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Contribution of transregional transport to particle pollution and health effects in Shanghai during 2013–2017

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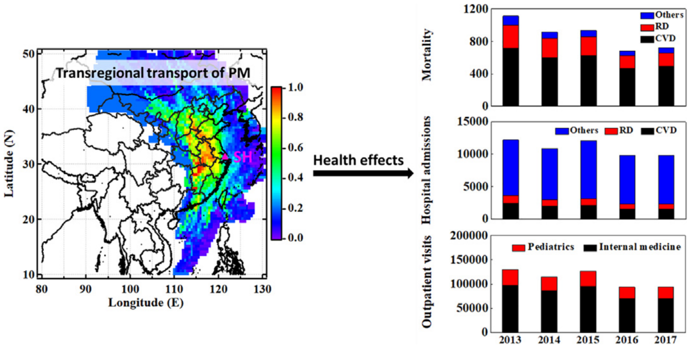
HIGHLIGHTS

- Contribution of transregional transport to PMs in Shanghai was quantified.
- Health effects of short-term exposure of $PM_{2.5\_CTRT}$ were assessed.
- Long-term exposure to moderate $PM_{2.5}$ deserves more attention in the future.

GRAPHICAL ABSTRACT



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ABSTRACT

Transregional transport plays an important role in air pollution. This study investigated the impact of transregional transport on particle pollution in Shanghai from 2013 to 2017. A conditional potential source contribution function (CPSCF) method with high time resolution (1 h) $PM_{2.5}$ and PM_{10} data was used to quantify the contribution of transregional transport. The corresponding health impact was also assessed. The average annual contribution of transregional transport to $PM_{2.5}$ ($PM_{2.5\_CTRT}$) and PM_{10} (PM_{10_CTRT}) was 22 and 30 $\mu g/m^3$, 18 and 24 $\mu g/m^3$, 19 and 24 $\mu g/m^3$, 14 and 19 $\mu g/m^3$, and 14 and 19 $\mu g/m^3$, for 2013 to 2017, respectively, thus accounting for 31–37% of total $PM_{2.5}$ and PM_{10}. As $PM_{2.5\_CTRT}$ is a dominant component of PM_{10_CTRT}, the health effects related to $PM_{2.5\_CTRT}$ were assessed to avoid double counting. The number of annual deaths associated with $PM_{2.5\_CTRT}$ in Shanghai during the study period ranged from 636 (95% confidence intervals: 350, 936) to 1039 (573, 1530), among which cardiovascular disease and respiratory disease accounted for 62.8–67.6% and 16.6–19.5% of mortality, respectively. $PM_{2.5\_CTRT}$-related deaths accounted for 5.3–8.2‰ of the total mortality in Shanghai during the study period. Between 9764 (9251, 10,277) and 12,190 (11,549, 12,830) cases of all-cause hospital admissions were attributable to $PM_{2.5\_CTRT}$ in Shanghai in one year, among which cardiovascular disease and respiratory disease hospital admissions accounted for 15.9–20.0% and 7.9–9.2%, respectively. Internal medicine and pediatrics outpatient visits related to $PM_{2.5\_CTRT}$ ranged from 70,684 (39,009, 100,829) to 97,380 (53,788, 138,793) cases and 23,185 (8302, 37,173) to 32,702 (11,726, 52,361) cases, respectively. The current work provides scientific evidence of the impact of transregional transport on air pollution and its health burden in Shanghai.

