https://doi.org/10.5194/acp-2020-708
Preprint. Discussion started: 16 November 2020

Atmospheric Chemistry and Physics Discussions
Open Access

Meteorological formation mechanism of regional transport in winter heavy air pollution events in the middle Yangtze River area, China

Yongqing Bai[1] Tianliang Zhao[2*] Yue Zhou[1*] Jie Xiong[1] Weiyang Hu[2] Yao Gu[2] Lin Liu[1] Shaofei Kong[3] Huang Zheng[3]

1. Hubei Key Laboratory for Heavy Rain Monitoring and Warning Research, Institute of Heavy Rain,China Meteorological Administration, Wuhan 430205, China
2. Key Laboratory for Aerosol-Cloud-Precipitation of China Meteorological Administration, Nanjing University of Information Science and Technology, Nanjing 210044, China
3. Department of Atmospheric Science, School of Environemtal Studies, China University of Geosciences (Wuhan), 430074

Correspondence: Tianliang Zhao (josef_zhao@126.com) and Zhou Yue (zhouyue8510@163.com)

Abstract: Anthropogenic emission, meteorological conditions, and regional transport are the three major factors influencing heavy air pollution in China. The Hunan and Hubei provinces in the middle Yangtze River region border China's main air pollution areas, serving as the hub of regional transport of air pollutants. The meteorological formation mechanism of regional transport of air pollutants on heavy air pollution in the Hunan and Hubei provinces still remain urgent to be addressed in depth. In this study, multivariate empirical orthogonal function (MV-EOF) analysis was performed to objectively select eight typical heavy pollution events in the two provinces that occured in January 2015–2019. Based on the regional surface environment, meteorological network data, atmospheric sounding data, ERA-interim reanalysis data, and a numerical simulation experiment, this study investigated the pattern of regional transport of air pollutants in the two provinces and its mechanism of regional meteorological conditions. The results showed that transporting air pollutants mainly passed through two transport pathways, namely the Nanxiang Basin-Yunmeng Plain pathway and the Dabie Mountain's Hilly Area-Yunmeng Plain pathway, existing anomalous near-surface northerly winds in the two provinces and their upstream area accompanied by southward penetration of a shallow cold layer, all of which jointly provide a dynamic condition for regional air pollutant transport. The weak cold-air mass degenerated as it passed through the Hunan–Hubei Plain, causing warm air to

https://doi.org/10.5194/acp-2020-708
Preprint. Discussion started: 16 November 2020

Atmospheric Chemistry and Physics Discussions

accumulate in the near-surface layer of the downstream area, where winds slowed down and converged, buffering the air pollutant transport and resulting in pollutants accumulation; the near-surface atmosphere of the Hunan and Hubei provinces was a non-stagnant condition (dry intrusion of cold air, anomalous northerly winds, and positive anomalies of boundary-layer height), which is conducive to the horizontal transport of air pollutants. However, the mid-high layers, characterized by temperature inversion and the presence of a "warm lid", had a stable stratification, inhibiting the diffusion of air pollutants to the upper layers; there is an obvious longitudinal vertical circulation above the Hunan–Hubei Plain, which results in the sinking and accumulation of air pollutants, thereby promoting rapid accumulation of air pollutants in the Hunan and Hubei provinces. In addition, extended empirical orthogonal function (EEOF) analysis was performed, revealing a quasi-4-d periodic oscillation pattern of air pollutants transport in the Hunan and Hubei provinces, which provides a reference for early prediction of its regional transport. The findings are of practical value in broadening the scientific understanding of the differences in the formation mechanism of heavy atmospheric pollution between the various regions of China and promoting environmental and ecological protection of the middle Yangtze Basin.

1 Introduction

At present, China is facing a severe air pollution situation, and in particular, regional atmospheric environmental problems characterized by the pollution of inhalable particulate matter (PM_{10}) and fine particulate matter ($PM_{2.5}$) are increasingly prominent, which is the main challenge in China's atmospheric environmental management (Kan et al., 2012; Zhao et al., 2013; Zhang et al., 2015). Under certain geographical and meteorological conditions, atmospheric pollutants diffuse and accumulate on a certain spatial scale. Air pollutants flow freely between cities and urban agglomerations and undergo trans-boundary transport, characterized by a combination of regional pollution and compound pollution, with regional joint prevention and control of pollutant transport becoming the focus of atmospheric environmental issues in China (Wu et al., 2013b; Miao et al., 2017; Lu et al., 2019a). Exploring meteorological mechanism of regional air pollutant transport, scientifically assessing the atmospheric environmental changes, and effectively regulating pollutant emissions constitute an important topic of atmospheric environmental research

https://doi.org/10.5194/acp-2020-708
Preprint. Discussion started: 16 November 2020

(Cheng et al., 2019; Zhang et al., 2019; Huang et al., 2020).

China's heavy atmospheric pollution often occurs in winter, and the pollution-promoting meteorological conditions in winter are usually about 40-100% worse than those in in other seasons (Zhang et al., 2018). The effects of meteorological conditions on the formation, distribution, maintenance, and change of aerosol pollution are significant (Tai et al., 2012; Ding et al., 2016; Guo et al., 2019). Excessive antropogenic emission, stable meteorological conditions, and regional transport of air pollutants are important factors in the formation of heavy air pollution (Zhang et al., 2012a; Guo et al., 2016a; Ning et al., 2018). Under stagnant meteorological conditions, weak winds, strong and thick temperature inversion layers, sinking motion and low mixing layer heights are extremely unfavourable for the diffusion of air pollutants, with these local meteorological conditions acting as an external driver for the formation of heavy air pollution (Wang et al., 2013a; Xu et al., 2016; Guo et al., 2016b; Ding et al., 2017).

Regional transport of air pollutants involves complex atmospheric physical and chemical processes and is influenced by many factors such as meteorological background field, topography, distribution of emission sources, and atmospheric chemical transformation (Wang et al., 2013b). The transport and accumulation of air pollutants result from the interaction between topographic conditions and meteorological conditions (Zhang et al., 2012b). Air pollutant transport under the control of the cold front system has a significant impact on the atmospheric level of $PM_{2.5}$ in Shanghai in winter (Xu et al., 2016). The weather processes leading to heavy pollution in Hong Kong mainly involve the transport of high-concentration aerosols carried by cold air (Yang et al., 2019). In the Pearl River Delta, 50-70% of $PM_{2.5}$ originates from long-distance transport, resulting in more severe pollution in the suburbs than in the nearby urban areas (Wu et al., 2013a). During the aerosol accumulation stage, $PM_{2.5}$ concentration in the Beijing-Tianjin-Hebei region increased from 24.2 to 289.8 $\mu g\, m^{-3}$, with the contributions of regional transport increasing from 12 % to 40 %, while the contribution of local emissions decreased from 59 % to 38 % (Chen et al., 2019). The rapid changes in the formation and dissipation process of heavy pollution in Beijing are mainly caused by the regional transport and the alternation between northerly and southerly air masses (Gao et al., 2016), and the regional transport is estimated to contribute to as much as 53%-70% in the explosive growth period of $PM_{2.5}$ (Li et al., 2017a). Fine particulates can be transported across a

https://doi.org/10.5194/acp-2020-708
Preprint. Discussion started: 16 November 2020

wide range and over a long distance with obvious trans-boundary transport characteristics, which has an important effect on the dynamics of atmospheric pollution (Kim et al., 2012; Khuzestani et al., 2017; Li et al., 2019; Yuan et al., 2019).

Hunan and Hubei provinces in the middle Yangtze River area have a special geographic location, forming the border of China's most concentrated areas of atmospheric pollution—the Central Plains, Fenwei Plain, North China Plain, and Yangtze River Delta region. Hunan and Hubei provinces are located in the downwind direction of the areas of heavy air pollution sources under the influence of winter monsoon, serving as a hub for the regional transport of air pollutants (Figure 1). The mechanism of regional air pollutant transport on the air pollution in the Hunan–Hubei Plain is a pressing issue of atmospheric environmental science calling for in-depth investigation. With the development of China's Yangtze River Economic Belt and middle Yangtze Basin, the atmospheric environment problems in Hunan and Hubei provinces have become increasingly prominent. Different from cumulative heavy pollution in central and eastern China, the pollutant-transport characteristics and the effect mechanism of meteorological conditions on heavy pollution processes in typical regions like Hunan and Hubei provinces have not yet been systematically investigated. To fill the knowledge gap, this study employed regional surface environment data, meteorological network data, atmospheric sounding data, and ERA-interim reanalysis data in combination with synthetic analysis, climate diagnosis, and numerical simulation to comprehensively investigate the mechanism of air pollutant transport on the process of heavy air pollution in winter in Hunan and Hubei provinces. The findings are of practical value in broadening the scientific understanding of the formation mechanism differences of heavy atmospheric pollution between various regions of China and promoting environmental and ecological protection of the middle Yangtze River area.

https://doi.org/10.5194/acp-2020-708
Preprint. Discussion started: 16 November 2020

Atmospheric Chemistry and Physics Discussions

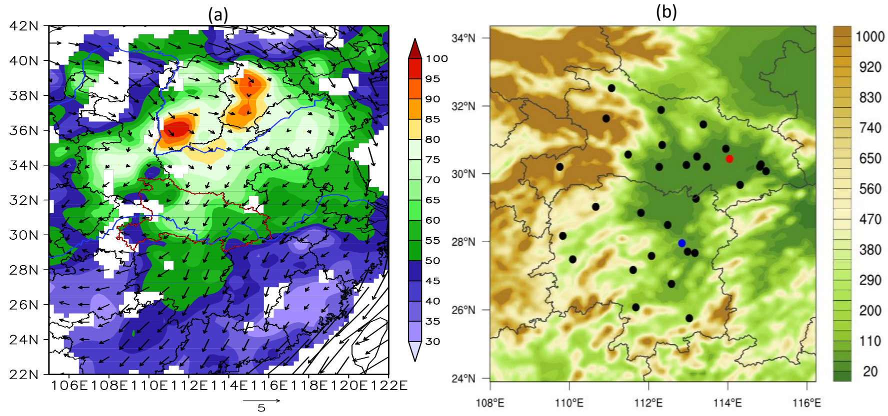


Figure 1 (a) Distribution of average $PM_{2.5}$ concentration (colour scale, in μg m^{-3}) and average ERA-interim 10-m wind vectors (denoted by arrows, in m s^{-1}) measured at the environmental monitoring stations of central and eastern China in January 2015-2019, and (b) topographic map of the distribution of environmental monitoring stations in 31 cities of Hunan and Hubei provinces (colour scale, in m), where the red point represents the Wuhan station, and the blue point represents the Changsha station.

2 Data and methods

2.1 Data source

The daily average $PM_{2.5}$ concentration in January 2015-2019 was obtained from China's National Ambient Air Quality Monitoring Network, which can be accessed through the data centre of the Ministry of Ecology and Environment (http://datacenter.mee.gov.cn/). For the same period, the hourly data of the surface meteorological elements such as sea level pressure (SLP), 2-m air temperature, and 10-m wind speed and wind direction, as well as the atmospheric sounding data of temperature and wind speed at 00 UTC each day at the Wuhan station and Changsha station, were sourced from China Meteorological Data Network (http://data.cma.cn/).

