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PM_{2.5} pollutant
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Modeling study of PM_{2.5} pollutant transport across cities in China's Jing–Jin–Ji region during a severe haze episode in December 2013

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To study the influence of particulate matter (PM) transported from surrounding regions on the high PM_{2.5} pollution levels in Beijing, the GRAPES-CUACE model was used to simulate a serious haze episode that occurred on 6–7 December 2013. The results demonstrate the model's suitability for describing haze episodes throughout China, especially in the Beijing–Tianjin–Hebei (Jing–Jin–Ji) region. A very close positive correlation was found between the southerly wind speed over the plain to the south of Beijing and changes in PM_{2.5} in Beijing, both reaching maximum values at ca. 900 hPa, suggesting the lower atmosphere was the principal layer for pollutant PM transport from its southern neighboring region to Beijing. During haze episodes, and dependent upon the period, Beijing was either a pollution source or sink for its surrounding area. PM input from Beijing's environs was much higher than the output from the city, resulting in the most serious pollution episode, with the highest PM_{2.5} values occurring from 00:00 to 10:00 UTC 7 December 2013. PM pollutants from the environs of the city accounted for over 50 % of the maximum PM_{2.5} values reached in Beijing. At other times, the Beijing area was a net contributor to pollution in its environs.

1 Introduction

Air pollution has become a serious problem in megacities around the world (Kanakidou et al., 2011), and the topic has been receiving increased attention because of the close relationship between air pollution and the atmospheric environment, human health and ecosystems (Kan et al., 2012; Liu et al., 2012). China's air pollution has become increasingly serious since the economic reforms of 1978, which allowed rapid economic development. Gross Domestic Product has grown by ca. 10 % per annum (China Statistical Yearbook, 2012, 2013). China is now considered as one of the engines of global economic growth, but this rapid growth has resulted in an increase in energy consumption, air pollution, and associated health effects (Chan et al., 2008).

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In recent years, haze has become a major pollution problem in Chinese cities (Wu et al., 2010; Du et al., 2011; Tan et al., 2011). Under the observation standards released by the China Meteorological Administration (CMA), haze is defined as a pollution phenomenon characterized by deteriorated horizontal visibility of < 10 km, caused by fine particulate matter (PM) suspended in the atmosphere (CMA, 2003). Haze occurs when sunlight is absorbed and scattered by high concentrations of atmospheric aerosols (E. Kang et al., 2013; Salinas et al., 2013). It has a negative impact on human health and the environment (Wu et al., 2005; Gurjar et al., 2010), and it changes the climate on a regional or global scale by altering solar and infrared radiation in the atmosphere (Wang et al., 2011; Yu et al., 2011; Chen et al., 2012).

With an increasing number of local and regional haze events reported by the media, much attention has been paid to reducing air pollutant emissions and to improving air quality across the cities (Huang et al., 2013; H. Kang et al., 2013; Xu et al., 2013; Tan et al., 2014), municipalities, and provinces of China (Cheng et al., 2014; Ji et al., 2014). The Jing–Jin–Ji region, located in central-eastern China, is not one of China's most economically developed and industrialized regions, but is the area that most frequently experiences haze episodes (Ji et al., 2014; H. Wang, 2014a; L. T. Wang et al., 2014). Beijing, at the center of the Jing–Jin–Ji region, is one of China's most economically developed cities, and has suffered from increasingly severe haze events (Duan et al., 2012; Wang et al., 2012; Liu et al., 2014; Quan et al., 2014). It is vital that air pollution in Beijing is studied in detail so as to inform policy aimed at averting irreversible environmental damage (Cheng et al., 2013; Zhang et al., 2014). The other areas of the Jing–Jin–Ji region should also be studied, as they are an important component of the wider region and affect Beijing directly via the transport of PM pollutants (Fu et al., 2014; Ying et al., 2014). In the present reported study, an online mesoscale haze forecasting model was used to study the transport of major air pollutants to and from Beijing and the other areas of the Jing–Jin–Ji region (Wang et al., 2013).

