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RESEARCH ARTICLE

Impacts of meteorological conditions on wintertime $PM_{2.5}$ pollution in Taiyuan, North China

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Abstract

Taiyuan frequently experiences heavy $PM_{2.5}$ pollution in winter under unfavorable meteorological conditions. To understand how the meteorological factors influence the pollution in Taiyuan, this study involved a systematic analysis for a continuous period from November 2016 to January 2017, using near-surface meteorological observations, radiosonde soundings, $PM_{2.5}$ measurements, and three-dimension numerical simulation, in combination with backward trajectory calculations. The results show that $PM_{2.5}$ concentration positively correlates with surface temperature and relative humidity and anti-correlates with near-surface wind speed and boundary layer height (BLH). The low BLH is often associated with a strong thermal inversion layer capping over. In addition to the high local emissions, it is found that under certain synoptic conditions, the southwesterly and southerly winds could bring pollutants from Linfen to Taiyuan, leading to a near-surface $PM_{2.5}$ concentration higher than 200 μg m^{-3}. Another pollution enhancing issue is due to the semi-closed basin of Taiyuan affecting the planetary boundary layer (PBL): the surrounding mountains favor the formation of a cold air pool in the basin, which inhibits vertical exchanges of heat, flux, and momentum between PBL and the free troposphere, resulting in stagnant conditions and poor air quality in Taiyuan. These findings can be utilized to improve the understanding of $PM_{2.5}$ pollution in Taiyuan, to enhance the accuracy of forecasting pollution, and to provide scientific support for policy makers to mitigate the pollution.

Keywords $PM_{2.5}$ · Meteorological condition · Boundary layer height · WRF model

Introduction

Taiyuan, the capital of Shanxi province, is one of the main manufacturing bases of North China, with a population exceeding 4.3 million and ~ 1.45 million motor vehicles. The elevation of the city is ~ 800 m, which is surrounded by mountains and located in a semi-closed basin (Fig. 1), with a north-to-south span of ~ 107 km and an east-to-west span of ~ 144 km. The altitude of the eastern mountains is between 1000 and 1500 m, and the altitudes of the western and northern mountains are ~ 1600 and ~ 1800 m, respectively. The economy of Taiyuan largely depends on the heavy manufacturing, which have led to the frequent $PM_{2.5}$ pollution (Xie et al. 2009; Tang et al. 2014; Xia et al. 2010; Guo et al. 2011). According to the Multi-resolution Emission Inventory for China (MEIC) provided by Tsinghua University (Huo et al. 2014; Liu et al. 2015), the industrial section contributes more than 60% of $PM_{2.5}$ in Taiyuan and adjacent regions. The major industry facilities in Taiyuan (Xie et al. 2009;

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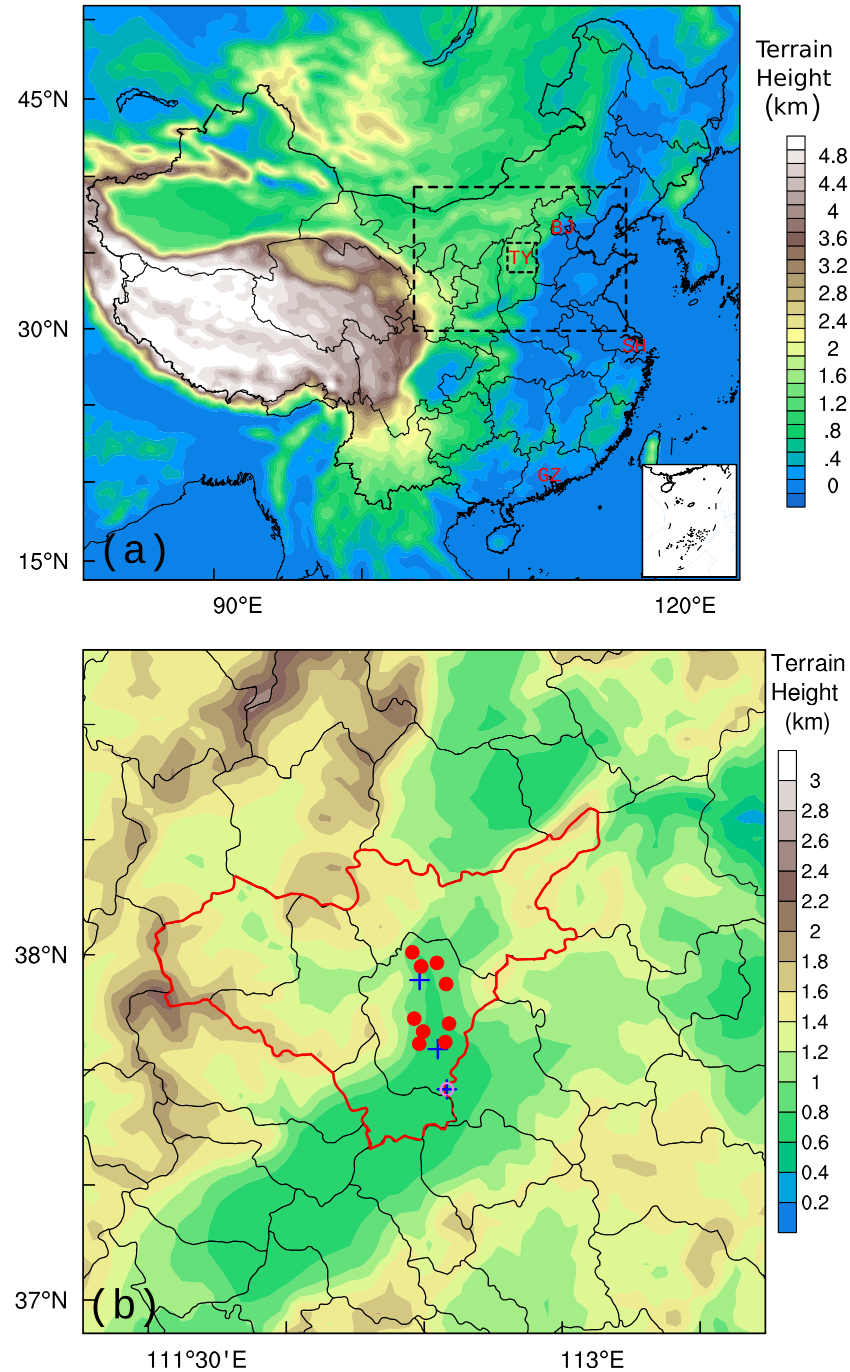
Fig. 1 **a** Map of model domains (denoted by dash line rectangles) and terrain height in China and **b** spatial distribution of meteorological stations (marked by blue crosses) and air quality sites (marked by red dots) of Taiyuan in the inner domain. In **a**, the locations of Taiyuan, Beijing, Shanghai, and Guangzhou are marked by the red texts "TY," "BJ," "SH," and "GZ", respectively. In **b**, the location of Taiyuan is denoted by the red solid lines, and the sounding station is marked by the purple circle



Jiang 2017) include Xishan Coal and Power Group Company Ltd., Taiyuan Heavy Machinery Making Group Company Ltd., and Taiyuan Iron & Steel Group Company Ltd.