Moreover, the contemporary ERA-interim daily reanalysis data were obtained (http://apps.ecmwf.int/datasets/data/) with a resolution of 0.25°×0.25° consisting of the atmospheric boundary-layer height, SLP, 2-m air temperature, 10-m wind vector components u and v at 00 UTC each day, as well as the geopotential height, temperature, vertical speed, and wind vector components u and v at different vertical layers at 00 UTC each day.

2.2 Multivariate and extended empirical orthogonal function decomposition (MV-EOF, EEOF)

The multivariate empirical orthogonal function decomposition (MV-EOF) is essentially the same as extended empirical orthogonal function decomposition (EEOF). They are both based on the classical empirical orthogonal function decomposition (EOF) to extend the spatial dimension of original data matrix in a different manner, that is, MV-EOF allows extension of multiple elements, while EEOF allows extension of multiple consecutive time points.

When using MV-EOF to study the spatio-temporal variation of the transport modes of pollutants, it is necessary to consider the eigenvectors of a combined ensemble of pollutant data and wind pressure field data. By extending the spatial dimension of $PM_{2.5}$ and wind pressure fields, it is possible to derive the distribution of typical multivariate modes and their time coefficients.

The EOF decomposition can reveal the spatial distribution structure of the element field, but the revealed structure is in a time-invariant form, failing to provide a time-dependent spatial distribution structure under disturbance. Based on the significant temporal autocorrelation of element field, EEOF can extend the original data matrix into observation data corresponding to multiple consecutive time points using a certain lag time, so that the time-dependent spatial distribution characteristics and regional transport patterns of pollutants can be obtained. When using EEOF to analyse the quasi-periodic oscillation and evolution characteristics of the region transport of $PM_{2.5}$, it is necessary to first separate the specific periodic components in the element field of $PM_{2.5}$, and then, perform EEOF decomposition on the separated data. The significant periods in the time series of $PM_{2.5}$ can be extracted using a power spectrum method, and the separation of specific periodic components from the element field can be achieved via a second-order Butterworth band-pass filter.

Moreover, other statistical methods such as synthetic analysis and correlation analysis were also applied in this study. It is noteworthy that the anomalies of each element used in the synthesis of a typical example were calculated using the average meteorological values in January 2015–2019.

3 Selection of regional air pollutant transport events

There are three main causes of heavy air pollution, namely anthropogeinc

https://doi.org/10.5194/acp-2020-708
Preprint. Discussion started: 16 November 2020

emissions far exceeding the environmental carrying capacity, unfavourable meteorological conditions, and regional transport of air pollutants. The local meteorological conditions leading to heavy cumulative pollution mainly include (1) poor air mobility and calm surface winds or small surface winds (wind speed less than 2 m s^{-1}), which are extremely unfavourable for the horizontal diffusion of pollutants; (2) stable atmospheric conditions, near-surface temperature inversion, and significant decrease of boundary-layer height, which are unfavourable for the vertical distribution of air pollutants. In contrast to the above conditions are the meteorological conditions leading to regional transport of heavy air pollution, which mainly include obviously enhanced surface winds and favourable horizontal diffusion conditions; under these transport-facilitating conditions, the pollutant concentration rises, which is mainly attributed to pollutant transport from the upstream areas, that is, the regional transport promotes a rapid local accumulation of pollutants.

The atmospheric circulation during the East Asian winter monsoon drives the regional transport of air pollutants in central and eastern China and facilitates the accumulation of air pollutants in the middle reaches of the Yangtze River (Yu et al., 2020). The $PM_{2.5}$ concentration in Wuhan usually rises rapidly under the influence of strong northerly winds (Lu et al., 2017, 2019b). The regional transport of air pollutants in the middle Yangtze River region is dominated by near-surface northerly airflow, which is air pollutant transport from northern China (Yue et al., 2016; Li et al., 2019; Xiao et al., 2020). As shown above, the transported air pollutants in Hunan and Hubei provinces is characterized by high regional concentration of $PM_{2.5}$, north–south pressure gradient, and anomalous northerly winds. Therefore, MV-EOF was adopted in this study to extract the common eigenvectors and time coefficients of four variables—daily average $PM_{2.5}$ concentration, 10-m wind vector components U and V, and SLP (00 UTC each day) in January 2015–2019 at 31 urban environmental monitoring stations of Hunan and Hubei provinces.

Figure 2 presents the spatial distribution and time coefficients of the MV-EOF mode featured by high $PM_{2.5}$ concentration, south–north pressure gradient, and anomalous northerly winds for the regional pollutant transport in Hunan and Hubei provinces. In particular, the Wuhan-centred urban agglomeration and Changsha–Zhuzhou–Xiangtan urban agglomeration had the most obvious spatial characteristics. This mode accounted for 12% of the total variance, and its time coefficient accounted for 48.4% of the total variance of the time series of daily averaged $PM_{2.5}$ in the two

https://doi.org/10.5194/acp-2020-708
Preprint. Discussion started: 16 November 2020

provinces, indicating that regional transport was almost the most dominant factor determining the changes in pollutant concentrations in the Hunan and Hubei provinces. After normalization of the time coefficient, eight typical regional transport events with maximum standard deviation of time coefficient were selected to explore the meteorological conditions leading to regional transport of heavy pollution in the Hunan and Hubei provinces (Table 1).

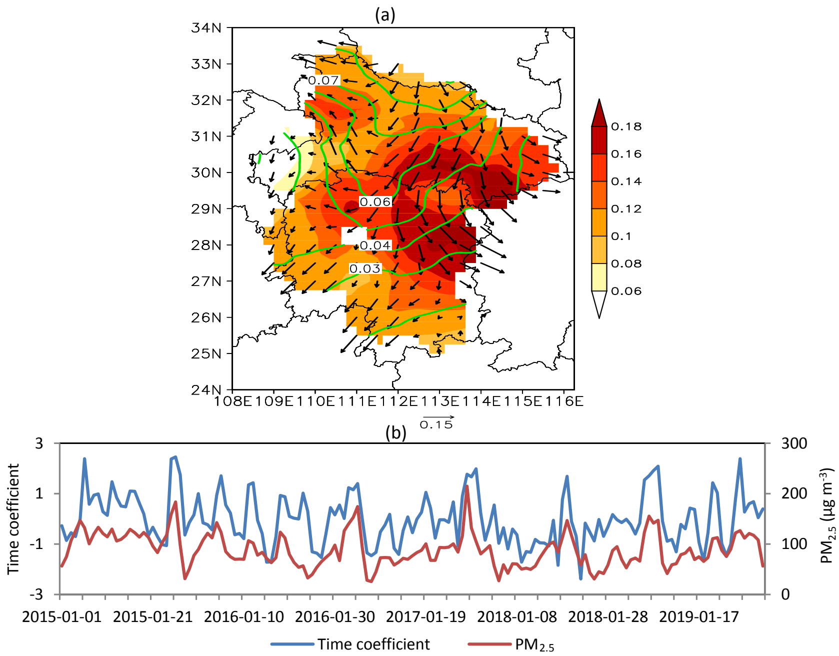


Figure 2 Spatial distribution of the MV-EOF mode (a) of $PM_{2.5}$ denoted by the colour scale, of wind vector with components U and V represented by arrows, and of SLP displayed by green contour lines (all the elements are dimensionless), and (b) its time coefficient and the time series of regional mean $PM_{2.5}$ concentration (in μg m^{-3}).

Table 1 Eight typical regional pollutant-transport events in the Hunan and Hubei provinces

No.	typical regional transport events (standard deviation of time coefficient)	regional mean $PM_{2.5}$ concentration (anomalies) (μg m^{-3})	regional mean wind speed (anomalies) (m s^{-1})	start and end of regional transport
1	Jan. 6, 2015 (2.38)	135 (45)	2.9 (2.1)	Jan. 4-7, 2015
2	Jan. 25, 2015 (2.37)	161 (71)	1.6 (0.7)	Jan. 23-27, 2015

https://doi.org/10.5194/acp-2020-708
Preprint. Discussion started: 16 November 2020

3	Jan. 26, 2015 (2.46)	185 (95)	0.9 (0.1)	Jan. 24-27, 2015
4	Jan. 5, 2016 (1.71)	123 (33)	2.4 (1.6)	Jan. 3-6, 2016
5	Jan. 30, 2017 (1.98)	104 (14)	2.5 (1.7)	Jan. 28-31, 2017
6	Jan. 7, 2019 (1.91)	143 (53)	1.5 (0.7)	Jan. 4-9, 2019
7	Jan. 8, 2019 (2.09)	146 (56)	1.2 (0.4)	Jan. 5-9, 2019
8	Jan. 26, 2019 (2.38)	125 (34)	1.7 (0.9)	Jan. 24-27, 2019

4 Air pollutant transport characteristics in Hunan and Hubei provinces and mechanism of meteorological conditions on the heavy air pollution process

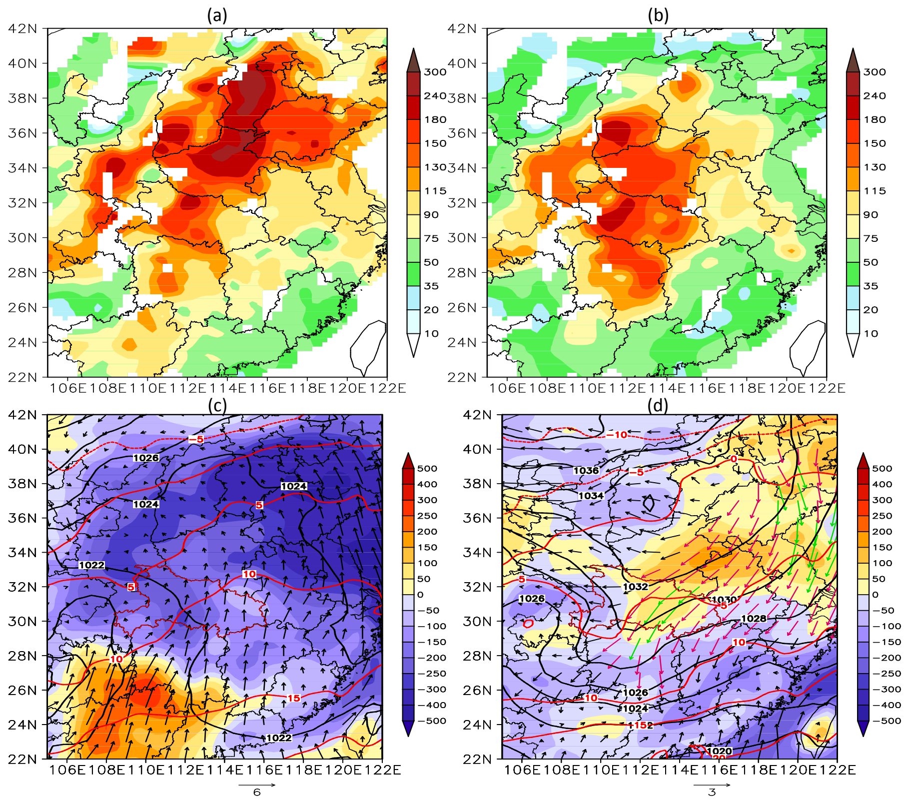
4.1 Air pollutant transport and the predictive regional characteristics

Figure 3 presents the spatial distribution of regional $PM_{2.5}$ concentration, anomaly, and surface synoptic situations obtained from eight typical pollutant-transport events on the onset day (0d) and two days earlier (-2d), respectively. As shown in the figure, the region at -2d was under the influence of a uniform pressure field and low air pressure, and a large range of stagnant weather patterns appeared in northern and central China, including an obvious characteristic of small southerly winds and calm winds, an obvious decrease in the atmospheric boundary-layer height, and a weak diffusion of pollutants in the horizontal and vertical directions, all jointly resulting in local cumulative heavy pollution. In particular, the air pollutant concentration was the highest in northern China and the Central Plains, with local $PM_{2.5}$ concentrations exceeding 250 μg m^{-3}, whereas the local air pollutant accumulation in Hunan and Hubei provinces occurred at a relatively low level.