2 Modeling

2.1 Model description

The new-generation Global/Regional Assimilation and PrEdiction System (GRAPES_Meso) and the Chinese Unified Atmospheric Chemistry Environment (CUACE) model developed by the Chinese Academy of Meteorological Science (CAMS), the CMA, were integrated to build an online chemical weather forecasting model, GRAPES-CUACE, focusing especially on haze pollution forecasting in China and East Asia (Zhang et al., 2008; Wang et al., 2009). GRAPES_Meso was adopted as the numerical weather prediction model for aerosol determination. It is a new-generation general hydrostatic/non-hydrostatic, multi-scale numerical model developed by the Research Center for Numerical Meteorological Prediction, CAMS, CMA (Zhang and Shen, 2008). The model uses standardized and module-based software and has been developed in accordance with strict software engineering requirements, including program-operated parallel calculations (Xue et al., 2008). Testing has shown that the design and application of the model meet these prerequisites, and that it can therefore serve as a good foundation for the sustainable development of a numerical prediction system for China (Chen et al., 2008). The large-scale horizontal and vertical transportation and diffusion processes for all gases and aerosols can also be processed using GRAPES_Meso's dynamic framework (Xu et al., 2008). Again, testing has demonstrated that both the design of the model's framework and its implementation meet the requirements of real-time operational weather forecasting, especially in China and East Asia. GRAPES_Meso has therefore been used as an operational, real-time, short-term weather prediction system in China since 2009 (Yang et al., 2008; Zhu et al., 2008).

The CUACE model was developed by the CAMS Centre for Atmosphere Watch And Services (CAWAS). It is a newly developed system for testing and forecasting air quality in China that includes four functions: treating aerosols; gas phase chemistry; emissions; and data assimilation (Gong et al., 2008). The detailed data capture

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by this model of processes such as aerosol sources, transport, dry and wet deposition, and dust removal both in and below clouds, clearly describes the interaction between aerosols and clouds (Zhou et al., 2008). CUACE has been designed as a unified chemistry model that can be easily coupled with any atmospheric model (e.g. regional air quality and climate models) at various temporal and spatial scales. It has thus been integrated online with GRAPES_Meso to produce the GRAPES-CUACE model (Wang et al., 2009, 2010, 2014c). Dust particles are divided into 12 size bins with diameter ranges of 0.01–0.02, 0.02–0.04, 0.04–0.08, 0.08–0.16, 0.16–0.32, 0.32–0.64, 0.64–1.28, 1.28–2.56, 2.56–5.12, 5.12–10.24, 10.24–20.48 and 20.48–40.96 μm (Gong, 2003), following guidelines provided by the measurement of soil dust size in Chinese desert regions during 1994–2001 (Zhang, 2003).

2.2 Model domain and parameters

In this study, GRAPES-CUACE was used to simulate a haze episode in December 2013. The model's vertical cap was set at ca. 30 km, with 31 vertical layers. As shown in Fig. 1, its domain covered the East Asia region (20–55° N, 90–140° E) with a horizontal resolution of 0.25° \times 0.25°. National Centers for Environmental Prediction (NCEP) 1° \times 1° reanalysis data were used for the model's initial and six-hour meteorological lateral direction input fields. The simulation period was 1–31 December 2013. The time step was set to 300 s, the forecasting time was 48 h, and the simulation began at 00:00 UTC every day.

3 Data description

This study employed CMA ground visibility and operational weather observation data. The data covered mainland China, including a total of 600 ground observation stations.

The daily mean PM_{2.5} concentrations were from surface observations made by the China National Environmental Monitoring Center (CNEMC, <http://www.cnpm25.com>).

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values during 1–31 December 2013, to test the validity of long-term simulations. As shown in Fig. 4, the simulated daily results were fairly close to the observed values for the 6–7 December haze episode. Beginning on 6 December, this episode was most severe on 7 December; and then PM_{2.5} levels decreased rapidly from 8 December onwards. The simulated results for Beijing were highly consistent with the trends in observed daily values for the whole of December. Simulated results for the other cities in the Jing–Jin–Ji region also showed close correlation with observed data for 6–7 December, even considering that the maximum value appeared one day earlier in HS and one day later in SH. While the simulated values for NJ were lower than the observed data, they essentially exhibited the same daily trends.

The results obtained by GRAPES-CUACE for the Jing–Jin–Ji region through its simulation of PM_{2.5} concentrations demonstrate the model's suitability for studying the impact of particulate transport on PM_{2.5} concentrations. The Jing–Jin–Ji region was therefore chosen as an appropriate study area.