In an annual cycle, the aerosol pollution in North China shows prominent seasonal variation (Miao et al. 2015a; Zhang et al. 2013), which is more serious in fall and winter due to the unfavorable meteorological conditions and substantial increase in energy for heating (Zhang et al. 2015; Zhang and Cao 2015). Besides, a majority of severe pollution events are found to be associated with dust storms, which occurred most frequently in spring (Wu et al. 2003; Shao and Dong 2006; Guo et al. 2017). In addition to the direct emissions, the chemical reactions and formations of secondary pollutants could further exacerbate the air pollution under certain synoptic conditions (Han et al. 2015; Huang et al. 2014).

On a local scale, the heavy pollution events frequently occur under the calm wind conditions associated with stable atmospheric stratification and shallow planetary boundary layer (PBL) (Miao et al. 2015a; Quan et al. 2014; Tie et al., 2015). The boundary layer height (BLH) is one of the most critical factors for air quality, since it determines the total vertical dispersion volume (Hu et al. 2014; Li et al. 2017; Miao et al. 2015b; Stull 1988). The PBL structure and its dynamical and chemical process therein exert a strong influence on the occurrence, maintenance, and dissipation of aerosol pollution (Li et al. 2017; Miao et al. 2015a, 2017a). On a regional scale, the synoptic conditions largely determine the transport pathways of pollutants, which likely provide the primary driving force for the day-to-day variations in air pollution level (Guo et al. 2017; Liu et al. 2009; Miao et al. 2017b; Ye et al. 2016).

Although the importance of meteorological conditions for air quality in north China has been recognized, most of these previous studies were carried out for the NCP and Beijing-Tianjin-Hebei regions (Hu et al. 2014; Miao et al. 2016; Ye et al. 2016). Only few studies have been conducted to investigate the chemical characteristics and health impacts of the severe pollution in Taiyuan (i.e., Meng et al. 2007; Tang et al. 2014; Xia et al. 2010; Zhang et al. 2010). How the meteorological conditions and terrains combine to influence the $PM_{2.5}$ pollution in Taiyuan, however, is yet to be well understood.

Thus, this study investigates the impacts of meteorological factors on the wintertime $PM_{2.5}$ pollution in Taiyuan by combining observation analyses and three-dimensional numerical simulations. The remainder of this paper is organized as follows. In "Data and methods" section, the observed data and models are described. In "Results" section, the impacts of meteorological conditions on $PM_{2.5}$ pollution in Taiyuan are analyzed. Finally, the main findings are summarized in "Conclusions" section.

Data and methods

Observed data

In this study, the aerosol pollution level in Taiyuan is denoted by near-surface $PM_{2.5}$ concentration measurements, collecting from nine air quality sites deployed by Taiyuan Environmental Protection Bureau (marked by the red dots in Fig. 1b). Given that the heavy aerosol pollution event frequently occurs in winter (Fig. S1), this study focuses on the most polluted months from November 2016 to January 2017. At each monitoring site, the hourly mass concentrations of $PM_{2.5}$ are measured using the micro oscillating balance method and/or the β absorption method from commercial instruments (Zhang and Cao 2015). The instrumental operation, maintenance, data assurance, and quality control are all properly conducted according to the China Environmental Protection Standards.

Besides, the meteorological variables recorded at three stations in Taiyuan (marked by the blue crosses in Fig. 1b) were analyzed, including the hourly 2-m temperature, 2-m relative humidity (RH), 10-m wind, and precipitation. The radiosonde soundings routinely measured in Taiyuan (marked by the purple circle in Fig. 1b) were also collected to verify the simulation results. The sounding balloons are launched twice a day at around 0800 and 2000 local time (LT). As illustrated in Fig. 1b, all these meteorological stations and $PM_{2.5}$ monitoring sites are distributed on the basin regions of Taiyuan, which represent well the meteorological conditions during the polluted months in the city. During the studied period, there were merely 11 rainy days in total, of which only 1 day has rainfall amount more than 1 mm (i.e., ~1.7 mm), suggesting that the occurrences of precipitation cannot significantly influence the wintertime $PM_{2.5}$ pollution in Taiyuan. Thus, the influence of precipitation on $PM_{2.5}$ pollution was not considered in this study.

WRF and HYSPLIT

To better understand the impacts of meteorological conditions on $PM_{2.5}$ pollution in Taiyuan, long-term three-dimensional simulations are conducted using the Weather Research and Forecasting model (WRF version 3.9) from 31 October 2016 to 31 January 2017. As illustrated in Fig. 1a, two nested domains with horizontal grid spacing of 15 and 3 km are used, with the MODIS land use data of 2012. The inner domain covers the whole Taiyuan City (Fig. 1b). In the vertical dimension, 48 vertical layers are set, extending from surface up to 100-hPa level, with 21 layers below 2 km AGL to better resolve the PBL structures and processes.

The physics parameterization schemes employed to the two nested domains include the Yonsei University (YSU) PBL scheme (Hong et al. 2006), Noah land surface scheme (Chen and Dudhia 2001) coupled with a single layer urban canopy model (Kusaka et al. 2001), RRTMG longwave/shortwave radiation scheme (Iacono et al. 2008), and WRF Single-Moment 6-class microphysics scheme (Hong and Lim 2006). Besides, Kain-Fritsch cumulus scheme (Kain 2004) is utilized to the outer domain. Based on the simulated potential temperature (PT) profiles in Taiyuan, the BLH is estimated using the 1.5-theta increase method (Hu et al. 2014; Nielsen-Gammon et al. 2008) that defines BLH as the level at which the PT first exceeds the minimum PT within PBL by 1.5 K.

For each day of the studied period, 40 hourly simulation is conducted beginning from 0800 LT of previous day. The first 16 h of each simulation are considered as a spin-up period, and the remaining 24 h are used for further analyses. The initial and boundary conditions are set up using the National Centre for Environmental Prediction (NCEP) global Final (FNL) reanalysis with a grid resolution of 1° × 1° (http://rda.ucar.edu/datasets/ds083.2/). Compared with a continuously long-term simulation, this re-initialized daily simulation employed in this study reduces the systematic model error, which has been widely used to study the regional climate (e.g., Hu et al. 2010).

On the basis of the hourly WRF simulation results, 24-hourly air mass backward trajectories are calculated using the Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model (Draxler and Hess 1998) ending at Taiyuan (37.867° N, 112.52° E, 100-m AGL). The HYSPLIT model traces four times of each day from November 2016 to January 2017 at 0200, 0800, 1400, and 2000 LT. In total, 364 backward trajectories are calculated. Based on these backward trajectories, the possible regional sources of $PM_{2.5}$ for Taiyuan are identified using the approach of potential source contribution function (PSCF) (Zhang et al. 2013).

The PSCF values in the ij-th grid is defined as m_{ij}/n_{ij}, where n_{ij} is the number of endpoints that fall in the ij-th grid and m_{ij} denotes the number of "polluted" trajectory endpoints in the ij-th grid. Four "polluted" threshold values are set to understand the potential sources of different $PM_{2.5}$ pollution level, which are 75, 100, 125, and 150 μg m^{-3}. The PSCF domain is in the range of 32.75–42.75° N, 103–122° E, with a grid resolution of 0.25° × 0.25°. To better reflect the uncertainty in cells with small n_{ij} values, the following weighting function w_{ij} was adopted (Wang et al. 2015; Zhu et al. 2011):

$$w_{ij} = \begin{cases} 1.00 & 80 < n_{ij} \\ 0.70 & 25 < n_{ij} \leq 80 \\ 0.42 & 15 < n_{ij} \leq 25 \\ 0.17 & n_{ij} \leq 15 \end{cases}$$

Results

In this section, the simulation results were first validated against the observations, and then the relationships between the meteorological parameters and wintertime $PM_{2.5}$ pollution in Taiyuan were examined. Finally, the impacts of multi-scale meteorological factors and terrains were unraveled based on the simulation outputs.