On the onset day of regional transport, atmospheric circulation underwent changes, that is, the surface south–north pressure gradient was enhanced. Affected by the lower part of the surface high-pressure system, the eastern cold air, which was dominated by north-easterly winds moved southwards, and the 2-m air temperature was reduced. The wind speeds in the two provinces and their upwind areas were increased obviously, and the atmospheric boundary layer was significantly elevated, with the Hunan–Hubei Plain located at the centre of an anomalous northerly wind belt. On the contrary, the wind speed in southern China was weakened and buffered the northerly airflow, which promoted the horizontal transport and accumulation of near-surface pollutants in the Hunan and Hubei provinces. With respect to pollution evolution over different regions, the $PM_{2.5}$ concentration in northern China and the Central Plains decreased, whereas the $PM_{2.5}$ concentration in the Hunan and Hubei provinces increased.

https://doi.org/10.5194/acp-2020-708
Preprint. Discussion started: 16 November 2020

With respect to the observed anomalous wind fields and $PM_{2.5}$ concentration distribution in Hunan and Hubei provinces (Figure 3e, f), there existed anomalous southerly winds in the early stage, accompanied by local pollutant accumulation; when regional air pollutant transport occurred, the wind fields turned into anomalous northerly winds, which resulted in increased air pollutant concentration in the Hunan–Hubei Plain, especially in the Wuhan-centred urban agglomeration and the Changsha–Zhuzhou–Xiangtan urban agglomeration where most areas experienced more than 50 μg m^{-3} of $PM_{2.5}$ concentration anomalies, indicating that regional transport of air pollutants would increase the rapid local accumulation of air pollutants in these high-density cities.



https://doi.org/10.5194/acp-2020-708
Preprint. Discussion started: 16 November 2020

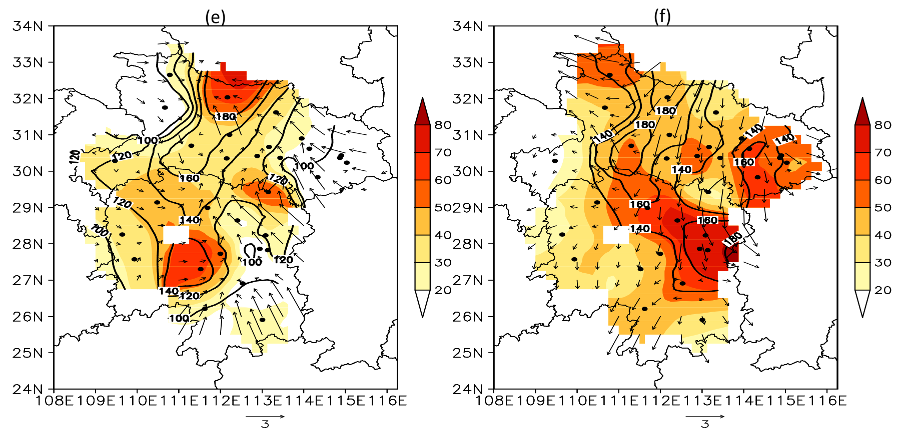


Figure 3 The spatial distribution of daily mean $PM_{2.5}$ concentration (in μg m^{-3}) in central and eastern China on the onset day (b) of eight typical pollution events and two days earlier (a); weather maps at the surface from the ERA-interim daily dataset for central and eastern China on the onset day (d) and two days earlier (c), where the colour scale indicates the anomalies (in m) of atmospheric boundary-layer height, the black contour lines represent SLP (hPa), the red contour lines represent the 2-m air temperature (in ℃), the arrows denote anomalous wind fields (in m s^{-1}), the red arrows represent more than 1.5 m s^{-1} of anomalies of wind speed, and the green arrow represents more than 2.5 m s^{-1} of anomalies of wind speed; spatial distribution of the daily mean $PM_{2.5}$ concentration (black contour lines, in μg m^{-3}) and anomalies (colour scale, in μg m^{-3}) as well as anomalous wind fields (arrows, in m s^{-1}) on the above onset day (f) and two days earlier (e) in the Hunan and Hubei provinces, with data from the observation stations of the two provinces.

Figure 4 shows the spatial distribution of 10-m wind speed observed at nationwide observation stations at 00UTC on the onset day of eight typical pollutant-transport events and the spatial distribution of 24-h temperature changes observed at the above stations. As shown in the diagrams, the Hunan and Hubei provinces as well as most of the eastern upstream area experienced a wind speed above 2 m s^{-1}, and the pollutants mainly passed through two transport pathways, namely the Nanxiang Basin-Yunmeng Plain pathway and the Dabie Mountain's Hilly Area-Yunmeng Plain pathway, where the local winds moved at a speed of above 3.5 m s^{-1}, transporting air pollutants towards the Hunan–Hubei Plain. The dynamic conditions for regional pollutant transport were triggered by the southward movement

https://doi.org/10.5194/acp-2020-708
Preprint. Discussion started: 16 November 2020

Atmospheric Chemistry and Physics Discussions

of weak cold air, which was similar to the process of a cold front system causing air pollutant transport from northern China to the Yangtze River Delta region (Kang et al., 2019). Under the influence of cold air, most of the northern regions experience temperatures of -5 to -2 ℃ within 24 h, and the 24-h temperature changes in Hunan and Hubei provinces were -3 to -2 ℃. Because of the weak southward cold air, its influence exists as far as only the Hunan province. After passing through the Hunan–Hubei Plain, the cold air degenerates, and the Guangdong-Guangxi hilly regions and Zhejiang-Fujian hilly regions in the south undergo positive temperature changes of 0-2 ℃, so wind speed reduces in these areas, causing air pollutants to stagnate and accumulate in the Hunan–Hubei Plain. As shown above, short-term activities of weak cold air are crucial for pollutant transport in the Hunan and Hubei provinces.

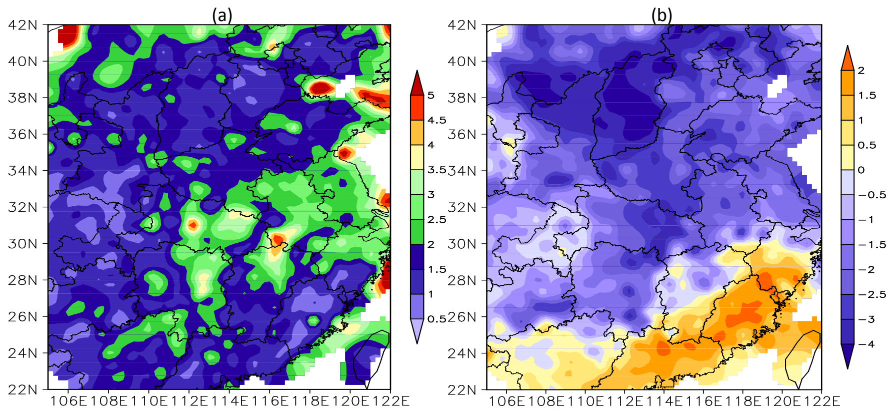


Figure 4 Spatial distribution of surface 10-m wind speeds (in m s^{-1}) during eight typical pollution events (a) and spatial distribution of 24-h temperature changes (in ℃) during the above events, with the data from nationwide observation stations at 00 UTC.

4.2 Circulation characteristics affecting regional transport

Figure 5 represents the spatial distribution of the correlation coefficient between the time series (sequences in Figure 2b) of a mode of regional pollutant transport and some meteorological parameters (SLP, boundary-layer height, and 10-m wind vector with components U and V) to verify the association between regional pollutant transport and surface synoptic situation. The results indicate that consistent with the analysis results of Figure 2d, the favourable meteorological conditions for air pollutant transport in the Hunan and Hubei provinces include anomalous northerly

https://doi.org/10.5194/acp-2020-708
Preprint. Discussion started: 16 November 2020

Atmospheric Chemistry and Physics Discussions

winds under the influence of the lower part of a surface high-pressure system and a high atmospheric boundary layer in the transport pathways of the Hunan–Hubei Plain and in its upstream area, all of which are conductive to diffusion and transport of air pollutants.

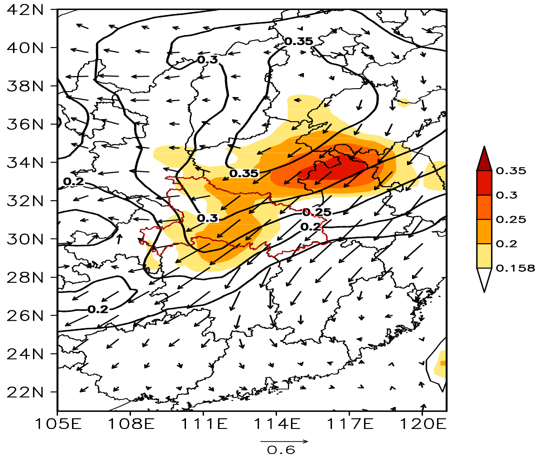


Figure 5 Spatial distributions of the correlation coefficients between the regional transport mode time coefficient and the meteorological parameters (SLP, boundary-layer height and 10-m wind vector) during the same period. The correlation coefficients of SLP denoted by black contour lines, the correlation coefficients of boundary-layer height denoted by the colour scale, and the correlation coefficients of 10-m wind vector denoted by arrows.

Figure 6 presents the surface synoptic situation and the synoptic situation at higher layers (850 hPa, 700 hPa, and 500 hPa) caused by eight typical pollutant-transport events. As shown in the figure, affected by the anomalous northerly airflow under the influence of the lower part of the surface high-pressure system in northern China, weak cold air penetrated southward to central China, driving air pollutants from the northern source areas to Hunan and Hubei provinces. The southward airflow showed a weaker convergence in southern and eastern China; moreover, warm air masses converged in the Hunan and Hubei provinces, acting as a buffer, so air pollutants were stagnated and accumulated in the Hunan–Hubei Plain, which accelerated the rapid local accumulation of pollutants. The synoptic situation at 850 hPa was similar to that of the surface, that is, the anomalous northerly winds carried the north-sourced pollutants to Hunan and Hubei provinces, and the

https://doi.org/10.5194/acp-2020-708
Preprint. Discussion started: 16 November 2020

convergence zone with positive anomalies of temperature tended to be uplifted northward, which made the upper atmospheric layer over the Hunan and Hubei provinces tend to be in a stable condition. At the mid-high layers of 700 hPa and 500 hPa, Hunan and Hubei provinces and their upstream area were markedly characterized by the presence of a "warm lid" under the influence of positive geopotential height anomalies, which prevented pollutants from diffusing to higher atmospheric layers during the transport process; moreover, a warm high-pressure system existed in the mid-high layers. All these characteristics indicated that it was a weak cold air system with a shallow boundary layer.