4.2 Wind field

PK is currently experiencing the severest haze pollution in its history. On the plains of Hebei to the south, the most seriously polluted area in China, haze and fog episodes are much more serious even than in Beijing. Seven of the 10 cities with the highest levels of PM_{2.5} pollution in China are located in this region (Wang et al., 2014a, b). The contribution made by cross-city pollutants transported from southern Hebei Province to levels of PM_{2.5} pollution in PK is receiving much attention. The construction of the wind field over this region, particularly the wind field pattern in the planetary boundary layer (PBL), is a key factor in determining the impact of the cross-city transport of PM_{2.5} pollutants.

The wind field was analyzed to study the impact that PM transport from its environs had on air pollution in PK during the haze episode of the present study. As Fig. 5a shows, PM_{2.5} concentrations in PK reached their maximum at 08:00 UTC 7 December. Stable southwesterly winds affected PK and the area to the south of PK, while the wind

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direction was northwesterly and the wind speed lower in the region to the north of PK. From both the observed and simulated data (Figs. 1–3), it is apparent that the region to the south of PK was the most polluted area, with the highest PM_{2.5}, lowest visibility and densest haze, and this region was therefore the likely main contributor to pollution levels in PK during this haze episode. The vertical section along 115.25° E (Fig. 5b) enabled us to explore the relationship between the wind field and PM_{2.5} concentrations and transport at different vertical heights. Figure 5b shows a southwesterly wind at 39° N blowing from the surface to the 800 hPa level in the region's southern sector. In the southern sector closest to PK, the southerly wind speed reached its maximum value at ca. 900 hPa; and PM_{2.5} also exhibited high values at the same height. Pollutants could thus be transported to PK by the stable southwesterly wind from the southern environs via the 900 hPa layer. The northerly, or very weak southerly, wind in the region north of 41° N, together with the southerly wind south of 39° N, led to the formation of a wind convergence field over PK stretching from the surface level to 900 hPa. This would have been beneficial to the accumulation of PM_{2.5} and the consequent aggravation of haze. The vertical section along 39.375° N describes a southerly wind in the region to the south of PK from 116 to 125° E (Fig. 5c). This southerly wind, extending from the surface to 800 hPa, reached its maximum velocity at 900 hPa in the area to the south of PK (116 to 118° E). PM_{2.5} concentrations were also significantly higher in this region; pollutants from the 116–125° E area would have been easily transported northward by the southerly wind. PK was most likely affected by this process, raising pollution levels and aggravating the haze. To verify these results, we analyzed the relationship between PM_{2.5} concentrations in PK and the wind field of the area to the south of PK (i.e. 113.5–118° E, 34.5–39.5° N) (Fig. 5a). In the analysis, positive average hourly wind speed (v) values were representative of a southerly wind, and negative v values a northerly wind. The results showed that, when there was southerly wind in the area to the south of PK, average PM_{2.5} concentrations in PK always increased (Fig. 6). This was most obvious on 7 December, when the highest PM_{2.5} values occurred, accompanied by

longer periods of stable southerly winds. When there was a northerly wind in the area to the south of PK, average PM_{2.5} concentrations in PK fell, and then stabilized.

4.3 PK's PM_{2.5} input and output

To investigate the contribution of PM_{2.5} transported from its surroundings to PK pollution levels, the transport rates (kg s⁻¹) for PM_{2.5} from four directions, east (E), west (W), south (S) and north (N), were calculated using the following formulas:

$$\text{Tran}_N(t) = \sum_{z=1}^7 \sum_{x=x_1}^{x_2} \text{PM}_{y_1}(x, z, t) \cdot \Delta x_{y_1} \cdot \Delta z_{y_1}(x, z) \cdot v_{y_1}(x, z, t)$$

$$\text{Tran}_S(t) = - \sum_{z=1}^7 \sum_{x=x_1}^{x_2} \text{PM}_{y_2}(x, z, t) \cdot \Delta x_{y_2} \cdot \Delta z_{y_2}(x, z) \cdot v_{y_2}(x, z, t)$$

$$\text{Tran}_E(t) = \sum_{z=1}^7 \sum_{y=y_1}^{y_2} \text{PM}_{x_1}(y, z, t) \cdot \Delta y(y) \cdot \Delta z_{x_1}(y, z) \cdot u_{x_1}(y, z, t)$$

$$\text{Tran}_W(t) = - \sum_{z=1}^7 \sum_{y=y_1}^{y_2} \text{PM}_{x_2}(y, z, t) \cdot \Delta y(y) \cdot \Delta z_{x_2}(y, z) \cdot u_{x_2}(y, z, t)$$