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1. Introduction

Atmospheric particles, including $PM_{2.5}$ and PM_{10}, are the main pollutants that cause haze and, more importantly, pose harmful effects to human health. These effects are closely related to the toxic components such as heavy metals and polycyclic aromatic hydrocarbons (PAHs). Animal, epidemiological and clinical studies agree that exposure to $PM_{2.5}$ and PM_{10} is a relevant risk factor (Hwang et al., 2005; Polichetti et al., 2009). For example, PM_{10} and $PM_{2.5}$ cause damage to the brain and cardiovascular system of mammals, affect body temperature, and lead to lung function decline (Guo et al., 2012; Hwang et al., 2005; Polichetti et al., 2009; Rice et al., 2015). $PM_{2.5}$ is more hazardous than PM_{10} because it contains smaller and more hazardous species that can penetrate deeper into the human body. For example, $PM_{2.5}$-bound PAHs accounted for >80% of PM_{10}-bound PAHs in a Chinese coal-based industrial city (Wu et al., 2014). A review study involving >120 cities in China found that a 10 $\mu g/m^3$ increase in $PM_{2.5}$ was associated with increases of 0.40%, 0.63%, and 0.75% in total non-accidental mortality, mortality due to cardiovascular disease, and mortality due to respiratory disease, respectively, while the increases associated with PM_{10} were 0.36%, 0.36%, and 0.42%, respectively (Lu et al., 2015). Shanghai is the leading city in the Yangtze River Delta region. With a population over 20 million, the population density of Shanghai (3816/km^2 in 2016) is the highest in China. The health effects caused by particle pollution, especially $PM_{2.5}$, are likely to be more serious in a mega city such as Shanghai.

Transregional or inter-regional transport plays an important role in air pollution. Ying et al. (2014) conducted a comprehensive and in-depth study on inter-regional (North, Northeast, East, Central, South, Southwest and Northwest) contributions to $PM_{2.5}$ nitrate and sulfate in China. For instance, nitrate in the North China Plain and the Middle and Lower Yangtze Plain regions significantly influenced nitrate concentrations in downwind areas as far as the Pearl River Delta (PRD) (Ying et al., 2014). The impact of long-range transport was especially obvious for sulfate in the PRD region in winter, with a transregional (North, East and Central China) contribution >80% (Ying et al., 2014). Focusing on mega cities, including Beijing, Shanghai, and Chongqing, and a large city cluster in the PRD, the results indicated stronger and more frequent interregional transport in winter (Ying et al., 2014). The impact of transregional or inter-regional transport has also been highlighted in a large number of previous studies (Chen et al., 2017; Fu et al., 2016; Hu et al., 2015; Wang et al., 2015b; Wang et al., 2014). However, very few studies have quantified the health impact of $PM_{2.5}$ attributable to transregional transport. Wang et al. (2017a) evaluated the effects of interprovincial trade on $PM_{2.5}$ pollution and public health across China. An investigation focusing on the contribution of transregional transport (CTRT) to particle pollution and the subsequent health burden in a mega city is desirable.

The aims of this study were thus to (1) identify potential regional source areas and quantify the CTRT to $PM_{2.5}$ and PM_{10} pollution in Shanghai from 2013 to 2017; and (2) assess the short-term health effects associated with $PM_{2.5}$ attributed to transregional transport. The study hypothesized that Shanghai is a receptor site and polluted air masses are transported from upwind areas to Shanghai, causing air pollution and the subsequent health burden.

2. Methods

2.1. Estimating the contribution of transregional transport

2.1.1. Potential source contribution function (PSCF)

The PSCF method, which associates concentrations of pollutants measured at a receptor site with backward trajectory simulations, has been widely used to locate the potential source areas of receptor sites (Han et al., 2018; Jeong et al., 2011; Jeong et al., 2013; Yao et al., 2016). The PSCF value indicates the probability that a source is located at latitude *i* and longitude *j*, described by Eq. (1) (Jeong et al., 2017):

$$PSCF_{ij} = \frac{m_{ij}}{n_{ij}} \tag{1}$$

where n_{ij} is the total number of trajectory endpoints falling in the grid (*i*, *j*), and m_{ij} is the number of trajectory endpoints corresponding to the concentration of an air pollutant at the receptor site above a specified threshold when air masses pass through the cell (*i*, *j*). Thus, the PSCF value of each grid ranges from 0 to 1, and grids with higher values make greater contributions to the receptor site.