Validation of WRF simulation

Figure 2 compares the simulated temperature, RH, and winds with the observations in Taiyuan from November 2016 to January 2017. Overall, the day-to-day variations of surface temperature and RH were well reproduced by the model, with a correlation coefficient of 0.94 ($p < 0.001$) and 0.74 ($p <$

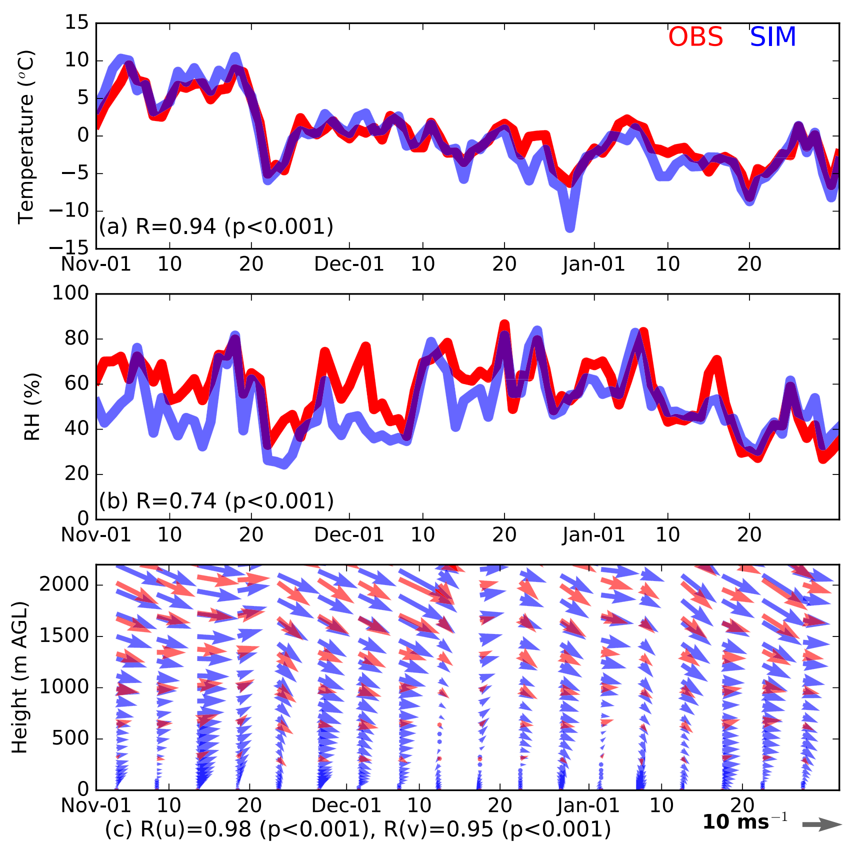


Fig. 2 Time series of observed (in red) and simulated (in blue) **a** 2-m temperature, **b** 2-m relative humidity (RH), and (**c**) horizontal wind vector profiles in Taiyuan from November 2016 to January 2017. The correlation coefficients (R) between the simulations and observations are given for each panel

0.001), respectively. Besides, the simulated wind profiles were also well consistent with those derived from soundings (Fig. 2c), with a correlation coefficient higher than 0.95 for both the *u*- and *v*-components. Such good agreements between the simulations and observations (Fig. 2) provided a sound basis for us to use the simulation results to elucidate the impacts of meteorological factors on air quality in Taiyuan. In the rest of this paper, the meteorological parameters presented were those derived from simulations unless otherwise noted.

Overall characteristics of wintertime $PM_{2.5}$ pollution in Taiyuan

The time series of observed daily $PM_{2.5}$ concentrations in Taiyuan from November 2016 to January 2017 are shown in Fig. 3a. The heavy $PM_{2.5}$ pollution tended to occur more frequently on the days with low wind speed, shallower PBL, and warmer air above (Fig. 3b, c). For example, during a pollution episode from December 30 to January 3, the averaged BLH in Taiyuan was merely ~ 130 m AGL, significantly lower than those of pre- and post-periods, accompanied with strong thermal inversion layer capping above the PBL (Fig. 3b); meanwhile, at the surface level, Taiyuan City was controlled by weak southerly winds (Fig. 3a).

Figure 4 shows the scattering plots between $PM_{2.5}$ concentration and five meteorological parameters, including 2-m temperature, 2-m RH, near-surface wind speed, BLH, and low tropospheric stability (LTS). Here, the LTS (Slingo 1987; Guo et al. 2016) is defined as the difference in PT between 1200 and 100 m AGL, which can be used to quantitatively describe the strength of thermal inversion above PBL in winter. Significant anti-correlation ($R = -0.38$, $p < 0.01$) was found between BLH and $PM_{2.5}$ concentration, implying that BLH played an important role in modulating the pollution level (Fig. 4d). Since the low BLH was often associated with strong thermal inversion (Fig. 3b), a significantly positive correlation ($R = 0.36$, $p < 0.01$) was noted between LTS and $PM_{2.5}$ concentration as expected (Fig. 4e).

Besides, at the surface level the $PM_{2.5}$ concentration significantly positive correlated with RH ($R = 0.48$, $p < 0.01$, Fig. 4b). The high RH could favor the partition of semi-volatile species into the aerosol phase (Hu et al. 2008; Zhang et al. 2015), leading to a high $PM_{2.5}$ concentration; meanwhile, the moister atmosphere normally accompanies lower BLH (Sandeep et al. 2014; Zhang et al. 2015), which could further enhance the concentrations of $PM_{2.5}$. Similarly, the 2-m temperature also significantly positive correlated with $PM_{2.5}$ concentration ($R = 0.34$, $p < 0.01$, Fig. 4a), which may be related to the cleaning effects of cold air from the north. In