$$\text{Tran}_{\text{net}}(t) = \text{Tran}_N(t) + \text{Tran}_S(t) + \text{Tran}_W(t) + \text{Tran}_E(t)$$

where Tran_N, Tran_S, Tran_E and Tran_W represent the PM_{2.5} transport rate for N, S, E and W, respectively (Fig. 7). Positive Tran values indicated net pollutant input into PK; negative Tran values described net pollutant output from PK. PM stands for PM_{2.5} concentration; x₁, x₂ (Fig. 7) are the westernmost and easternmost PK longitudes, respectively, and the subscripts y₁, y₂ (Fig. 7) are the southernmost and northernmost PK latitudes; t stands for time; Δx, Δy, Δz indicate the individual grid distances of the x, y, z axes; u stands for the easterly/westerly wind speed (negative for easterly wind); and v stands for the southerly/northerly wind speed (negative for northerly wind).

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rection of input/output pollutant transport. Net pollutant output turned southward; the output rate was clearly greater than the input rate from the north during the period 12:00–24:00 UTC.

The net transport rate for PK on 7 December was positive before 10:00 UTC, rising from ca. zero to a maximum of 118.1 kg s^{-1} at 06:00 UTC, and then began to decline to consistently negative values after 11:00 UTC (Fig. 8d). This suggests that the input of pollutants into PK exceeded the output during the period 00:00–10:00 UTC. After 11:00 UTC, input transport rates into PK were markedly reduced, resulting in a net negative transport of pollutants, indicating that PK was a source of pollutants for its environs. Combined with the results from Fig. 8c, there was net pollutant output to PK's east and south. By analyzing Fig. 8c and d, it can be seen that changes in the net transport rate for PK correlated with the transport rate southward. This was principally because westerly input and easterly output were basically equal and so offset one another. The northward transport rate was consistently low, and the variable southward transport rate therefore had an enormous influence on the PK area. These results indicate that pollutant transport between PK and its southern environs had the most significant impact on pollution levels in PK in comparison to other areas.

4.4 Contribution of pollutant transport to $\text{PM}_{2.5}$ concentrations over PK

In order to evaluate the contribution made by pollutants transported from its environs to PK $\text{PM}_{2.5}$ pollution, the total $\text{PM}_{2.5}$ suspended in the atmosphere between the surface and a height of 3000 m over the PK area during this haze episode was calculated, according to the formula

$$\text{Total}_{\text{PM}_{2.5}}(t) = \sum_{z=1}^7 \sum_{x=x_1}^{x_1} \sum_{y=y_1}^{y_2} \text{PM}(x, y, z, t) \cdot \Delta x(y, t) \cdot \Delta y(y, t) \cdot \Delta z(x, y, z, t),$$

along with the net hourly transport amount (Fig. 9). Total $\text{PM}_{2.5}$ changed little during 6 December, but did rise slightly after a small decline at 12:00 UTC when the net

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hourly output transport value decreased. The total $PM_{2.5}$ amount continued rising on 7 December and began to accelerate sharply until 09:00 UTC (4555.4 t) with a large net hourly input. After 12:00 UTC, net hourly transport became highly negative, and total $PM_{2.5}$ decreased rapidly. By the end of 7 December, the total $PM_{2.5}$ suspended in the atmosphere over PK was consistent with the values for 6 December. As Fig. 9 shows, this sharp rise in total $PM_{2.5}$ began at 12:00 UTC on 6 December, and ended at 12:00 UTC on 7 December, when total $PM_{2.5}$ reached its maximum value before beginning to decrease. As the calculation results in Table 1 show, the total $PM_{2.5}$ suspended over the PK area increased by ca. 2727 t from 12:00 UTC 6 December to 12:00 UTC 7 December. Net input was 1497 t, accounting for 55% of the total $PM_{2.5}$ increase. The remaining 1230 t could be attributed to local emissions, and accounted for 45% of the total $PM_{2.5}$ increase (Fig. 10). This suggests that the transport of particle pollutants from its environs made a significant contribution to the peak $PM_{2.5}$ values over PK during this haze episode.