In the present study, the annual average concentrations of $PM_{2.5}$ and PM_{10} were set as the specified thresholds. The HYbrid Single Particle Lagrangian Integrated Trajectory model was used to calculate 72-h backward trajectories sourced at Shanghai (31.22° N, 121.48° E) at a height of 50 m above ground level every hour. Meteorological data were downloaded from the re-analysis dataset of the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR). The PSCF domain was set from 10 to 50° N and from 80 to 130° E in 0.5 × 0.5 grid cells (Zhao et al., 2015). To minimize the uncertainty caused by potential source areas with a small number of endpoints, PSCF values were down weighted by applying an arbitrary weight function, W_{ij}, as follows (Jeong et al., 2017):

$$W_{ij} = \left\{ \begin{array}{c} 1.0\ n_{ave} \le n_{ij} \\ 0.75\ \frac{1}{2} n_{ave} \le n_{ij} < n_{ave} \\ 0.5\ \frac{1}{4} n_{ave} \le n_{ij} < \frac{1}{2} n_{ave} \\ 0.2\ 0 < n_{ij} < \frac{1}{4} n_{ave} \end{array} \right\} \tag{2}$$

where n_{ave} is the average number of endpoints per grid, which is about 80 in this study (78.8 and 79.1 for common and leap years, respectively).

2.1.2. Conditional potential source contribution function (CPSCF) method

The PSCF method provides qualitative information on the source areas of a receptor site. The CFSCF method proposed by Jeong et al. (2011, 2013, 2017) improved the PSCF method to quantify the contribution of long-range transport to a receptor site. The method was successfully used to investigate the impact of long-range transport on SO_2, NO_2, CO, PM_{10}, and carbonaceous aerosols in Seoul, Korea.

The detailed principles of the CPSCF method can be found elsewhere (Jeong et al., 2017). The method classifies the air mass pathways into two categories. When more than two backward trajectory endpoints are in a grid and the PSCF values are larger than 0.8, the air mass is classified as PS (an air mass that Passed over the Source region) (Jeong et al., 2017). All other air masses are classified as non-PS. Thus, the average concentration of a pollutant at a receptor site can be separated into PS and non-PS parts, as follows (Jeong et al., 2017):

$$\text{Average} = \left[C_p \times \frac{ND_p}{TND}\right] + \left[C_c + \frac{ND_c}{TND}\right] \tag{3}$$

where C_p and C_c are the mean concentrations of the pollutants under the PS and non-PS conditions; ND_p and ND_c are the number of days under the PS and non-PS conditions; and TND is the total number of days during the analysis period. The left-hand-side of Eq. (3) represents the CTRT, and the right-hand-side indicates the local contribution. One of the advantages of CPSCF calculation is that the method is independent of chemical mechanisms and emission inventories because the target pollutants measured at a receptor site have already been subjected to chemical processes during transport from upwind polluted areas (Jeong et al., 2017).

Table 1
Exposure-response coefficients (β, presented as % change per 10 μg/m^3 increase in PM$_{2.5}$ concentration) of various types of health outcomes due to PM$_{2.5}$ exposure.

Health endpoints	β (%)	95% CI	References
Total non-accidental mortality	0.40	(0.22, 0.59)	Lu et al. (2015)
Mortality due to CVD	0.63	(0.35, 0.91)	Lu et al. (2015)
Mortality due to RD	0.75	(0.39, 1.11)	Lu et al. (2015)
Hospital admissions			
All-cause	0.19	(0.18, 0.20)	Liu et al. (2018)
CVD	0.23	(0.20, 0.26)	Liu et al. (2018)
RD	0.26	(0.22, 0.1)	Liu et al. (2018)
Outpatient visits			
Internal medicine	0.49	(0.27, 0.7)	Xie et al. (2014)
Pediatrics	0.56	(0.2, 0.9)	Xie et al. (2014)

CI: Confidence intervals, CVD: Cardiovascular disease, RD: Respiratory disease.

The uncertainties of the CPSCF method were estimated by calculating the standard deviation of the CTRT values using different backward trajectory runtimes (36, 48, 60, and 72 h) and PS criterions (0.75, 0.80, and 0.85), because these parameters can affect the CTRT results (Jeong et al., 2017). For example, the uncertainty of the CTRT for PM$_{10}$ in Seoul from 2001 to 2014 ranged from 22.6 to 38.2%, with an average uncertainty of 30.5% (Jeong et al., 2017).