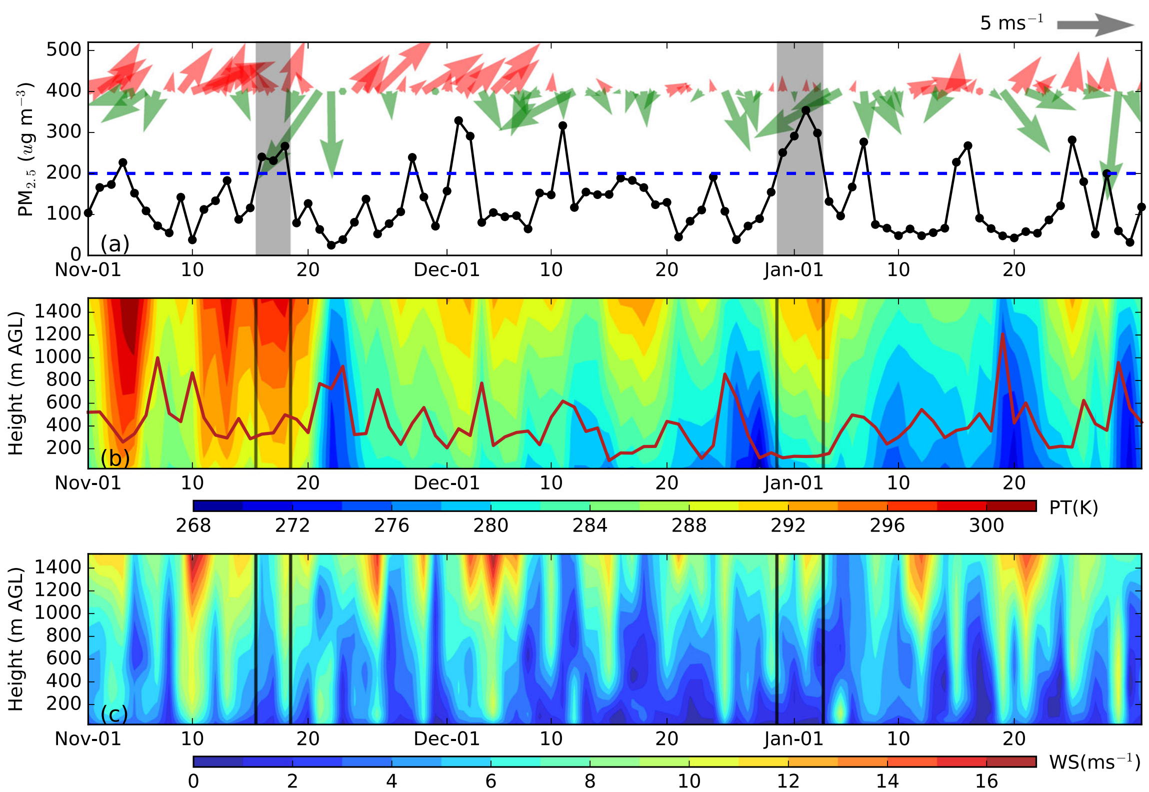


Fig. 3 **a** Time series of observed daily $PM_{2.5}$ concentration and time-height sections of simulated **b** potential temperature (PT) and **c** horizontal wind speed in Taiyuan from November 2016 to January 2017. The simulated daily near-surface horizontal winds (~ 25 m AGL) in Taiyuan are presented in **a**, in which the northerly and southerly winds are denoted as the green and red vectors, respectively. The time series of simulated daily boundary layer height (BLH) in Taiyuan is also shown as the red line in **b**

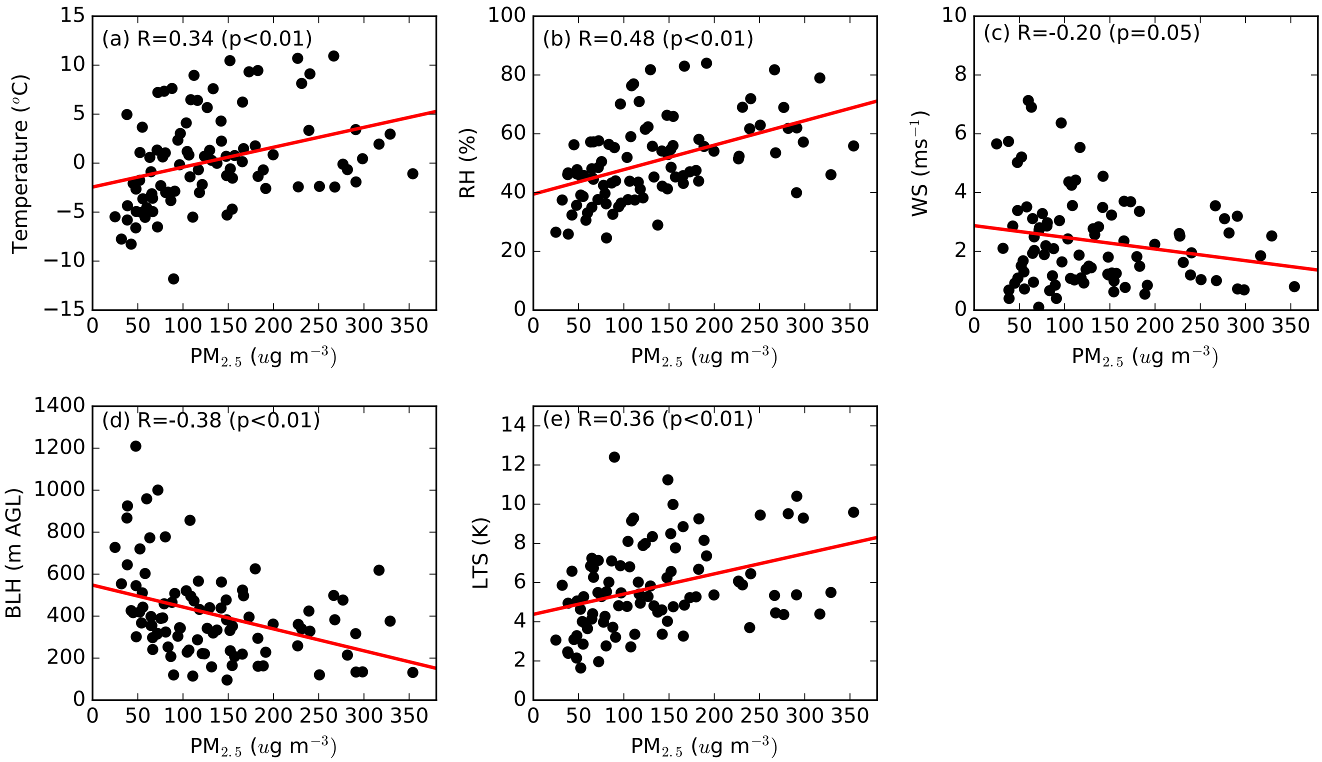


Fig. 4 Scatter-plots showing the correlation relationships between daily $PM_{2.5}$ concentration and simulated meteorological variables in Taiyuan from November 2016 to January 2017, including **a** 2-m temperature, **b** 2-m relative humidity (RH), **c** near-surface wind speed (WS, at ~ 25 m AGL), **d** boundary layer height (BLH), and **e** lower tropospheric stability (LTS). Here the LTS is defined as the difference in potential temperature between 1200 and 100 m AGL. The linear regression line and correlation coefficient (R) between the $PM_{2.5}$ concentration and meteorological factor is also shown for each panel

winter, the cold advections to Taiyuan are often associated with strong northerly winds (Fig. 3a, b), which could bring in cold and relatively clean air from the northern Mongolia regions, leading to low temperature and $PM_{2.5}$ concentration in Taiyuan. By contrast, the stagnant conditions favoring the accumulation of $PM_{2.5}$ are typically characterized by high temperature and weak wind. Thus, $PM_{2.5}$ concentration reversely correlated with near-surface wind speed ($R = -0.20$, $p = 0.05$, Fig. 4c). The similar relationships between $PM_{2.5}$ concentration, temperature, RH, and wind speed in winter could also be found in other regions of North China, such as Beijing (Zhang et al. 2015) and Xiong'an (Miao and Liu 2017).