5 Conclusions

The GRAPES-CUACE online mesoscale chemical weather forecasting model was used to study the influence of PM transported from its near environs on high $PM_{2.5}$ pollution levels in PK during a severe haze episode on 6–7 December 2013. Simulated results were compared with ground-level horizontal visibility, weather phenomena as observed by CMA, and surface $PM_{2.5}$ concentrations observed by CNEMC, to evaluate the model's ability to accurately describe haze pollution in China. The 3-D wind field over the Jing–Jin–Ji region and its relationship with $PM_{2.5}$ variations in PK, the input/output pollutant transport rates for PK and its N, S, E and W environs, the total input, output and net pollutant transport amounts for PK, and the total $PM_{2.5}$ suspended in the atmosphere over PK, were all calculated in relation to the possible contribution of $PM_{2.5}$ transported from its environs to the high $PM_{2.5}$ pollution levels in PK during the aforementioned severe haze episode. The results can be summarized as follows:

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counting for 55% of the total PM_{2.5} increase during this period. The remaining 1230t could be attributed to local emissions, and accounted for 45% of the total PM_{2.5} increase. This suggests that PM transport from its environs significantly influenced the peak PM_{2.5} values over PK during this episode.

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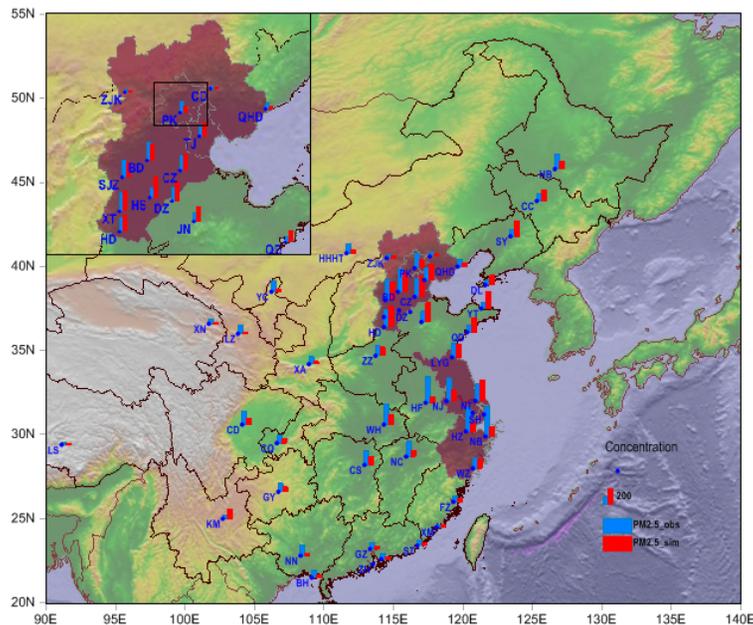


Figure 1. Mean observed and simulated PM_{2.5} (μg m⁻³) for 6–7 December 2013.

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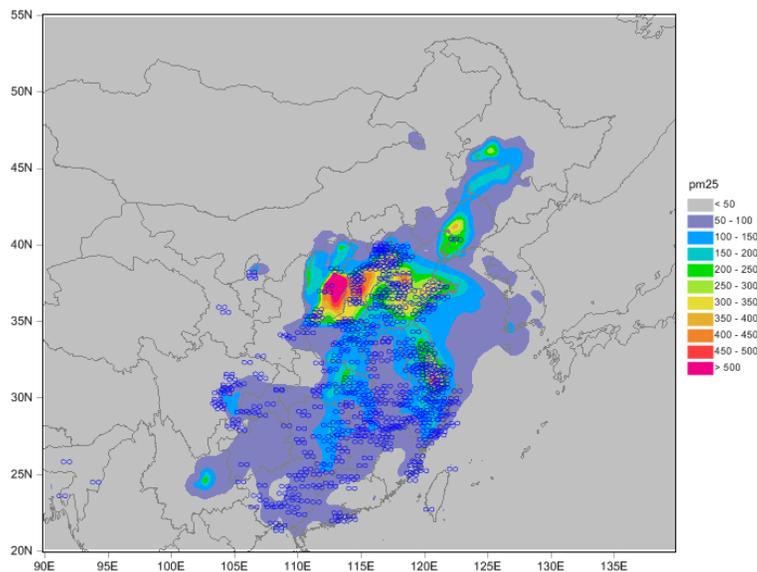
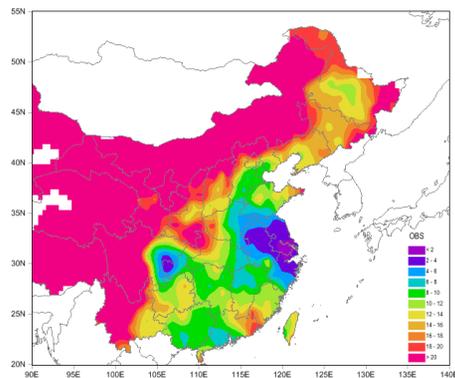


Figure 2. Simulated PM_{2.5} (shaded) and weather phenomena observed at 14:00 UTC 7 December 2013.

