_{2.5}$ concentrations and 10-m winds (Fig. ~~S3~~S4) in the 8 phases of QWO during the 23 typical events were composited, respectively. The QWO of regional $PM_{2.5}$ transport is connected with the "weekly-cycle" synoptic process of $PM_{2.5}$ transport and accumulation over CEC (Fig. ~~S3~~S4), and it is powered mainly by the Siberian High circulation with the synoptic-scale disturbance of EAWM circulation (Figs. 6 and 7).

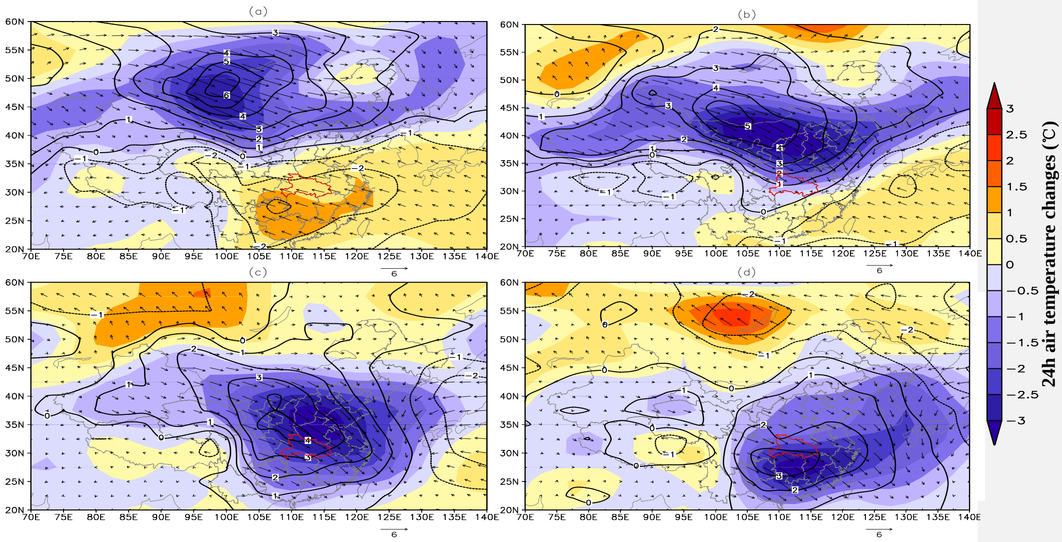
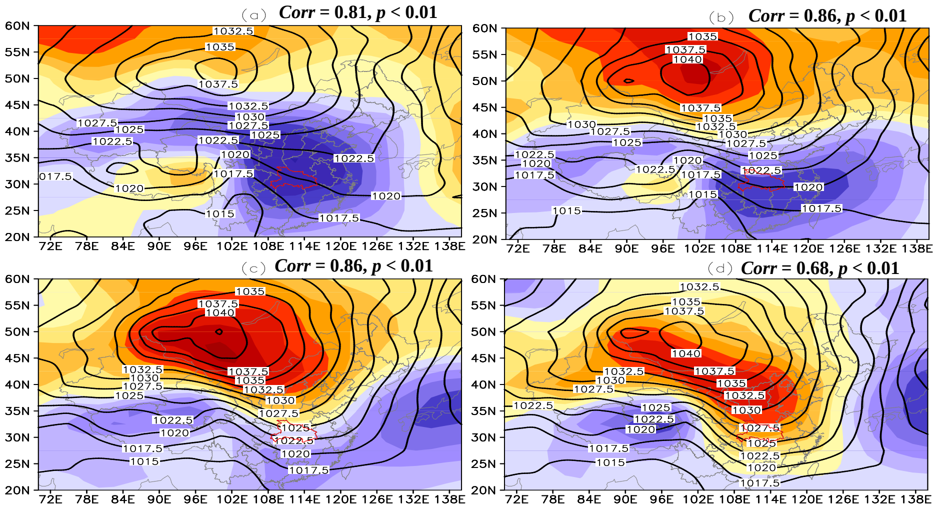


Figure 6. The composited differences between the current day and the previous day of SLP (black contour lines, unit: hPa), 1000 hPa air temperature (color contours, unit: ℃) and wind vectors (unit: m s^{-1}) in the first four phases (a-d) of QWO during the 23 typical events.