Figure 5a shows the top and bottom 25% of $PM_{2.5}$ concentrations. The top 25% $PM_{2.5}$ concentrations were within ~ 180 to 310 μg m^{-3}, with an average of 247 μg m^{-3}, significantly higher than the bottom 25% concentrations (51 ± 11 μg m^{-3}). When the top 25% $PM_{2.5}$ concentrations happened, the 2-m temperature was within − 2.5 to 9.5 °C, with an average of 2.5 °C. In contrast, the bottom 25% $PM_{2.5}$ concentrations were observed when the temperature was between − 6.4 and 1.0 °C, with a lower average temperature of − 3.3 °C (Fig. 5b). The days of top 25% $PM_{2.5}$ concentration were with 2-m RH of 59.4 ± 11.7%, apparently higher than those (41.7 ± 8.8%) of the days of bottom 25% concentration (Fig. 5c). In addition, the top 25% $PM_{2.5}$ concentrations were found to be associated with lower BLH (319 ± 145 m AGL) and higher LTS (6.7 ± 2.0 K), comparing with those of bottom 25% $PM_{2.5}$ days (Fig. 5d, e). The presence of thermal inversion layer above PBL could suppress the development of PBL to some extent and limit the total dispersion volume, resulting in a high $PM_{2.5}$ concentration in Taiyuan. The near-surface wind speeds of top and bottom $PM_{2.5}$ concentration were also shown in Fig. 5f; it was found that the top 25% $PM_{2.5}$ concentrations tended to occur under calm wind conditions.

The multi-linear regression function between the $PM_{2.5}$ concentration and these local meteorological factors was derived:

$$\mathrm{EST} = 36.799–0.056 \times \mathrm{BLH} + 6.310 \times \mathrm{LTS} + 1.798 \times \mathrm{RH} + 5.565 \times T–4.174 \times \mathrm{WS}$$

where the EST denoted the estimated $PM_{2.5}$ concentration and T and WS represented the 2-m temperature (°C) and near-surface wind speed, respectively. Comparing the estimations with observations (Fig. 6), it was found that the day-to-day variations of $PM_{2.5}$ concentration could be generally well reproduced by the regression function ($R = 0.63$, $p < 0.001$). According to the daily $PM_{2.5}$ limit of Chinese Ambient Air Quality Standards (75 μg m^{-3}), there were in total 66 $PM_{2.5}$

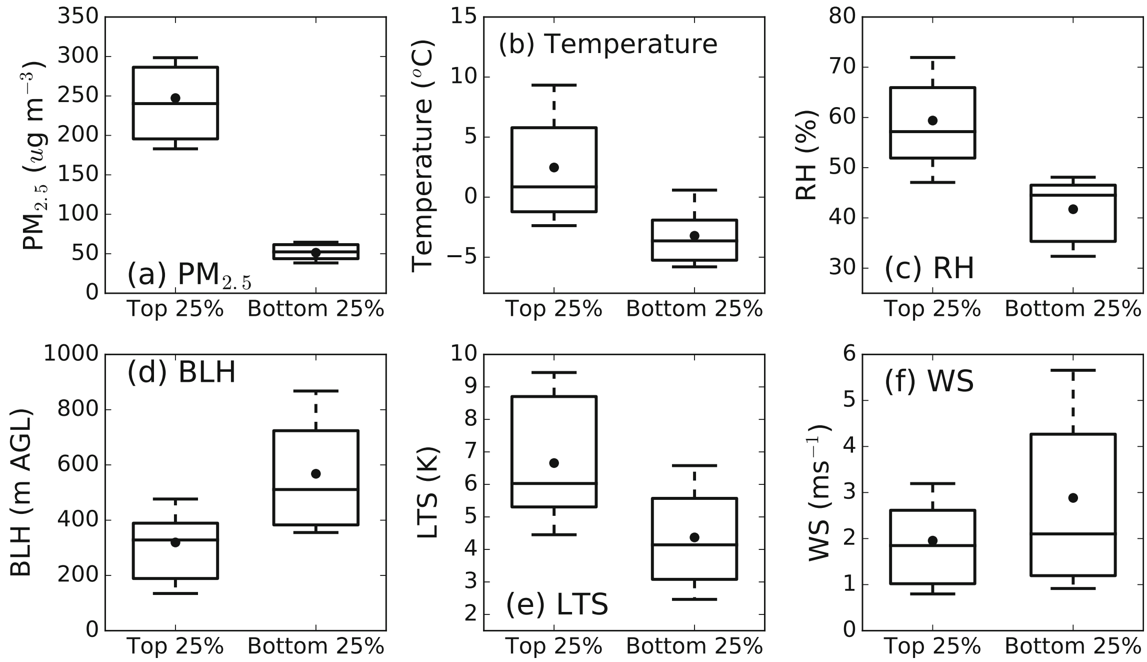


Fig. 5 Box-whisker plots showing the different characteristics between top 25% and bottom 25% $PM_{2.5}$ concentrations in Taiyuan, including **a** $PM_{2.5}$ concentration, **b** 2-m temperature, **c** 2-m relative humidity (RH), **d** boundary layer height (BLH), **e** lower tropospheric stability (LTS), and **f** near-surface wind speed (WS). The central box represents the values from the lower to upper quartile (25th to 75th percentile). The vertical line extends from the 10th percentile to the 90th percentile. The middle solid line represents the median. The dot represents the mean value. Note that all the meteorological parameters are derived from the WRF simulations

polluted days from November 2016 to January 2017, and around 97% (64 days) of these exceedance days were accurately predicted by the regression function (Fig. 6). It indicated that this function of local meteorological parameters could well predict the occurrences of $PM_{2.5}$ exceedance day. However, from the perspective of pollution level, the linear function failed to estimate the peak concentrations of several extreme pollution episodes, suggesting that there existed processes cannot be well described by the linear function of local meteorological factors, such as the formation of secondary pollutants (Han et al. 2015; Huang et al. 2014) and regional transport of pollutants (Miao et al. 2017b and Miao et al. 2018).

To further understand the regional transport of pollutants to Taiyuan, the $PM_{2.5}$ concentrations according to their respective wind directions are presented in Fig. 7. Excluding the wind directions with few samples (less than 5), the southwesterly winds were found to be associated with the highest $PM_{2.5}$ concentration in Taiyuan, followed by the southerly winds. Thus, it is suggested that the southwesterly and southerly