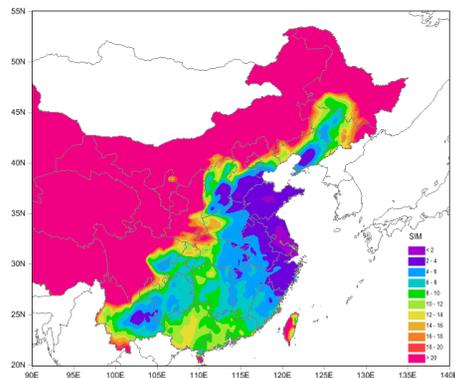
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(a)



(b)

Figure 3. Mean (a) observed and (b) simulated visibility for 6–7 December 2013.

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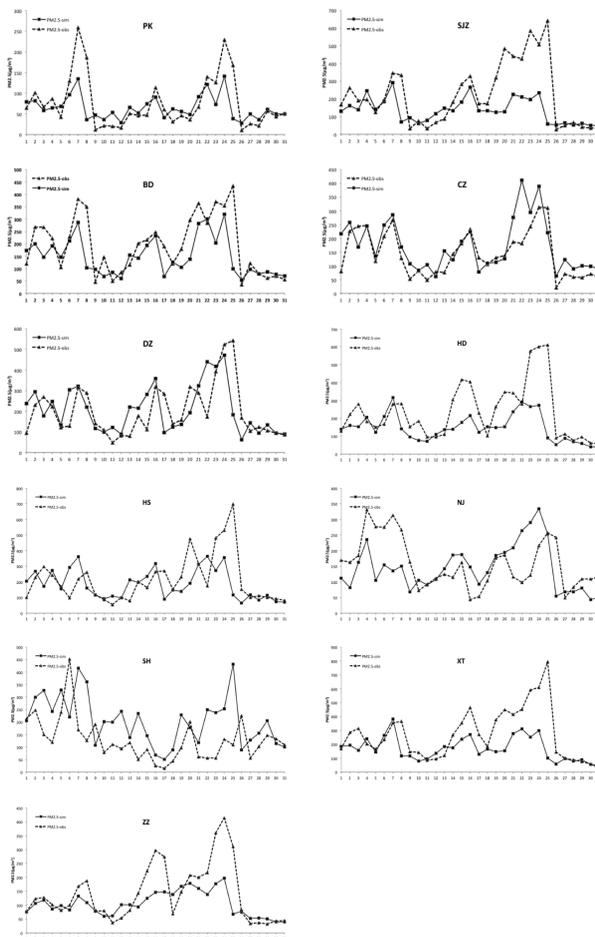


Figure 4. Daily variations in observed and simulated PM_{2.5} ($\mu\text{g m}^{-3}$) for 1–31 December 2013 at stations in PK, SJZ, BD, CZ, DZ, HD, HS, NJ, SH, XT and ZZ.

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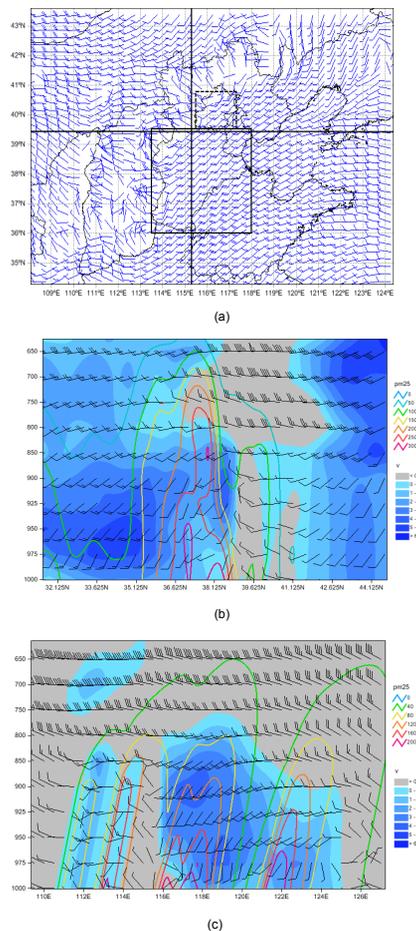


Figure 5. (a) Horizontal wind field at 900 hPa, its vertical section at (b) 115.25° E and (c) 39.375° N at 08:00 UTC 7 December 2013.