The condition of uniform pressure in the front of Siberian High could favor the $PM_{2.5}$ accumulation over the NCP for triggering regional $PM_{2.5}$ transport over CEC (Fig. 7a). The regional heavy pollution of $PM_{2.5}$ >150 μg m^{-3} lasts for 1-2 days (Figs. ~~S3a~~ S4a and ~~S3b~~S4b). With the development of the Siberian High, the extension of the high pressure guides the cold air to advance southward (Park et al., 2014). As the result of the increasing air pressure gradients, the strong northerly winds in the EAWM circulation system, deliver high-level $PM_{2.5}$ air mass from NCP to THB (Figs. 7a-d, Figs. ~~S3a~~S4a-d). In addition, the cold and high air pressure system with the abnormal northerly airflows moves from the Siberia-Mongolia region to CEC in the first four phases (Fig. 6), providing beneficial synoptic circulation patterns for regional $PM_{2.5}$ transport. Thus, the periodic extension of the Siberian High with the associated strong cold air intrusion is an important driver in the regional $PM_{2.5}$ transport over CEC.

Notably, we can see that in the first four phases, the SLP_{QWO} positive anomalies occur, develop, and expand southward from the Siberia-Mongolia region to CEC (Figs. 7a-d). The synoptic-scale disturbance with the extension of Siberian High and the southward movement of cold air could drive the regional $PM_{2.5}$ transport over CEC (Figs. 7a-d). The situation of the last four phases is opposite to the SLP_{QWO} negative anomalies in Siberia-Mongolia region, inhibiting the Siberian High and cold air intrusion (Figs. 7e-h). The low and uniform pressure is beneficial to the accumulation of $PM_{2.5}$. Therefore, the periodic changes in the synoptic-scale disturbance of the EAWM circulation impel the QWO of regional $PM_{2.5}$ transport over CEC.



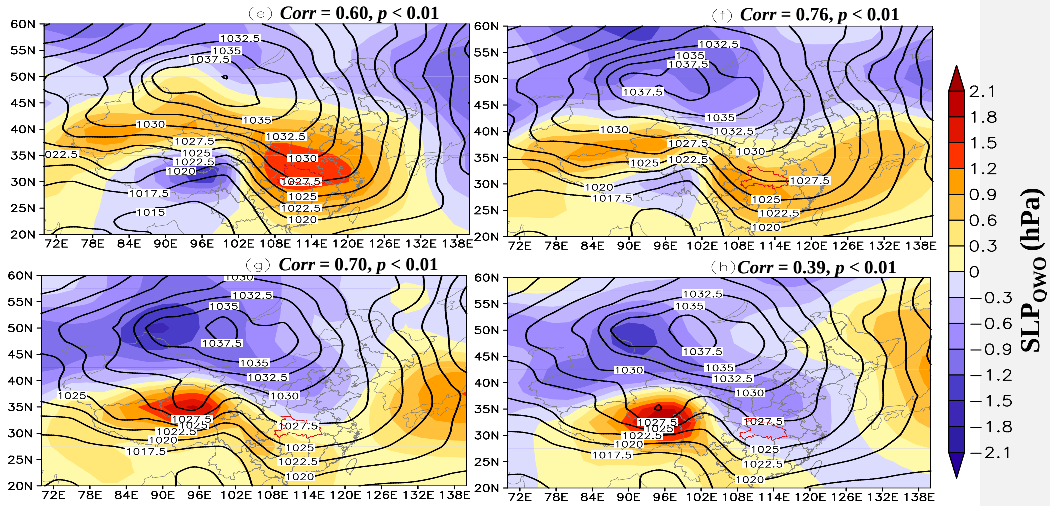


Figure 7. Composited SLP (black contour lines, unit: hPa) and its synoptic-scale filter component SLP_{QWO} (color contours, unit: hPa) in the 8 phases (a-h) of QWO during the 23 typical events. *Coor* represents the spatial correlation coefficients between SLP_{QWO} and the load of SLP_{QWO} decomposed by EEOF in Fig. S4.

In addition, the EEOF decomposition is carried out on the SLP_{QWO} field in the winters of 2015-2019 to recognize the periodic activities in the synoptic scale of the EAWM circulation. The cold air activity of EAWM presents QWO (Wu and Wang, 2002). The positive (negative) synoptic-scale disturbance occurs in the Siberia-Mongolia region, and then spreads to CEC along the northwest-southeast path, contributing to the 8-d cycle of QWO (Fig. ~~S4~~S5). Notably, the spatial correlation coefficients between the load of SLP_{QWO} decomposed by EEOF (Fig. ~~S4~~S5) and the SLP_{QWO} composited during 23 typical events (Fig.7) are highly positively correlated in the 8 phases, respectively. Therefore, the QWO in the synoptic-scale activities of the Siberian high is an important factor for driving the QWO of regional $PM_{2.5}$ transport over CEC.