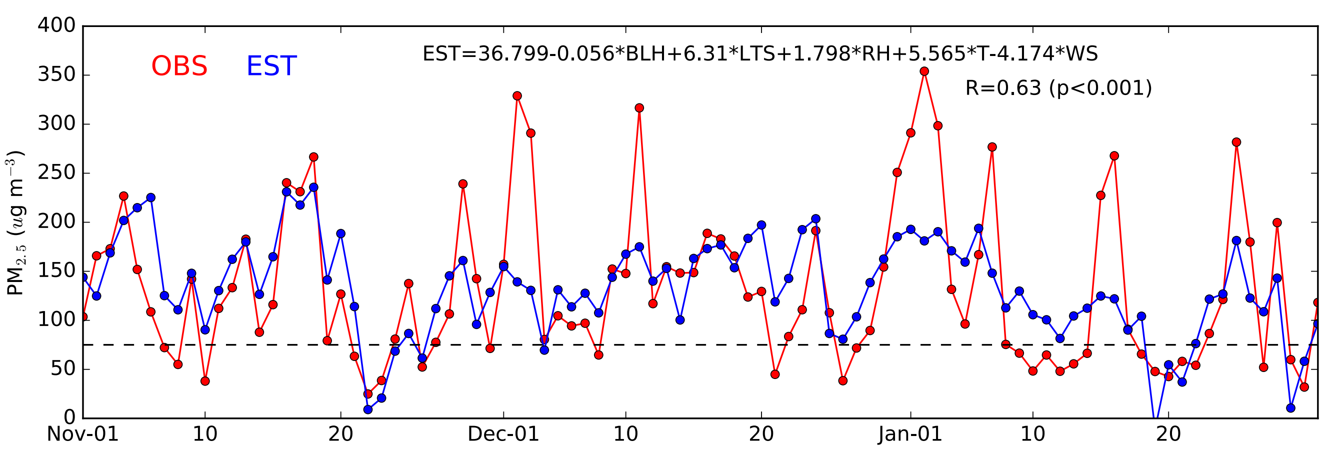


Fig. 6 Time series of observed (in red) and estimated (in blue) daily $PM_{2.5}$ concentration in Taiyuan from November 2016 to January 2017. The estimations are calculated using the multi-linear regression function that involves the boundary layer height (BLH), lower tropospheric stability (LTS), 2-m relative humidity (RH), 2-m temperature (*T*, °C), and near-surface wind speed (WS). The correlation coefficient (*R*) between the observed and estimated $PM_{2.5}$ concentrations is also given. The black dash line shows the daily $PM_{2.5}$ concentration limit of the Chinese Ambient Air Quality Standards (75 μg m^{-3})

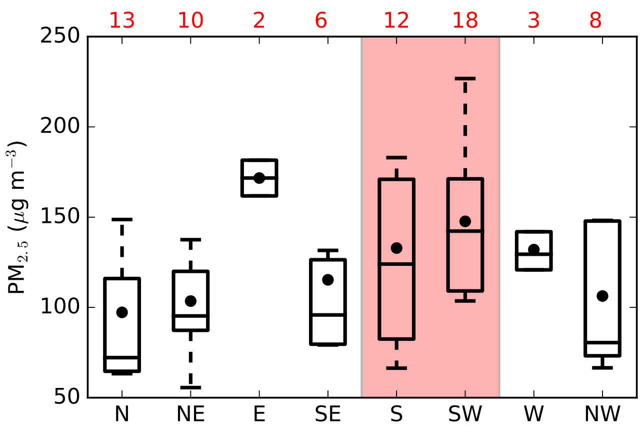


Fig. 7 Box-whisker plots with the $PM_{2.5}$ concentrations according to their respective wind directions. The wind direction categories are set as 337.5° < N ≤ 22.5°, 22.5° < NE ≤ 67.5°, 67.5 < E ≤ 112.5°, 112.5° < SE ≤ 157.5°, 157.5° < S ≤ 202.5°, 202.5° < SW ≤ 247.5°, 247.5° < W ≤ 292.5°, 292.5° < NW ≤ 337.5°. The sampling number of each wind direction is also given at top of panel. The daily $PM_{2.5}$ concentrations greater than the 90th percentile value and less than 10th percentile value are not included

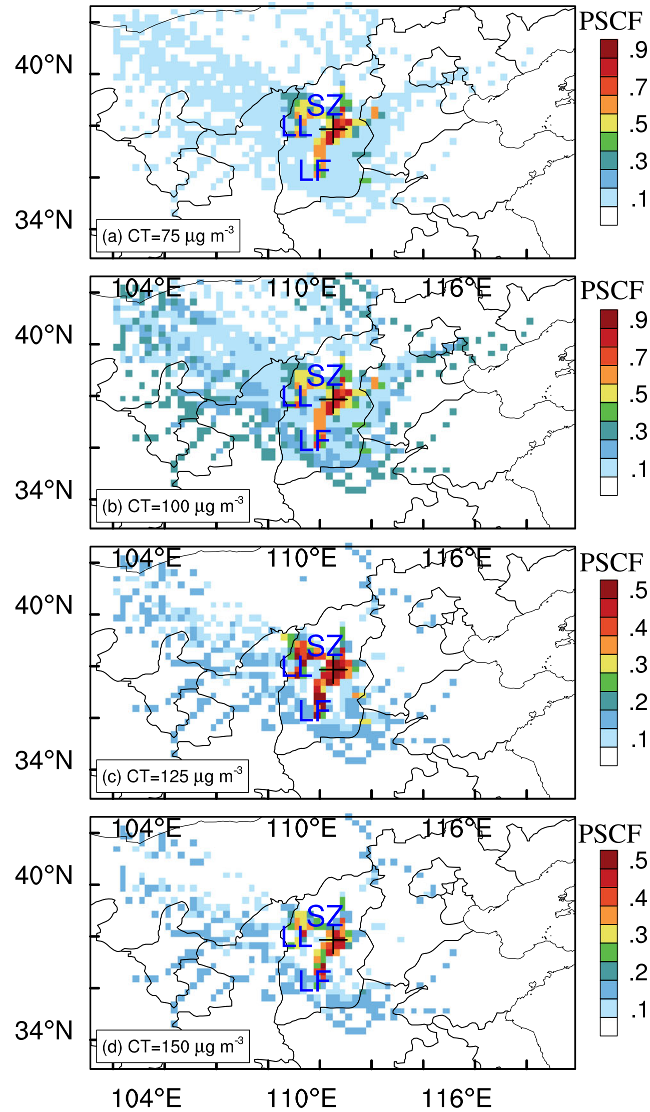


Fig. 8 Maps of potential source contribution function (PSCF) for the $PM_{2.5}$ pollution in Taiyuan with different polluted concentration thresholds (CT), including **a** 75 μg m^{-3}, **b** 100 μg m^{-3}, **c** 125 μg m^{-3}, and **d** 150 μg m^{-3}. The location of Taiyuan is marked by the black cross, and locations of Shuozhou, Luliang, and Linfen are denoted by the blue texts "SZ," "LL," and "LF," respectively

winds could transport pollutants from upstream adjacent regions to Taiyuan. Figure 8 shows the PSCF maps of the potential sources of $PM_{2.5}$. Irrespective of the different polluted thresholds applied, the potential sources contributed to the $PM_{2.5}$ pollution in Taiyuan, included the southwest regions (Linfen), the northwest regions (Shuozhou and Luliang), and Taiyuan itself. Comparing with the spatial distributions of $PM_{2.5}$ emissions (Fig. S2), the southwest potential source regions identified from the PSCF analysis coincided with the high $PM_{2.5}$ emissions in Linfen, indicating that the pollutants emitted from Linfen could be easily transported to Taiyuan under the control of southwesterly and southerly winds (Figs. 3a and 7). In addition to the high local emissions, such an external transport could further exacerbate the pollution level under certain synoptic conditions.

In the following section, two heavy $PM_{2.5}$ pollution episodes in Taiyuan with southwesterly winds were analyzed to further understand the impacts of meteorological conditions and terrains, including 15 to 18 November and 30 December to 3 January.