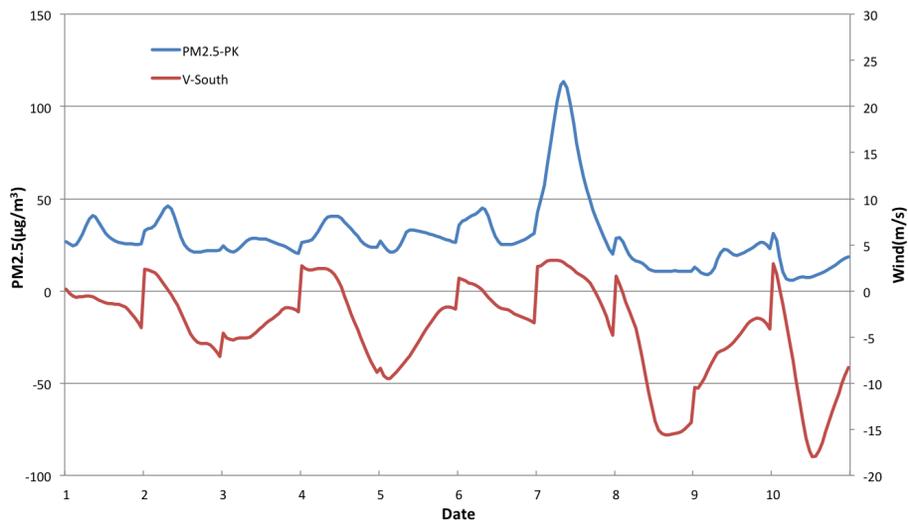


Figure 6. Hourly variations in $\text{PM}_{2.5}$ ($\mu\text{g m}^{-3}$) in PK and mean southerly wind speed (negative for northerly wind) for the region to the south of PK, 1–10 December 2013.

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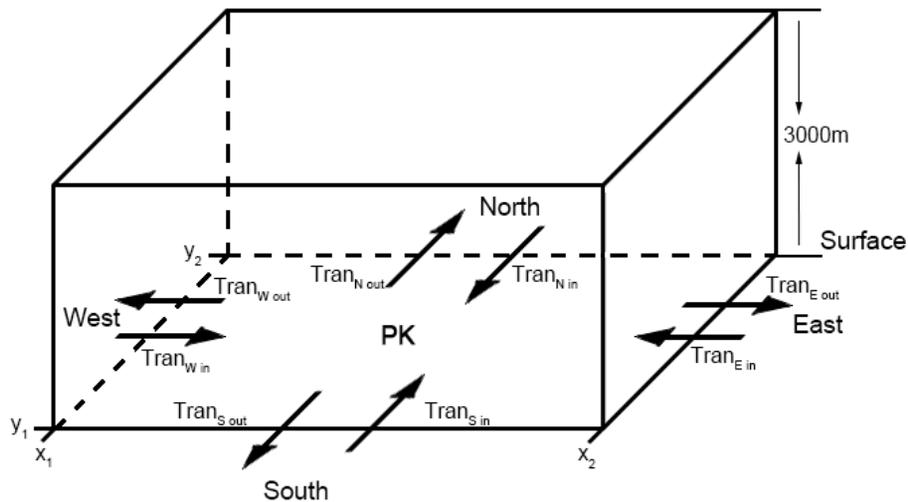
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**Figure 7.** Schematic diagram of pollutant transport between PK and its surrounding regions.