4 Conclusions

Exploring the periodical oscillations of $PM_{2.5}$ pollution over CEC and the meteorological effect is crucial for understanding the change in the atmospheric environment and improving regional air quality forecasts. In this study with constructing a dataset of the daily $PM_{2.5}$ TF, the EEOF and statistical methods are used to identify the QWO of regional $PM_{2.5}$ transport with the spatiotemporal variations over CEC in winters from 2015 to 2019. The source-receptor relationship is recognized between NCP and THB with the QWO of regional $PM_{2.5}$ transport over CEC with the typical EAWM climate. Furthermore, it is revealed that the driving effect of synoptic-scale disturbance of EAWM circulations on the QWO of regional $PM_{2.5}$ transport over China.

The variations of $PM_{2.5}$ TF over CEC are dominated by the first leading monopole mode and the second meridional dipole mode. The monopole mode indicates the high $PM_{2.5}$ flux along the channel of regional $PM_{2.5}$ transport from NCP to THB under the governs of the EAWM circulations, and the dipole mode exhibits a pattern of south-north out-phase with two centers existing respectively in the upwind NCP and the downwind THB in regional transport of $PM_{2.5}$ over CEC. In terms of the long-term changes in air pollution of 2015–2019, the regional $PM_{2.5}$ transport over CEC is featured with the QWO, verifying a source-receptor relationship for the regional $PM_{2.5}$ transport from NCP to THB in 2 days. Such changes are incurred by the QWO in the activities of the Siberian High, and this synoptic-scale disturbance of the EAWM circulations is generated in the Siberia-Mongolia region, and then develops, marching into CEC, regulating the QWO of regional $PM_{2.5}$ transport.

The EEOF analysis with the temporal lag of the spatial fields is able to better characterize the spatial and temporal evolution of perturbations, especially propagating waves in the atmosphere (Weare and Nasstrom, 1982; Qian et al., 2019; Yang et al., 2024b). Due to its technical advantages, the EEOF method is commonly employed to extract atmospheric oscillation patterns to reveal the impacts and mechanisms of atmospheric fluctuations and monsoon circulation on regional weather, climate, and atmospheric environments (Dey et al., 2018; Qian et al., 2019; Yang et al., 2024b). In this study, we employed the EEOF method to identify regional $PM_{2.5}$ transport modes in synoptic scale, by constructing $PM_{2.5}$ transport flux vectors (TFV) and the magnitude (TFM) with the product of near-surface $PM_{2.5}$ concentrations and wind components at 1079 stations across China during the winters of 2015-2019. We performed EEOF analysis on $PM_{2.5}$ TFV and TFM, resulting in the spatial structure of $PM_{2.5}$ transport flux under the temporal disturbances at the synoptic scale, and revealing the connection between synoptic-scale disturbances in the EAWM and QWO in regional $PM_{2.5}$ transport in CEC. Our study focuses on the driving effects of synoptic-scale disturbances associated with cold air activity with the anomalous northerly winds in EAWM on QWO of regional $PM_{2.5}$ transport over CEC, exacerbating $PM_{2.5}$ pollution in the downwind THB.

Differently from the studies on stagnant meteorological conditions associated with $PM_{2.5}$ accumulations (Gao et al., 2020; Wu et al., 2023; Yang et al., 2024b), this study provides new insights into the understanding of regional $PM_{2.5}$ transport with source-receptor relationship with the meteorological mechanism in atmospheric environment change.

Based on the 5-winter (2015-2019) observations of $PM_{2.5}$ concentrations and the corresponding meteorological reanalysis data, this study with the climate statistical and diagnostic methods investigates the QWO of regional $PM_{2.5}$ transport in China with the influence of synoptic-scale disturbance of EAWM circulation, providing a new insight into the understanding of regional air pollutant transport with meteorological drivers in atmospheric environment changes. Besides the EEOF method used in this study, the alternative methods of wavelet analysis, power spectrum analysis, and band-pass filtering could be used in further study. Future studies with utilizing long-term observations of air pollutants and meteorology over CEC could more comprehensively understand the variations in the regional transport of particles and the gaseous precursors with their contributions to air pollution, through the integration of artificial intelligence and physical-chemical process analyses.

Data availability. All data used in this paper can be provided upon request from Yongqing Bai (2007byq@163.com)

Author contributions. YB and TZ conceived the study. YB designed the graphics and wrote the manuscript with help from TZ, KM, YZ, JX, XS, LS, YY, YZ, WH and JY were involved in the scientific discussion. All authors commented on the paper.

Competing interests. The authors declare that they have no conflict of interest.

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