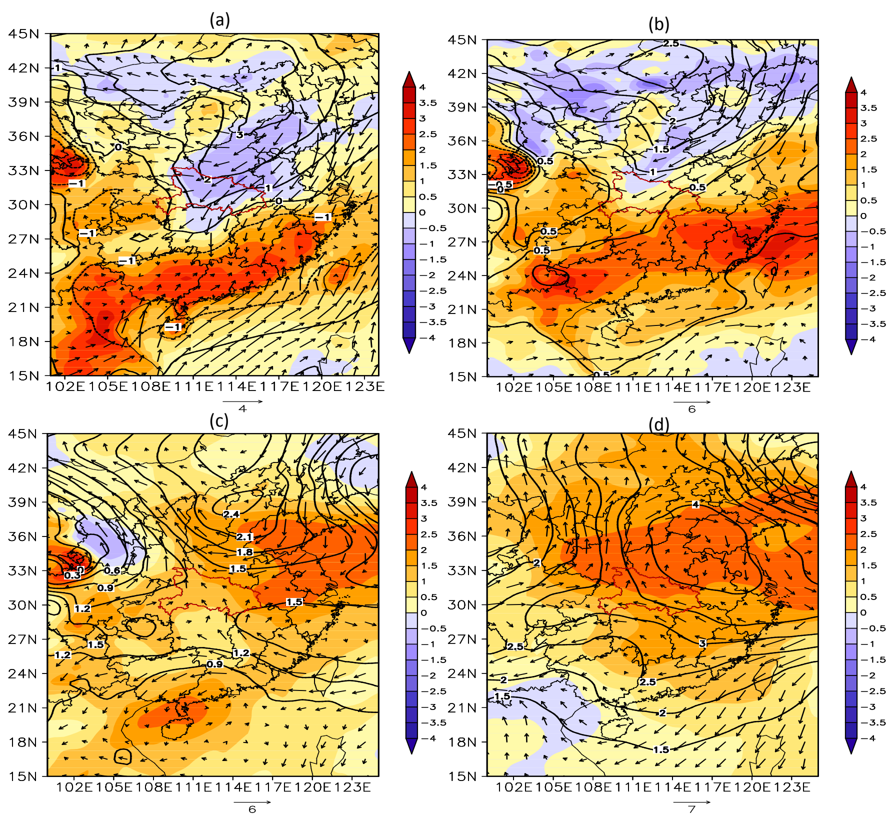


Figure 6 The surface synoptic situation (a) and the synoptic situation at higher layers of 850 hPa (b), 700 hPa (c), and 500 hPa (d) synthesised from eight typical pollutant-transport events. The black contour lines represent the anomalies of surface SLP (in hPa) and high-altitude geopotential height (in dagpm); the colour scale represents temperature anomalies (in ℃); the arrows represent anomalous wind fields (in m s^{-1}) from the ERA-interim daily dataset at 00:00 UTC.

https://doi.org/10.5194/acp-2020-708
Preprint. Discussion started: 16 November 2020

Atmospheric Chemistry and Physics
Discussions

The atmospheric circulation situation on pollution-free days showed that strong cold-air advection with strong winds would have an obvious positive effect on the removal of air pollutants. To better understand the differences between the meteorological conditions for air pollutant transport into the Hunan and Hubei provinces and the meteorological conditions for air pollutant removal from the region, the synoptic situation for strong winds to remove pollution was synthesized from eight events in which air pollutants were removed by strong winds. Next, the element-wise differences of the synoptic situation between the above two types of events were calculated, as shown in Figure 7. For the surface synoptic situation, there was no significant difference in the 10-m wind vectors between the two types of events in the Hunan and Hubei provinces, but in the case of strong winds removing the pollutants, the cold high-pressure system in northern China was stronger, with strong cold airflow sweeping across the Hunan and Hubei provinces and directly affecting the coastal areas of southern and south-eastern China. The wind speeds in the coastal areas were anomalously high, where no warm air masses converged to buffer pollutant transport, so air pollutants failed to accumulate in the Hunan and Hubei provinces. Moreover, the differences in the synoptic situation at the mid-high layers indicated that when strong winds were removing the air pollutants, the northerly winds were stronger, the cold air masses were thicker, and no stationary atmospheric states could be formed in the mid-high layers above Hunan and Hubei provinces, which facilitated vertical diffusion of pollutants.

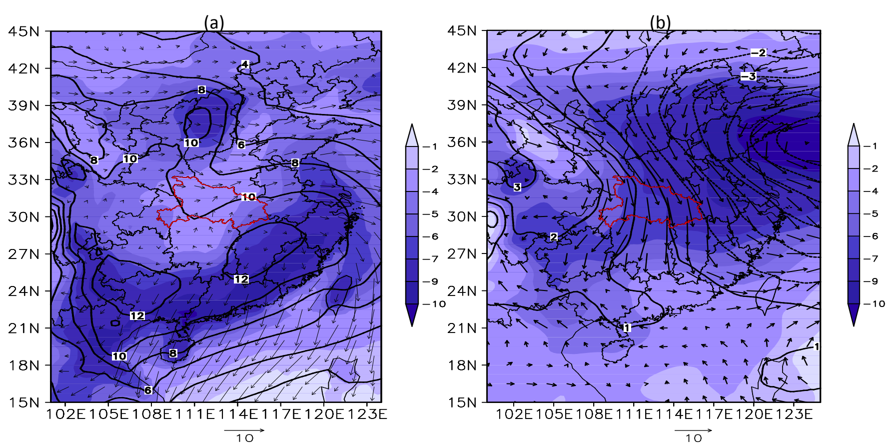


Figure 7 Element-wise differences in synthesized synoptic situations between eight

https://doi.org/10.5194/acp-2020-708
Preprint. Discussion started: 16 November 2020

Atmospheric Chemistry and Physics
Open Access
EGU
Discussions

events of big wind-induced pollutant removal and eight events of big wind-induced pollutant input at the surface (a) and the atmospheric layer of 700 hPa (b), with the black contour lines representing the surface SLP differences (in hPa) and the high-altitude geopotential height differences (in dagpm), the colour scale representing the temperature differences (in ℃), and the arrows representing the wind field differences (in m s^{-1}) from the ERA-interim daily dataset at 00:00 UTC.

4.3 Influence of atmospheric vertical structure on regional transport

Figure 8 presents the longitudinal cross-sectional structure of the pollutant-transport channel along the Hunan–Hubei Plain (synthesised from eight typical pollutant-transport events). There was a clear longitudinal vertical circulation above the plain, which spanned the latitudes of 26.5 °N–32.5 °N and vertically extended to the layer of 650 hPa, with the central height corresponding to an air pressure of 800 hPa. The mid-high layers above the 800-hPa layer were dominated by weak southerly airflow, whereas below the 800-hPa layer, strong northerly airflow was observed, with wind speed anomalies reaching 2–5 m s^{-1}. The northerly airflow rose in the south of the plain, but it underwent circulation and sank in the north of the plain. The longitudinal vertical circulation structure was triggered by the southward penetration of the weak cold air with a shallow boundary layer. The southward moving weak cold air was wedged into the bottom of the warm air, and the warm air was uplifted, not only leading to stable stratification similar to that in the frontal zone but also forming a high-altitude "warm lid" above the Hunan–Hubei Plain and the upstream area, which suppressed the vertical diffusion of pollutants during their transport. The cold air exhibited weak activity, and wind speed anomalies turned negative in the downstream area, where warm air was squeezed and underwent convergence, rising and moving northward in a roundabout manner. Later, the warm air transformed into a sinking airflow when blocked by the high-altitude "warm lid", which resulted in air pollutant accumulation and completion of the longitudinal vertical circulation. Vertical circulation played an important role in the transport and formation of heavy pollution in the Hunan and Hubei provinces, promoting the north-sourced pollutants to migrate and accumulate towards the Hunan–Hubei Plain. In addition, the stable stratification at mid-high layers inhibited the escape of air pollutants, thereby confining them within the atmospheric boundary layer and promoting rapid accumulation of air pollutants in the plain.

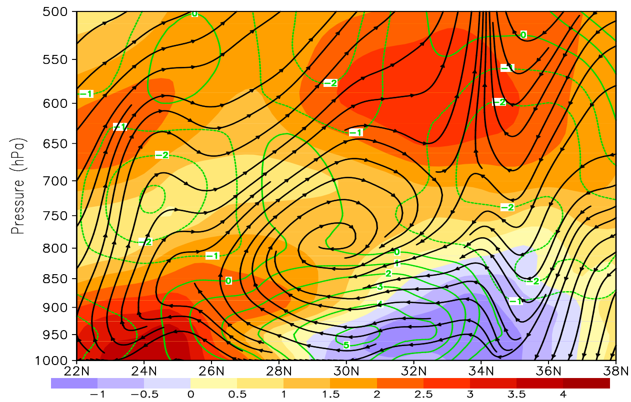


Figure 8 The longitudinal cross-sectional distribution of meteorological conditions synthesised from eight typical pollutant-transport events (112.25 °E–113 °E on average), where the black flow lines represent longitudinal circulation (synthesised by ***v*** and ***w***, vertical velocity is multiplied by 10), the green contour lines represent wind speed anomalies (in m s^{-1}), and the colour scale represents temperature anomalies (in ℃).

Based on the daily atmospheric sounding data at 00UTC recorded at the Wuhan station and Changsha station in Hunan and Hubei provinces, vertical sounding profiles of temperature and wind speed were synthesised from eight typical pollutant-transport events (Figure 9). It is evident that during pollutant transport, the surface wind speeds at the Wuhan station reached 5 m s^{-1}; in near-surface layers below 950-hPa, wind speeds and air temperature increased and decreased with the layer height, respectively, indicative of the non-stagnant state of the near-surface atmospheric structure and the “openness” of the transport channel, which facilitated the transport of a large amount of pollutants to the Hunan and Hubei provinces. In contrast, there appeared an obvious temperature inversion layer at 950-900 hPa, where the wind speeds decreased with height, forming stable atmospheric stratification which suppressed the vertical diffusion of pollutants during their transport; at 800-750 hPa, there existed another stable stratified structure, which confined air pollutant transport within the atmospheric boundary layer. Analysis of the sounding data from the Changsha station gave a consistent result, but the transport channel gradually “shrank”. The atmosphere below 975 hPa was in a non-stationary state. Above 975 hPa, the temperature inversion layer was thin, but the isothermal

https://doi.org/10.5194/acp-2020-708
Preprint. Discussion started: 16 November 2020

layer was thicker.