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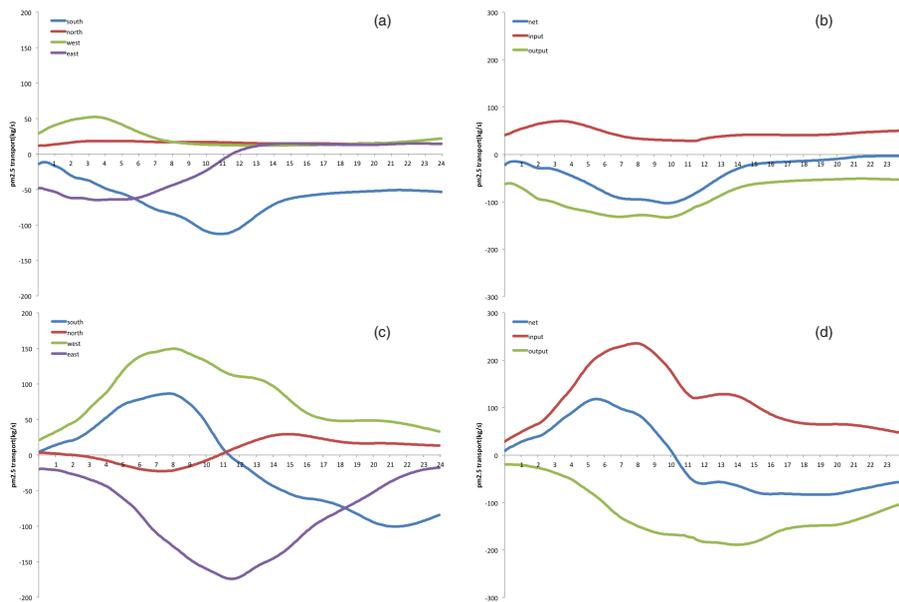


Figure 8. PM_{2.5} transport rates (kg s^{-1}) from S, N, W and E of PK on **(a)** 6 and **(c)** 7 December. Total input, output and net PM_{2.5} transport rate (kg s^{-1}) from PK's environs on **(b)** 6 and **(d)** 7 December.

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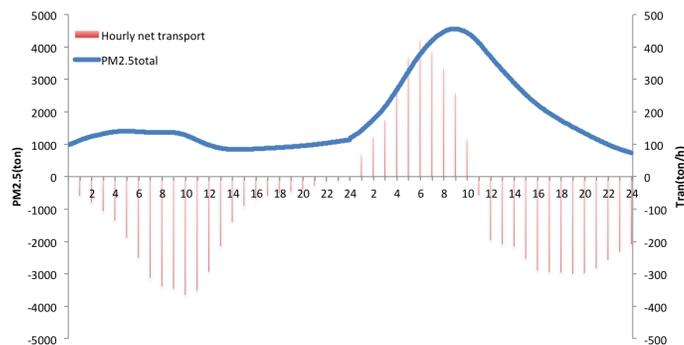


Figure 9. Total PM_{2.5} (ton) suspended in the atmosphere from the surface to 3000 m over the PK area and the net hourly PM_{2.5} input (ton h⁻¹) for PK during 6–7 December 2013.

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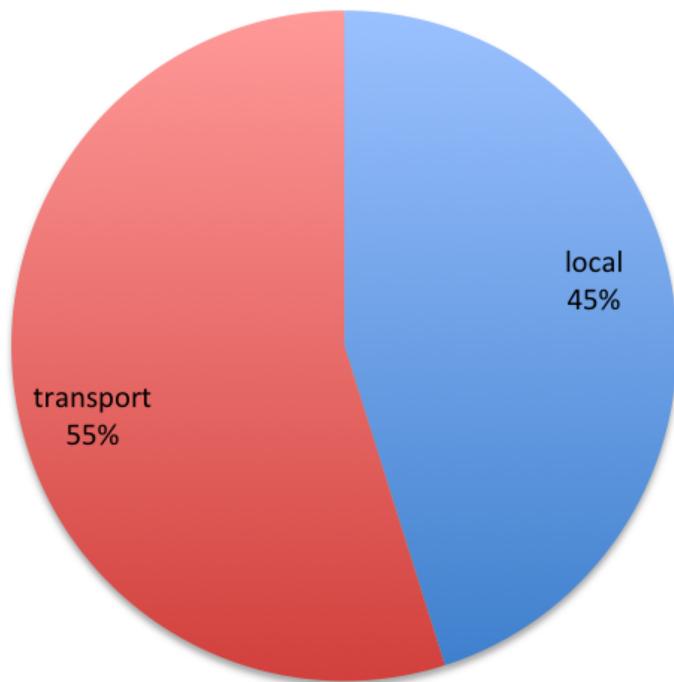


Figure 10. Contribution made by net transport and local emissions to PM_{2.5} increases in PK, 6–7 December 2013.

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