Impacts of synoptic patterns and terrains: case studies

From 15 to 16 November, the $PM_{2.5}$ concentration in Taiyuan quickly increased from 116 to 240 μg m^{-3} and persisted an extreme high concentration (> 200 μg m^{-3}) for the continuous 3 days until 19 November (Fig. 3a). As the 750-hPa geopotential height fields shown in Fig. 9a–d, there were southeast-to-northwest gradients across Taiyuan during this pollution episode (15, 17, 18 November), which supported southwesterly prevailing winds to Taiyuan. These southwesterly winds not only brought the pollutants from southwestern regions to Taiyuan (Figs. 8 and S2) but also the relatively warmer air (Fig. 9a–d). As a result, these southwesterly advections enhanced the thermal inversion layer capping over PBL in Taiyuan (Figs. 3b and 10a), leading to shallow PBL and poor dispersion condition. By contrast, as the pressure gradients across Taiyuan turned into a northwest-to-southeast pattern from 19 to 22 November, the pollution in Taiyuan became lighter under the influences of strong northerly winds (Figs. 3a and 9e–f).

Similar synoptic conditions and associated $PM_{2.5}$ pollution level also occurred during another pollution episode from 30 December to 3 January (Fig. 3a). From 27 to 29 December, the relatively good air quality in Taiyuan region was found to be associated with the strong northerly prevailing winds (Figs. 3a and 11a, b). Then, as the prevailing winds turned to the

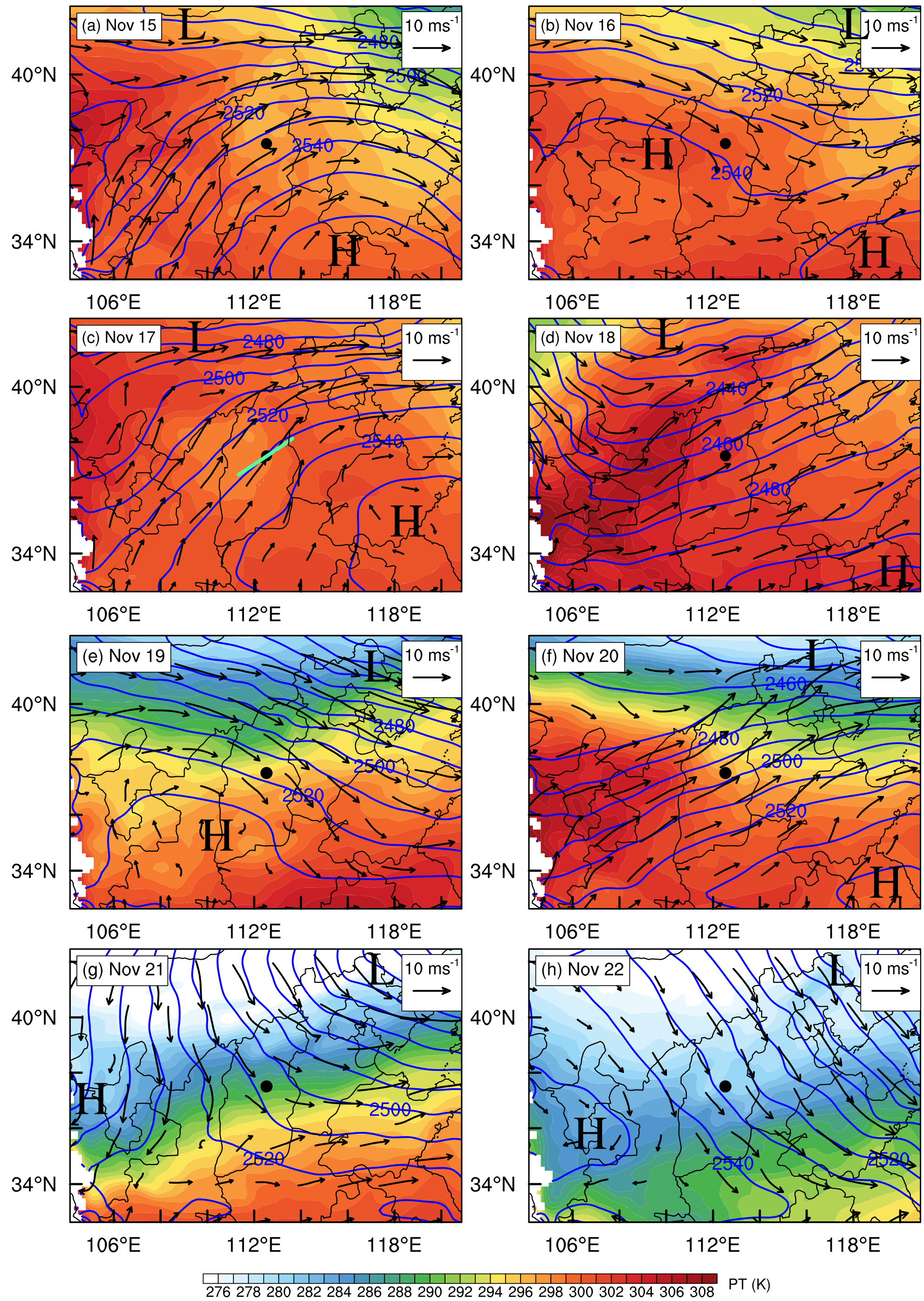


Fig. 9 Spatial distributions of simulated 750-hPa geopotential height (blue lines) and potential temperature (PT), overlaid with wind vector fields at 1400 LT on (**a**–**h**) 15–22 November 2016. The location of Taiyuan is marked by the black dot for each panel. The green line cutting through Taiyuan in **c** indicates the location of cross sections shown in Fig. 10. The texts "H" and "L" mark the approximate locations of high pressure and low pressure, respectively

southwesterly winds from 30 December to 3 January (Figs. 3 and 11c, d), heavy $PM_{2.5}$ pollution occurred in Taiyuan, influenced by both the regional transport of $PM_{2.5}$ and low BLH (Fig. 3).

In addition to large-scale synoptic condition, the semi-closed basin of Taiyuan could also play a role in modulating the thermal and dynamic structure of PBL, as well as the pollution level. As illustrated in Figs. 10a, c, due to the drainage flow and blocking effects of surrounding terrain elevations (Chow et al. 2012), a cold air pool was formed in the basin of Taiyuan with extreme stable stratification, which could inhibit the downward transport from the free tropospheric momentum (Miao et al. 2015a; Whiteman et al. 1999), leading to weak PBL winds within the basin (Figs. 10b, d and 11). These stagnant conditions induced by the surrounding terrain heights favor the accumulation of pollutants, which must be partly responsible for the poor wintertime air quality in Taiyuan. Similar impacts of terrain have