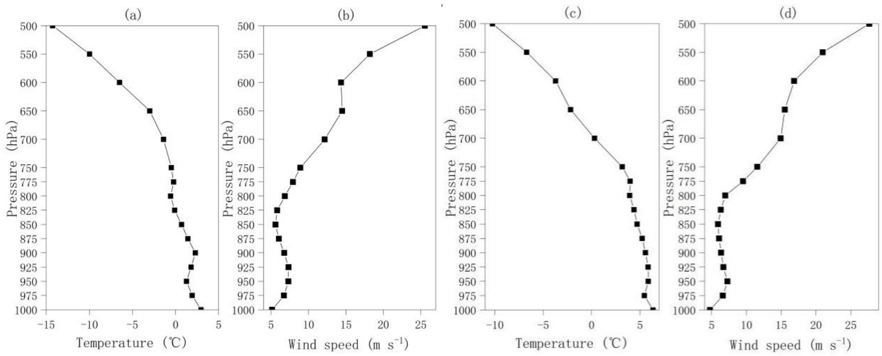


Figure 9 Atmospheric sounding profiles of temperature (a, c) and wind speed (b, d) of the Wuhan station (a, b) and Changsha station (c, d) synthesised from eight typical air pollutant transport events

Regional means of relevant meteorological parameters were calculated separately for the upstream area of Hubei province, Hubei province, and Hunan province and the downstream area of Hunan province to further investigate the vertical variation of meteorological conditions during pollutant transport in different areas (Figure 10). The results showed that in the Hunan and Hubei provinces and their upstream areas, (1) the temperature anomalies below 950 hPa decreased with height, which was consistent with the atmospheric sounding results of the meteorological stations; (2) below 850 hPa, there existed anomalous northerly winds with high speeds, with the atmosphere exhibiting non-stationary characteristics; and (3) at mid-high layers, the temperature anomalies significantly increased with height, where there existed anomalous southerly low-speed winds and stable atmospheric stratification, with anomalous “warm lid” characteristics. The low-altitude wind fields diverged in the Hubei province and its upstream area but converged in the Hunan province and its downstream area, leading to air pollutant transport and accumulation. In the downstream area, the anomalous winds turned south, buffering transport of air pollutants.

https://doi.org/10.5194/acp-2020-708
Preprint. Discussion started: 16 November 2020

Atmospheric Chemistry and Physics Discussions

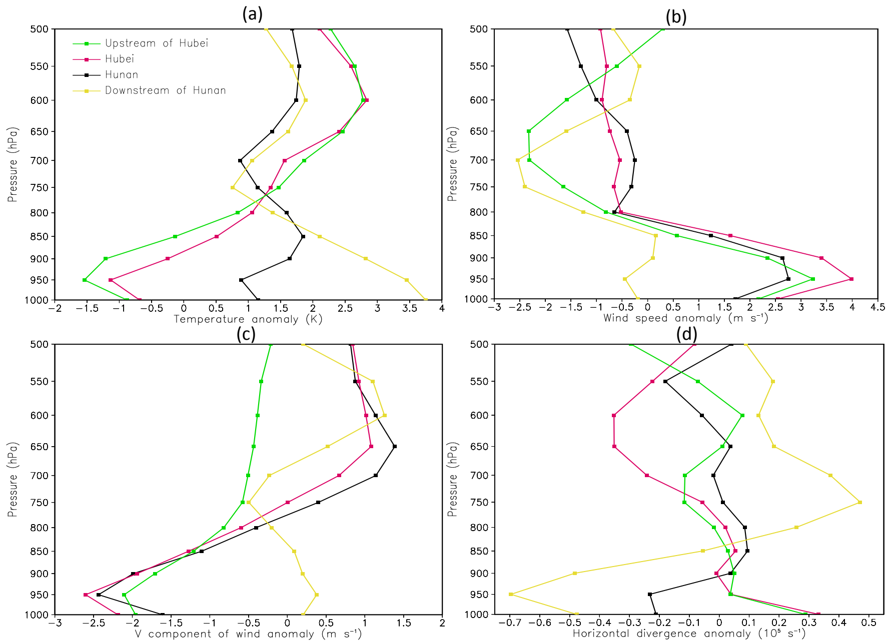


Figure 10 Synthesized vertical profiles of temperature anomaly (a), wind speed anomaly (b), v component of wind anomaly (c), and horizontal divergence anomaly (d) in different geographical areas during eight typical pollutant-transport events, where the green lines represent the upstream area (33-36 °N, 112-118 °E), the red line Hubei province (30-33 °N, 111-116 °E), the black line Hunan province (26-30 °N, 110-114 °E), and the yellow line the downstream area (23-26 °N, 109-115 °E).

As shown above, the mechanisms of meteorological conditions on air pollutant transport and the heavy pollution process in the Hunan and Hubei provinces are the following: (1) the anomalous northerly winds in the near-surface layer of the Hunan and Hubei provinces and their upstream area are accompanied by the southward penetration of a shallow cold layer, which provides dynamic conditions for regional pollution transport; (2) weak cold air degenerates as it passes through the Hunan–Hubei Plain, causing warm air to accumulate in the near-surface layer of the downstream area, where winds slow down and converge, buffering pollutant transport and thereby resulting in pollutant accumulation; (3) the atmosphere in the near-surface layer of the Hunan and Hubei provinces is in a non-stationary state (dry intrusion of cold air, anomalously strong winds, and positive anomalies of boundary-layer height), which is conducive to the horizontal transport of pollutants; (4) the mid-high layers have stable stratification, characterized by temperature inversion and the presence of a "warm lid", which inhibits the diffusion of pollutants to the upper layers; and (5) there is obvious longitudinal vertical circulation above the Hunan–Hubei Plain, and the regional transport is confined within the atmospheric boundary layer, which results in sinking and accumulation of the pollutants, thereby promoting rapid accumulation of pollutants in the Hunan and Hubei provinces.

5 Quasi-4-d periodic oscillation of pollutant transport in the Hunan and Hubei provinces

5.1 Quasi-4-d evolution characteristics of regional transport of $PM_{2.5}$

Regional transport is associated with the synoptic scale. The East Asian winter monsoon has a short-term 4-6-day cycle of weak cold air activity. Power spectrum analysis revealed that the time coefficient of the regional transport mode had a significant period of 5-6 days, which was associated with the short-term weak cold air activity of the East Asian winter monsoon. To explore the spatial evolution characteristics of the eigenvector of regional pollution transport, EEOF was used to analyse the spatio-temporal field of $PM_{2.5}$ and 10-m wind vector in central China (Hunan and Hubei provinces and the upstream area of the Henan province).

To reveal the effect of the short-term cycle of weak cold air activity on regional transport, a second-order Butterworth band-pass filter with a 4-6-day filtering window was applied on a synoptic scale to the time series of $PM_{2.5}$ and 10-m wind vector collected at 48 urban environmental monitoring stations in central China in January 2015–2019. Next, the time series of each station with a period of 4-6 days was synthesized to form a data matrix, which was subjected to EEOF decomposition based on a lag time of 2 days. The first two eigenvectors passed the significance test. The first and second eigenvectors of $PM_{2.5}$ (10-m wind vector), referred to as EEOF1 and EEOF2 respectively, cumulatively accounted for 48.9% (37.4%) of the total variance. The eigenvectors described by EEOF1 and EEOF2 represent situations at different instances of time during the periodic process, with EEOF1 leading EEOF2 in phase by a quarter of a period (1 days).

The time coefficient of EEOF eigenvectors for $PM_{2.5}$ had a good correlation with that for the 10-m wind vector (Figure 11). The EEOF2 time series of $PM_{2.5}$ was significantly positively correlated with the EEOF1 time series of 10-m wind vector (coor = 0.5), indicative of the driving of regional transport by strong winds; the

https://doi.org/10.5194/acp-2020-708
Preprint. Discussion started: 16 November 2020

EEOF1 time series of $PM_{2.5}$ was significantly negatively correlated with the EEOF2 time series of 10-m wind vector (coor = -0.6), indicative of the removal of transported pollutants by strong winds.

Figure 11 illustrates the eigenvectors (i.e., spatial distribution of the eigenvectors EEOF2 and EEOF1) of $PM_{2.5}$ in the order of increasing time lags, namely 0 day, 1 day, and 2 days for EEOF2, followed by 0 day for EEOF1. The results showed that the eigenvector of EEOF1 at a 1-day (2-day) (omitted from illustration) time lag was similar to that of EEOF2 at a 0-day (1-day) time lag, that is, the four eigenvectors constituted a 4-day oscillation period of the regional transport. Because of the correlation of EEOF time coefficient between $PM_{2.5}$ and 10-m wind vector, the eigenvectors of 10-m wind vector were arranged in the order of EEOF1 (sequentially at time lags of 0, 1, and 2 days) and EEOF2 (at a time lag of 0 d) to correspond to the above eigenvectors of $PM_{2.5}$.

As shown in Figure 11, the EEOF eigenvectors at different time lags reflected the spatial evolution characteristics of regional air pollutant transport, and the regional transport had a quasi-4-d oscillation period, with the synoptic situation undergoing the same evolution as revealed earlier in this study. On the first day, stable meteorological conditions occurred and weak winds prevailed in the whole region, with air pollutant accumulation in the upstream area of northern Henan province. On the 2nd day, the cold air penetrated southward, and the wind speeds in the upstream area increased, continuously and cumulatively transporting air pollutants to the Hunan and Hubei provinces, mainly through the Nanxiang Basin and the low hills of the Dabie Mountain. On the third day, the northerly winds in the Hunan and Hubei provinces and their upstream area reached maximum speeds, and the near-surface layer was in a non-stationary state; the air pollutants were transported along two pathways (the Nanxiang Basin-Yunmeng Plain pathway and the Dabie Mountain's Hilly Area-Yunmeng Plain pathway) to the Hunan–Hubei Plain, where they accumulated; Meanwhile, air pollutants in the upstream area of northern Henan province were removed by strong winds. The mechanism of air pollutant transport and heavy pollution formation in the Hunan and Hubei provinces has been discussed earlier in this study. On the fourth day, strong winds continued to influence the upstream area, where the local pollutants were fully removed, leading to completion of regional pollutant transport.

https://doi.org/10.5194/acp-2020-708
Preprint. Discussion started: 16 November 2020

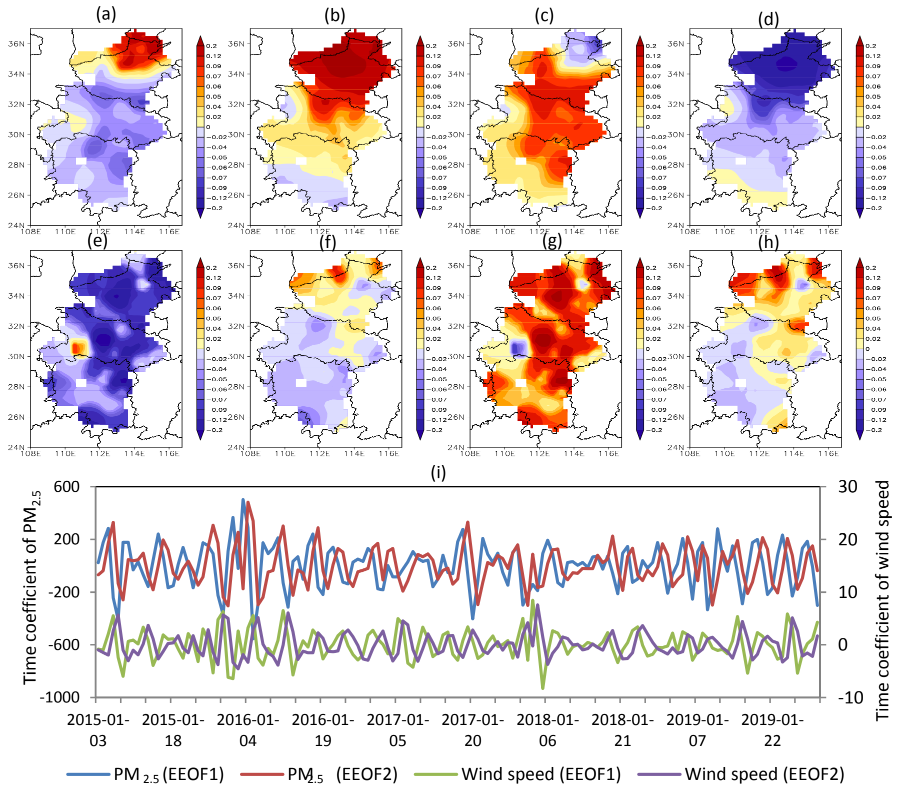


Figure 11 Eigenvectors (a-h) of the EEOF1 and EEOF2 at different time lags for $PM_{2.5}$ and 10-m wind vector during regional pollutant transport and the time coefficients (i). For $PM_{2.5,}$ EEOF2 exhibited time lags of 0 (a), 1 (b), and 2 days (c), and EEOF1 exhibited a time lag of 0 day (d); for the 10-m wind vector, EEOF1 exhibited time lags of 0 d (e), 1 d (f), and 2d (g), and EEOF2 exhibited a time lag of 0 day (h).

5.2 Numerical simulation validation

The regional transport event during January 3 and 6, 2016 selected from table 1, which corresponded to the maximum positive values of the EEOF time coefficient, was used WRF-Chem model to simulate pollutant-transport characteristics and meteorological transport conditions in Hunan and Hubei provinces, and a closure experiment was performed on pollutant emission sources to verify the important contribution of regional transport to the rapid accumulation of air pollutants in the Hunan–Hubei Plain.

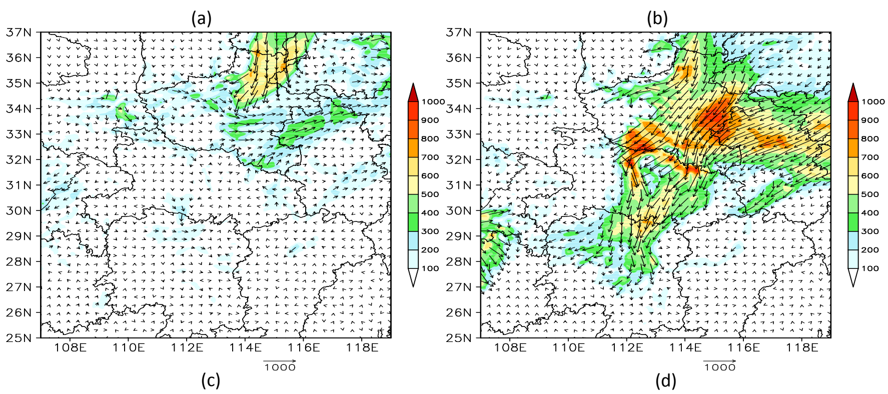
WRF-Chem is a new-generation mesoscale three-dimensional air quality model

https://doi.org/10.5194/acp-2020-708
Preprint. Discussion started: 16 November 2020

Atmospheric Chemistry and Physics Discussions

(Grell et al., 2005), which is jointly developed by NOAA, NCAR, and UCAR and allows on-line coupling of meteorological conditions and atmospheric chemistry. A central China-specific environmental meteorology numerical model system with the WRF-Chem model as the core component demonstrated good performance in forecast evaluation and application (Bai et al., 2016, 2020), and the scheme for localized testing of the model is documented in detail elsewhere (Bai et al., 2016). The air pollutant transport process during January 3-6, 2016, in the Hunan and Hubei provinces was simulated here by the above numerical model system based on the MIX anthropogenic emissions inventory for Asia in January 2016 (Li et al., 2017b), with the initial and boundary atmospheric conditions set using the NCAR FNL data with a resolution of 1 °× 1 °.

Figure 12 shows the evolving spatial distribution of the regional transport flux of $PM_{2.5}$ at 00 UTC during January 3-6, 2016. The results indicate that the simulation results were very similar to the EEOF analysis results. The regional pollution transport was subject to a quasi-4-d period consisting of the following sequential events: pollutant accumulation in the upstream calm wind zone, pollutant inputs along the Nanxiang Basin and the hilly area of the Dabie Mountain, pollutant transport and accumulation in the Hunan–Hubei Plain, and dissipation and removal of regional pollution.



https://doi.org/10.5194/acp-2020-708
Preprint. Discussion started: 16 November 2020

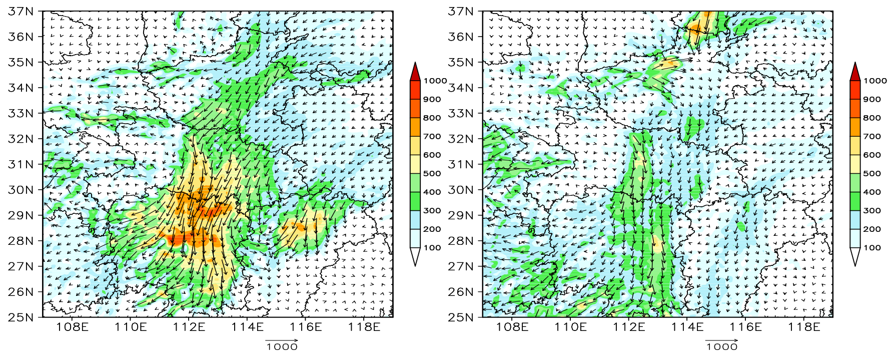


Figure 12 Spatial distribution of the regional transport flux of $PM_{2.5}$ simulated by the WRF-Chem model (the arrows denote $PM_{2.5}$ transport flux, and the colour scales denote modulus length in μg m^{-2} S^{-1}) at 00 UTC on January 3 (a), January 4 (b), January 5 (c), and January 6 (d) in 2016.

Figure 13 presents a longitudinal cross-sectional profile of the regional transport pathway within the atmospheric boundary layer along the Hunan–Hubei Plain at different transport times. The results indicated that the main transport pathway of air pollutants was below 1-km height in the atmospheric boundary layer. Air pollutants were inputted and accumulated along the Nanxiang Basin and then transported to the Hunan–Hubei Plain under the driving force of the northerly airflow, whereas the southerly airflow acted as a buffer to prevent air pollutants from moving further southward, which resulted in rapid accumulation of the transported pollutants; the maximum values of $PM_{2.5}$ transport flux were observed near a height of 400-600 m. The atmosphere below 1-km height in the atmospheric boundary layer of the Huan–Hubei Plain was in a non-stationary state, while there existed obvious isothermal stratification in the atmosphere above the pathway, which limited the upward diffusion of pollutants. The simulation results verified the above-mentioned effect mechanism of meteorological conditions on air pollutant transport and heavy pollution in the Hunan and Hubei provinces.

https://doi.org/10.5194/acp-2020-708
Preprint. Discussion started: 16 November 2020

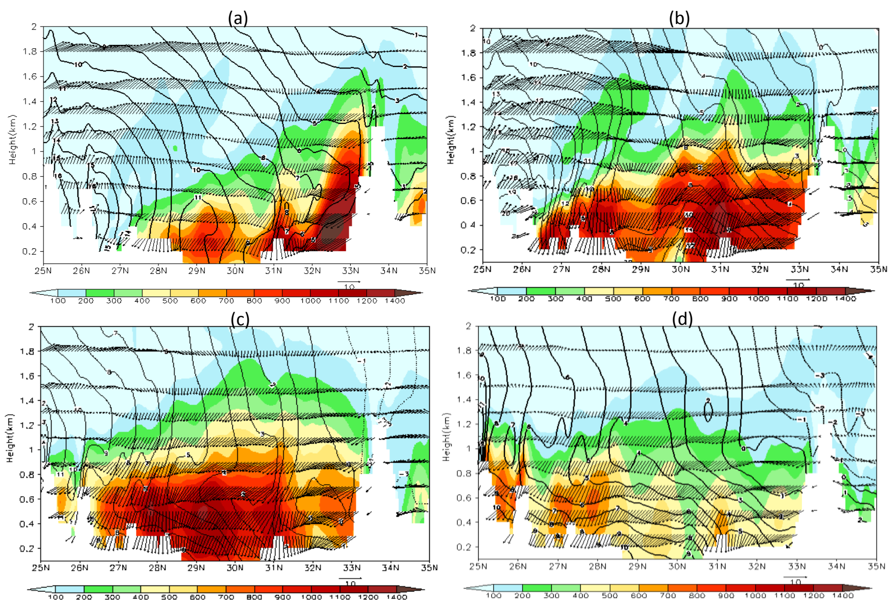


Figure 13 Longitudinal cross-sectional profiles simulated by the WRF-Chem model for pollutant transport along 112.25 °E at 00 UTC of January 4 (a), 12 UTC of January 4 (b), 00 UTC of January 5 (c), and 12 UTC of January 5 (d) in 2016, where the colour scales represent $PM_{2.5}$ transport flux (in μg m^{-2} s^{-1}), the arrows represent horizontal wind fields (in m s^{-1}), and the black contour lines represent temperature (in ℃).

A closure experiment was conducted by hypothetically shutting down the anthropogenic emission sources in the Hunan and Hubei provinces and simulating the $PM_{2.5}$ flux component and flux percentage in the two provinces contributed by $PM_{2.5}$ transport from exogenous sources. Figure 14 presents a simulated time-dependent vertical profile on the Jianghan Plain in the closure experiment. The results showed that the vertical distribution of pollutants during their transport was affected by the northerly winds in the boundary layer. An increase in wind speed led to an increase in $PM_{2.5}$ transport, with transport from exogenous sources contributing as high as 60-80% to the near-surface $PM_{2.5}$ and as high as 80-90% to $PM_{2.5}$ at a height of 600-900 m, which indicated that the regional transport had a significant promotional effect on pollutant accumulation in the Hunan and Hubei provinces. Because of the instability of near-surface atmospheric layer, the transported exogenous $PM_{2.5}$ accumulated first on the surface (18-19 UTC on January 4) and then accumulated continuously for 3-4 h

https://doi.org/10.5194/acp-2020-708
Preprint. Discussion started: 16 November 2020

at the bottom of the isothermal layer at a height near 700 m, which indicated that the high-altitude accumulation of transported pollutants was closely related to stable atmospheric stratification.