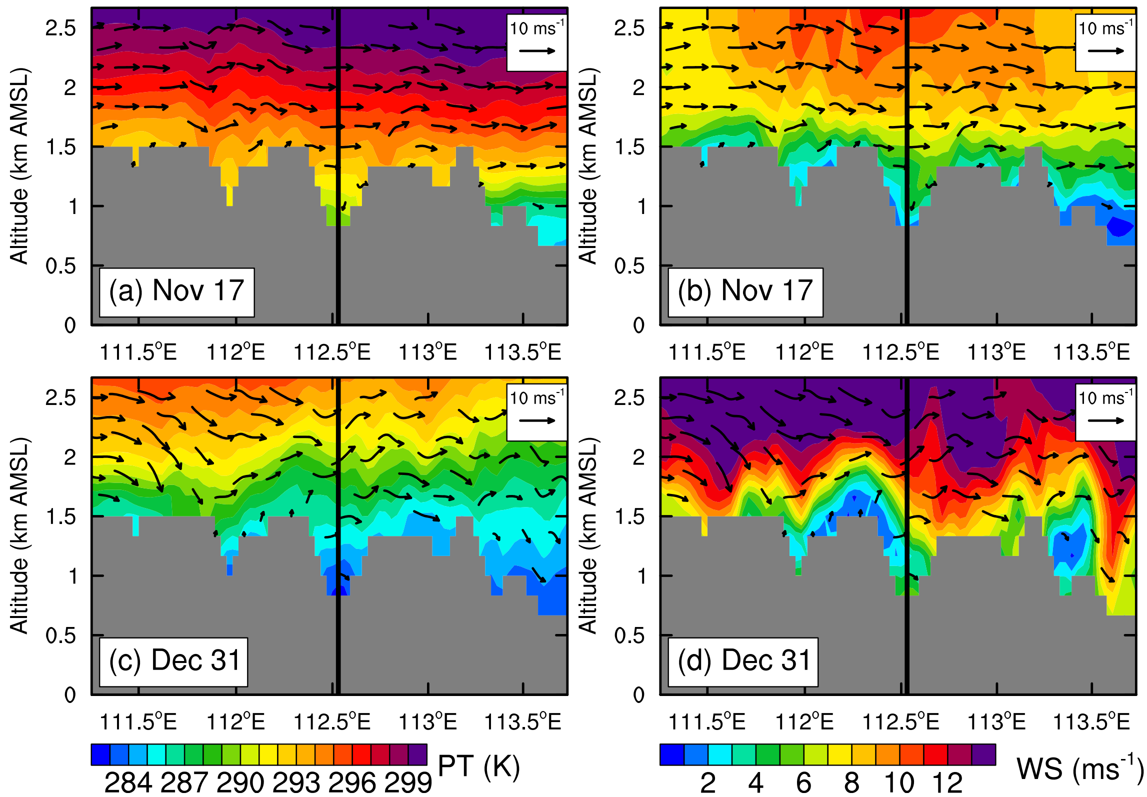


Fig. 10 Vertical cross sections of simulated (left) potential temperature (PT) and (right) wind speed (WS) on (**a**, **b**) 17 November and (**c**, **d**) 31 December 2016. The location of Taiyuan is marked by the black line for each panel. The locations of cross section are denoted by the green line in Fig. 9c. Note that the vertical velocity is multiplied by a factor of 10 when plotting the wind vectors

also been reported in the Beijing-Tianjin-Hebei region (Miao et al. 2015a), the Colorado Plateau in the USA (Banta and Cotton 1981; Whiteman et al. 1999), and the Scott Base in Antarctica (Sinclair 1988).

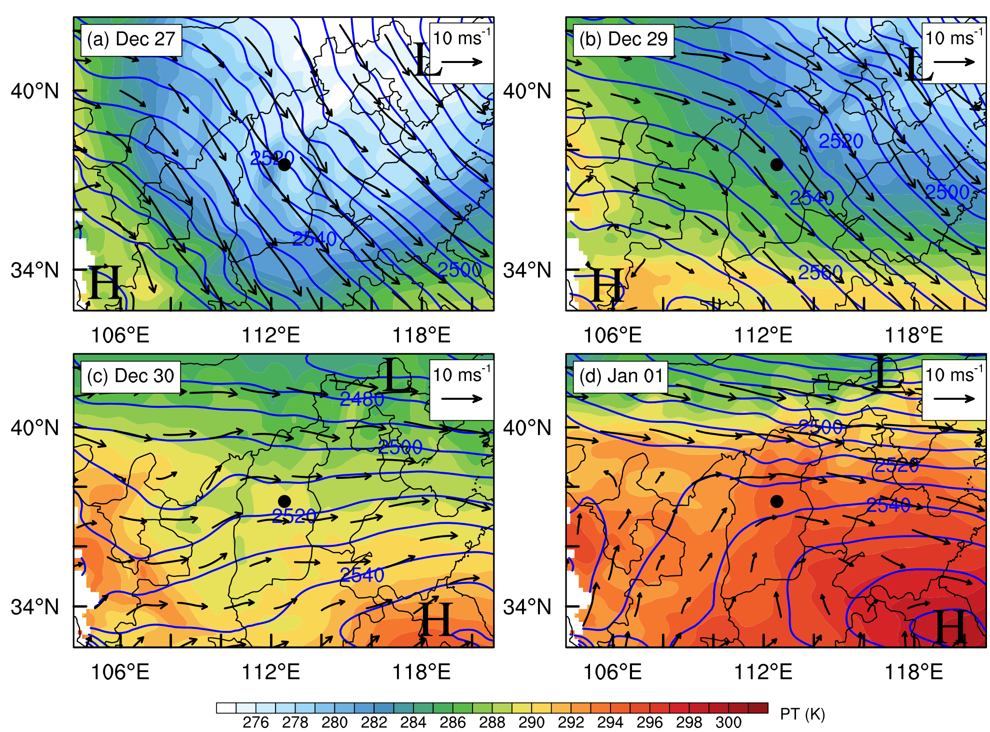


Fig. 11 Similar as Fig. 9, but for the 750-hPa geopotential height fields and potential temperature (PT) fields from **a**–**d** 27 December 2016 to 1 January 2017

Conclusions

This study investigated the impacts of meteorological factors on $PM_{2.5}$ pollution in Taiyuan for a continuous period from November 2016 to January 2017, using near-surface meteorological observations, radiosonde soundings, aerosol measurements, and numerical simulations of WRF and HYSPLIT.

Substantially different correlations between $PM_{2.5}$ concentration and local meteorological parameters were found. At the surface level, the $PM_{2.5}$ concentration exhibited positive correlations with temperature and RH, and anti-correlations with wind speed, indicating that the heavy pollution in winter tended to occur in a warm and humid day with calm wind. Besides, the $PM_{2.5}$ concentration anti-correlated with BLH, demonstrating the important roles of PBL in modulating the pollution level. The shallow PBL is often associated with a strong thermal inversion layer capping over, exhibiting a positive correlation between $PM_{2.5}$ concentration and LTS.

Based on these significantly correlated meteorological factors, a multi-linear regression function of $PM_{2.5}$ concentration was derived, which accurately predicts the occurrence of $PM_{2.5}$ exceedance days in winter but fails to estimate the peak concentrations of extreme pollution events. This finding suggested that there existed non-linear and non-local processes exacerbating the pollution, which cannot be described by the linear regression function of local parameters. Both the statistical analysis of wind directions and simulations of backward trajectory indicate that the southwesterly and southerly winds can bring pollutants from Linfen to Taiyuan, thereby exacerbating the pollution there.

In addition, the semi-closed basin of Taiyuan could also play a role in exacerbating the pollution level under certain synoptic patterns. The surrounding terrain elevations favored the formations of cold air pool in the basin, which could inhibit the downward transport from the free tropospheric momentum, resulting in stagnant conditions and poor air quality in Taiyuan.

This study generates important information for the role meteorological parameters play in in the formation of wintertime $PM_{2.5}$ pollution in Taiyuan. It provides a knowledge base for decision makers to implement effective $PM_{2.5}$ pollution control. Although this study focused on the importance of meteorological conditions, the chemical processes also cannot be overlooked (Han et al. 2015; Huang et al. 2014), which warrants further studies using online coupled chemical transport models such as WRF-Chem (Grell et al. 2005).

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