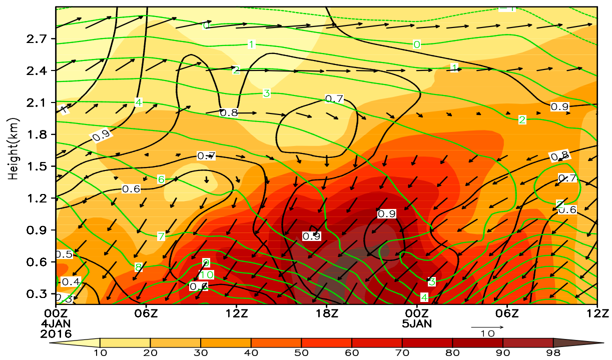


Figure 14 A height-time profile (30 °N, 112.25 °E) simulated by the WRF-Chem model for pollutant transport after hypothetical closure of the local anthropogenic emission sources of Hunan and Hubei provinces, where the colour scales represent the concentration of $PM_{2.5}$ transported from exogenous sources (in μg m^{-3}), the arrows represent horizontal wind fields (in m s^{-1}), the green contour lines represent temperature (in °C), and the black contour lines represent the percent contribution of exogenous sources to $PM_{2.5}$ transport ($PM_{2.5}$ concentration in the closure experiment divided by $PM_{2.5}$ concentration in a control experiment).

6 Conclusions and discussions

The Hunan–Hubei Plain in the middle Yangtze Basin has a special geographical location. It forms a border of China's areas with the most concentrated atmospheric pollution—the Central Plains, Fenwei Plain, North China Plain, and Yangtze River Delta region—and is located in the downwind direction of the areas of heavy pollution sources under the influence of winter monsoon, serving as a hub for the regional transport of atmospheric pollutants in China. The extent and mechanism of the effect of regional pollutant transport on air pollution in the Hunan–Hubei Plain is a pressing issue in atmospheric environmental science, calling for in-depth investigation. Different from cumulative heavy pollution in central and eastern China, the pollutant transport characteristics and the effect mechanism of meteorological conditions on heavy pollution processes in typical regions like Hunan and Hubei provinces have not been systematically investigated yet.

https://doi.org/10.5194/acp-2020-708
Preprint. Discussion started: 16 November 2020

Different from the cumulative heavy pollution under unfavourable local meteorological conditions, the atmospherically transported heavy air pollution is under favourable meteorological conditions for horizontal diffusion, that is, the atmospheric boundary layer is high, the wind speeds in the near-surface layer are anomalously high, and the $PM_{2.5}$ concentration tends to grow rapidly under the influence of strong northerly winds. The MV-EOF method was employed in this study to extract a typical mode of regional pollutant transport, which was characterized by high $PM_{2.5}$ concentration, south–north pressure gradient, and anomalous northerly winds in the Hunan and Hubei provinces in January 2015–2019. The time coefficient of the MV-EOF mode accounted for 48.4% of the total variance of the average $PM_{2.5}$ concentration in the two provinces, which indicated that regional pollutant transport was almost the dominant factor determining the changes in pollutant concentration in the region; regional transport caused the $PM_{2.5}$ concentration anomalies in the Wuhan-centred urban agglomeration and the Changsha–Zhuzhou–Xiangtan urban agglomeration to exceed 50 μg m^{-3}, promoting rapid local accumulation of pollutants in these high-density cities.

By synthesizing eight typical pollutant-transport events in Hunan and Hubei provinces in conjunction with surface meteorological observation data, atmospheric sounding data, and reanalysis data, this study comprehensively analyzed the effect mechanism of meteorological conditions on air pollutant transport and accumulation (Figure 15). Transporting air pollutants mainly passed through the Nanxiang Basin and the low hills of the Dabie Mountain. The anomalous northerly winds in the near-surface layer of the Hunan and Hubei provinces and their upstream area were accompanied by southward penetration of a shallow cold layer, which provided dynamic conditions for regional air pollutant transport. The weak cold air degenerates as it passes through the Hunan–Hubei Plain, causing warm air to accumulate in the near-surface layer of the downstream area, where winds slow down and converge, buffering pollutant transport and resulting in pollutant accumulation; the atmosphere in the near-surface layer of the Hunan and Hubei provinces is in a non-stationary state (dry intrusion of cold air, anomalously strong winds, and positive anomalies of boundary-layer height), which is conducive to the horizontal transport of pollutants. The mid-high layers have stable stratification, characterized by temperature inversion and the presence of a "warm lid", which inhibits the diffusion of air pollutants to the upper layers; there is obvious longitudinal vertical circulation above the Hunan–Hubei

https://doi.org/10.5194/acp-2020-708
Preprint. Discussion started: 16 November 2020

Atmospheric Chemistry and Physics Discussions

Plain, which confines the regional transport within the atmospheric boundary layer where the pollutants sink and accumulate, thereby promoting rapid accumulation of pollutants in Hunan and Hubei provinces. These results are also verified by numerical simulations.

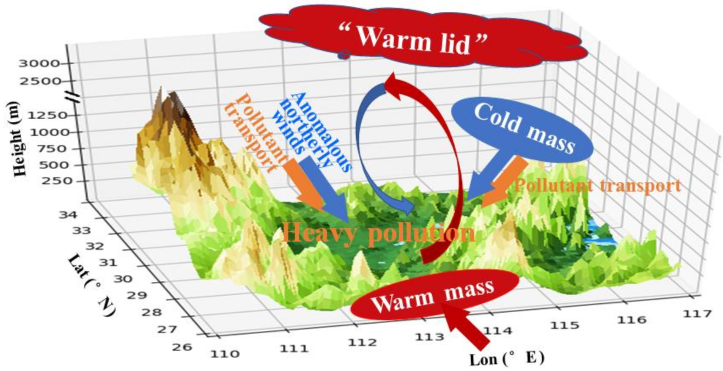


Figure 15. Meteorological mechanism of regional transport in winter heavy air pollution events in the middle Yangtze Basin areas over China

The activities of weak cold air are crucial for pollutant transport in the Hunan and Hubei provinces. EEOF analysis revealed that the regional pollutant transport in the two provinces is subject to a quasi-4-d period consisting of the following sequential events: pollutant accumulation in the upstream calm wind zone, air pollutant input along the Nanxiang Basin and the hilly area of the Dabie Mountain, pollutants transport and accumulation in the Hunan–Hubei Plain, dissipation and removal of regional pollution; this is associated with the short-term 4-6-day cycle of weak cold air activity during the East Asian winter monsoon. It is noteworthy that the continuous accumulation of air pollutants in the upstream area and the sudden changes of synoptic situation (i.e., a change from a uniform surface pressure field to a surface high-pressure system whose lower part strongly influences the surface, an increase of the south–north pressure gradient, and the formation of anomalous northerly airflow) can be used as a predictive warning sign for air pollutant transport in the Hunan and Hubei provinces.

In addition, from a geographic aspect, the Hunan and Hubei provinces are in a large exoreic basin, which is bounded by the Jing Mountain, Dahong Mountain, and Dabie Mountain to the north, the Wuling Mountains to the west, the Mufu Mountain and Luoxiao Mountain to the east, and the Xuefeng Mountain and its foothills to the

Atmospheric Chemistry and Physics Discussions
Open Access

south and has an area of more than 130,000 km^2. It is necessary to have deeper insights into the concentrating effect of this special sub-basin topography and the underlying surface of the complicated basin on regional air pollutant transport, as well as the mechanism of the multi-scale synergistic effect of local circulation, synoptic situation, and East Asian monsoon climate change on regional air pollutant transport.

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

Author contributions. YB , TZ, and YZ conducted the study design. JX, WH, and SK provided the observational data. WH, YG, HZ and LL assisted with data processing. YB wrote the paper with the help of LL and SK. TZ, YZ, JX, LL, and SK were involved in the scientific interpretation and discussion. All authors provided commentary on the paper.

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

Acknowledgment. The authors are grateful to Associate Professor Zhao Shuyun, Department of Atmospheric Sciences, School of Environmental Sciences, China University of Geosciences (Wuhan) for the useful comments on improving the first draft of this paper.

Financial support. This research has been supported by the National Natural Science Foundation of China (grant no. 41830965; 42075186), the National Key Research and Development Project of China (grant no. 2016YFC0203304).

References

Bai, Y., Qi, H., Liu, L., Cui, C., Lin, C., and Tan, C.: Development and Preliminary Application of Environmental Meteorology Numerical Model System in Central China(in Chinese), Plateau Meteor., 35, 1671-1682, 10.7522/j.issn.1000-0534.2015.00086, 2016.

Bai, Y., Qi, H., Zhao, T., Zhou, Y., Liu, L., Xiong, J., Zhou, Z., Cui, C.: Simulation of the responses of rainstorm in the Yangtze River Middle Reaches to changes in anthropogenic aerosols emissions. Atmos. Environ., 220, 117081, 10.1016/j.atmosenv.2019.117081, 2020.

Chen, L., Zhu, J., Liao, H., Gao, Y., Qiu, Y., Zhang, M., Liu, Z., Li, N., and Wang, Y.: Assessing the

https://doi.org/10.5194/acp-2020-708
Preprint. Discussion started: 16 November 2020

Atmospheric Chemistry and Physics Discussions

formation and evolution mechanisms of severe haze pollution in the Beijing–Tianjin–Hebei region using process analysis, Atmos. Chem. Phys., 19, 10845-10864, 10.5194/acp-19-10845-2019, 2019.

Cheng, J., Su, J., Cui, T., Li, X., Dong, X., Sun, F., Yang, Y., Tong, D., Zheng, Y., Li, Y., Li, J., Zhang, Q., and He, K.: Dominant role of emission reduction in PM 2.5 air quality improvement in Beijing during 2013–2017: a model-based decomposition analysis. Atmos. Chem. Phys. 19, 6125–6146.10.5194/acp-19-6125-2019, 2019.

Ding, A., Huang, X., Nie, W., Chi, X., Xu, Z., Zheng, L., Xu, Z., Xie, Y., Qi, X., Shen, Y., Sun, P., Wang, J., Gao, M., Carmichael, G. R., Wang, Y., Saide, P. E., Yu, M., Xin, J., Liu, Z., and Wang, Z.: Modeling study of the 2010 regional haze event in the North China Plain, Atmos. Chem. Phys., 16, 1673-1691, 10.5194/acp-16-1673-2016, 2016.

Ding, Y., Wu, p., Liu, Y., Song, Y.: Environmental and Dynamic Conditions for the Occurrence of Persistent Haze Events in North China, Engineering, 3, 266-271, 10.1016/J.ENG.2017.01.009, 2017.

Grell, G. A., Peckham, S. E., Schmitz, R., McKeen, S. A., Frost, G., Skamarock, W. C., and Eder, B.: Fully coupled “online” chemistry within the WRF model, Atmos. Environ., 39, 6957-6975, 10.1016/j.atmosenv.2005.04.027, 2005.

Guo, J., He, J., Liu, H., Miao, Y., Liu, H., and Zhai, P.: Impact of various emission control schemes on air quality using WRF-Chem during APEC China 2014, Atmos. Environ., 140, 311-319, 10.1016/j.atmosenv.2016.05.046, 2016a.

Guo, J., Miao, Y., Zhang, Y., Liu, H., Li, Z., Zhang, W., He, J., Lou, M., Yan, Y., Bian, L., and Zhai, P.: The climatology of planetary boundary layer height in China derived from radiosonde and reanalysis data, Atmos. Chem. Phys., 16, 13309-13319, 10.5194/acp-16-13309-2016, 2016b.

Guo, J., Li, Y., Cohen, J. B., Li, J., Chen, D., Xu, H., Liu, L., Yin, J., Hu, K., and Zhai, P.: Shift in the temporal trend of boundary layer height in China using long‐term (1979‐2016) radiosonde data. Geophys. Res. Lett., 46, 6080-6089. https://doi.org/10.1029/2019GL082666, 2019.

Huang, X. Ding, A., Wang, Z., Ding., K. Gao. J., Chai., F., and Fu. C.: Amplified transboundary transport of haze by aerosol-boundary layer interaction in China, Nat. Geosci., 13, 428-434, doi:10.1038/s41561-020-0583-4, 2020.

Kan, H., Chen, R., and Tong, S.: Ambient air pollution, climate change, and population health in China, Environ. Int., 42, 10-19, 10.1016/j.envint.2011.03.003, 2012.

Kang, H., Zhu, B., Gao, J., He, Y., Wang, H., Su, J., Pan, C., Zhu, T., and Yu, B.: Potential impacts of cold frontal passage on air quality over the Yangtze River Delta, China, Atmos. Chem. Phys., 19, 3673-3685, 10.5194/acp-19-3673-2019, 2019.

Khuzestani, R.B., Schauer, J. J., Wei, Y., Zhang, L., Cai., T., Zhang, Y., Zhang, Y.: Quantification of the sources of long-range transport of PM2.5 pollution in the Ordos region, Inner Mongolia, China, Environ. Pollut., 229, 1019-1031, 10.1016/j.envpol.2017.07.093, 2017.

Kim, C.-H., Park, S.-Y., Kim, Y.-J., Chang, L.-S., Song, S.-K., Moon, Y.-S., and Song, C.-K.: A numerical study on indicators of long-range transport potential for anthropogenic particulate matters over northeast Asia, Atmos. Environ., 58, 35-44, 10.1016/j.atmosenv.2011.11.002, 2012.

Li, J., Du, H., Wang, Z., Sun, Y., Yang, W., Li, J., Tang, X., and Fu, P.: Rapid formation of a severe regional winter haze episode over a mega-city cluster on the North China Plain, Environ. Pollut., 223, 605-615, 10.1016/j.envpol.2017.01.063, 2017a.

Li, M., Zhang, Q., Kurokawa, J.-i., Woo, J.-H., He, K., Lu, Z., Ohara, T., Song, Y., Streets, D. G., Carmichael, G. R., Cheng, Y., Hong, C., Huo, H., Jiang, X., Kang, S., Liu, F., Su, H., and Zheng, B.: MIX: a mosaic Asian anthropogenic emission inventory under the international collaboration framework of the MICS-Asia

https://doi.org/10.5194/acp-2020-708
Preprint. Discussion started: 16 November 2020

Atmospheric Chemistry and Physics Discussions

and HTAP, Atmos. Chem. Phys., 17, 935-963, 10.5194/acp-17-935-2017, 2017b.

Li, M., Yuan, K., Hu, K., and Liu, W.: Trigger mechanism and main factors of urban heavy pollution processes in Wuhan(in Chinese). Torrential Rain Disaster., 38(6), 624-631. 10.3969/j.issn.1004-9045.2019.06.007, 2019.

Li, R., Mei, X., Wei L., Han, X., Zhang, M., Jing, Y.: Study on the contribution of transport to PM2.5 in typical regions of China using the regional air quality model RAMS-CMAQ, Atmos. Environ., 214, 116856, https://doi.org/10.1016/j.atmosenv.2019.116856, 2019.

Lu, M., Tang, X., Wang, Z., Gbaguidi, A., Liang, S., Hu, K., Wu, L., Wu, H., Huang, Z., and Shen, L.: Source tagging modeling study of heavy haze episodes under complex regional transport processes over Wuhan megacity, Central China. Environ. Pollut., 231, 612–621, 10.1016/j.envpol.2017.08.046, 2017.

Lu, Y., Wang, Y., Zhang, W., Klaus, H., Bi, F., Zuo, J., Jiang, H., Zhang Z., Feng, K., Liu, Y., and Xue., W.: Provincial air pollution responsibility and environmental tax of China based on interregional linkage indicators, J. Clean. Prod., 235, 337-347,10.1016/j.jclepro.2019.06.293, 2019a.

Lu, M., Tang, X., Wang, Z., Wu, L., Chen, X., Liang, S., Zhou, H., Wu, H., Hu, K., Shen, L., Yu, J., and Zhu, J.: Investigating the Transport Mechanism of PM2.5 Pollution during January 2014 in Wuhan, Central China, Adv. Atmos. Sci., 36, 1217-1234, 10.1007/s00376-019-8260-5, 2019b.

Miao, Y., Guo, J., Liu, S., Liu, H., Li, Z., Zhang, W., and Zhai, P.: Classification of summertime synoptic patterns in Beijing and their associations with boundary layer structure affecting aerosol pollution, Atmos. Chem. Phys., 17, 3097-3110, 10.5194/acp-17-3097-2017, 2017.

Ning, G., Wang, S., Yim, S. H. L., Li, J., Hu, Y., Shang, Z., Wang, J., and Wang, J.: Impact of low-pressure systems on winter heavy air pollution in the northwest Sichuan Basin, China, Atmos. Chem. Phys., 18, 13601-13615, 10.5194/acp-18-13601-2018, 2018.

Tai, A. P. K., Mickley, L. J., and Jacob, D. J.: Impact of 2000-2050 climate change on fine particulate matter ($PM_{2.5}$) air quality inferred from a multi-model analysis of meteorological modes. Atmos. Chem. Phys., 12, 11329-11337, 10.5194/acp-12-11329-2012, 2012.

Wang, Y., Yao, L., Wang, L., Liu, Z., Ji, D., Tang, G., Zhang, J., Sun, Y., Hu, B., and Xin, J.: Mechanism for the formation of the January 2013 heavy haze pollution episode over central and eastern China, Sci. China Earth Sci., 57, 14-25, 10.1007/s11430-013-4773-4, 2013a.

Wang, Z., Li, J., Wang, Z., Yang, W., Tang, X., Ge, B., Yan, P., Zhu, L., Chen, X., Chen, H., Wand, W., Li, J., Liu, B., Wang, X., Wand, W., Zhao, Y., Lu, N., and Su, D.: Modeling study of regional severe hazes over mid-eastern China in January 2013 and its implications on pollution prevention and control, Sci. China Earth Sci., 57, 3-13, 10.1007/s11430-013-4793-0, 2013b.

Wu, D., Fung, J. C. H., Yao, T., and Lau, A. K. H.: A study of control policy in the Pearl River Delta region by using the particulate matter source apportionment method, Atmos. Environ., 76, 147-161, 10.1016/j.atmosenv.2012.11.069, 2013a.

Wu, J., Guo, J., and Zhao, D.: Characteristics of aerosol transport and distribution in East Asia, Atmos. Res., 132-133, 185-198, 10.1016/j.atmosres.2013.05.018, 2013b.

Xiao, Z., Miao, Y., Du, X., Tang, W., Yu, Y., Zhang, X., Che, H.: Impacts of regional transport and boundary layer structure on the PM2.5 pollution in Wuhan, Central China, China. Atmos. Environ., 230, 117508, 10.1016/j.atmosenv.2020.117508, 2020.

Xu, J., Chang, L., Qu, Y., Yan, F., Wang, F., Fu, Q.: The meteorological modulation on PM2.5 interannual oscillation during 2013 to 2015 in Shanghai, China. Sci. Total Environ., 572, 1138–1149, 10.1016/j.scitotenv.2016.08.024, 2016.

https://doi.org/10.5194/acp-2020-708
Preprint. Discussion started: 16 November 2020

Xu, X., Zhao, T., Liu, F., Gong, S. L., Kristovich, D., Lu, C., Guo, Y., Cheng, X., Wang, Y., and Ding, G.: Climate modulation of the Tibetan Plateau on haze in China, Atmos. Chem. Phys., 16, 1365-1375, 10.5194/acp-16-1365-2016, 2016.

Yang, Y., Yim, S. H. L., Haywood, J., Osborne, M., Chan, J. C. S., Zeng, Z., Cheng, J. C. H.: Characteristics of heavy particulate matter pollution events over Hong Kong and their relationships with vertical wind profiles using high‐time‐resolution Doppler lidar measurements. J. Geophys. Res.-Atmos., 124, 9609–9623, 10.1029/2019JD031140, 2019.

Yuan, C., Lau, W. K. M., Li, Z., and Cribb, M.: Relationship between Asian monsoon strength and transport of surface aerosols to the Asian Tropopause Aerosol Layer (ATAL): interannual variability and decadal changes, Atmos. Chem. Phys., 19, 1901-1913, 10.5194/acp-19-1901-2019, 2019.

Yue, Y., Wang, X., Zhang, M., Cao, W., Zhou, Y., Chen, S., and Zhu, Y.: Air quality condition in Wuhan and its relationship to meteorological factors(in Chinese). Torrential Rain Disaster., 35(3), 271–278. 10.3969/j.issn.1004-9045.2016.03.010,2016.

Yu, C., Zhao, T., Bai, Y., Zhang, L., Kong, S., Yu, X., He, J., Cui, C., Yang, J., You, Y., Ma, G., Wu, M., and Chang, J. : Heavy air pollution with a unique “non-stagnant” atmospheric boundary layer in the Yangtze River middle basin aggravated by regional transport of PM_{2.5} over China. Atmos. Chem. Phys., 20, 7217–7230. 10.5194/acp-20-7217-2020,2020.

Zhang, J., Zhu, T., Zhang, Q., Li, C., Shu, H., Ying, Y., Dai, Z., Wang, X., Liu, X., Liang, A., Shen, H., and Yi, B.: The impact of circulation patterns on regional transport pathways and air quality over Beijing and its surroundings, Atmos. Chem. Phys., 12, 5031-5053, 10.5194/acp-12-5031-2012, 2012a.

Zhang, X., Wang, Y., Niu, T., Zhang, X., Gong, S., Zhang, Y., and Sun, J.: Atmospheric aerosol compositions in China: spatial/temporal variability, chemical signature, regional haze distribution and comparisons with global aerosols, Atmos. Chem. Phys., 12, 779-799, 10.5194/acp-12-779-2012, 2012b.

Zhang, X., Wang, J., Wang, Y., Liu, H., Sun, J., and Zhang, Y.: Changes in chemical components of aerosol particles in different haze regions in China from 2006 to 2013 and contribution of meteorological factors, Atmos. Chem. Phys., 15, 12935-12952, 10.5194/acp-15-12935-2015, 2015.

Zhang, X., Zhong, J., Wang, J., Wang, Y., and Liu, Y.: The interdecadal worsening of weather conditions affecting aerosol pollution in the Beijing area in relation to climate warming, Atmos. Chem. Phys., 18, 5991-5999, 10.5194/acp-18-5991-2018, 2018.

Zhang, X., Xu, X., Ding, Y., Liu, Y., Zhang, H., Wang, Y., and Zhong, J.: The impact of meteorological changes from 2013 to 2017 on PM2.5 mass reduction in key regions in China, Sci. China Earth Sci., 10.1007/s11430-019-9343-3, 2019.

Zhao, X., Zhao, P., Xu, J., Meng, W., Pu, W., Dong, F., He, D., and Shi, Q.: Analysis of a winter regional haze event and its formation mechanism in the North China Plain, Atmos. Chem. Phys., 13, 5685-5696, 10.5194/acp-13-5685-2013, 2013.