2.2. Estimating the health effects

Solid evidence of the correlation between daily mortality or morbidity and air pollution has been provided by numerous epidemiological studies (Atkinson et al., 2014). The following equation is widely used to express the relationship between short-term health effects and PM$_{2.5}$ (Huang et al., 2012; Wang et al., 2015a):

$$\Delta E = P \times IR\left[1 - \frac{1}{exp[\beta(c - c_0)]}\right] \quad (4)$$

where ΔE denotes the number of estimated cases of specified health outcomes caused by PM$_{2.5}$; P indicates the exposed population; IR is the incidence rate of mortality or morbidity; β is the exposure-response coefficient; c is the observed concentration of PM$_{2.5}$; and c_0 is the threshold concentration. In this study, we only select those health outcomes that can be quantitatively estimated, including total non-accidental mortality, mortality due to cardiovascular disease (CVD) and respiratory disease (RD), hospital admissions for CVD and RD, and outpatient visits (pediatrics and internal medicine).

The exposure-response coefficient (β) is important for assessing health effects, and there are large differences in the results reported in China and abroad. Fang et al. (2016) summarized the exposure-response coefficients from the cohort studies on PM$_{2.5}$ and mortality. PM$_{2.5}$ levels ranged from 3 μg/m^3 to 94 μg/m^3 in China, and every 10 μg/m^3 increase in PM$_{2.5}$ was associated with a −15.5%–23.1% change in total mortality, −22.3%–56.5% change in cardiovascular mortality, and −5.5–45.3% change in respiratory mortality (Fang et al., 2016). In this study, the principle of selecting exposure-response coefficients for PM$_{2.5}$ from the literature prioritizes studies performed in Shanghai, then the Yangtze River Delta, and then other mega cities in China. A comprehensive meta-analysis was selected (Lu et al., 2015), which reports a combined estimation from 10 studies focusing on the relationship between daily mortality and PM$_{2.5}$ in Chinese mega cities (4 of the 10 studies were conducted in Shanghai). Few studies reported the relationship between PM$_{10}$ and hospital admissions and outpatient visits (including emergency room visits) in Shanghai (Cao et al., 2009; Chen et al., 2010). Only one study investigated the association between daily outpatient visits for respiratory diseases and PM$_{2.5}$ in Shanghai (Wang et al., 2018). The incidence rate for respiratory disease-related outpatient visits in Shanghai is not available. Therefore, the exposure-response coefficients for hospital admissions (all-cause, CVD, and RD) in this study refer to a study of PM$_{2.5}$ concentrations and hospital admissions in 26 of China's largest cities, including Shanghai (Liu et al., 2018) and the exposure-response coefficients for outpatient visits (internal medicine and pediatrics) refer to a study in Beijing (Xie et al., 2014). The exposure-response coefficients (β) of various types of health outcomes due to PM$_{2.5}$ exposure are summarized in Table 1.

C$_0$ is the threshold value of PM$_{2.5}$, which indicates that no deaths would be associated with PM$_{2.5}$ below this concentration. There seems to be no threshold concentration for the health effects of atmospheric PM$_{2.5}$ because a linear relationship was observed between PM$_{2.5}$ and daily deaths even at a very low PM$_{2.5}$ concentration (Schwartz et al., 2002). Thus, C_0 was set at zero in this study, as in some previous studies (Huang et al., 2012; Wang et al., 2017b; Wang et al., 2015a).

3. Results and discussion

3.1. Input

3.1.1. PM$_{2.5}$ and PM$_{10}$ concentrations

The hourly PM$_{2.5}$ and PM$_{10}$ concentrations in Shanghai from January 1, 2013 to December 31, 2017 were obtained from the Shanghai Environmental Monitoring Center. The distributions of these concentrations are plotted in Fig. 1. The annual concentrations of PM$_{2.5}$ and PM$_{10}$ were 62 and 82 μg/m^3, 52 and 71 μg/m^3, 53 and 68 μg/m^3, 45 and 59 μg/m^3, and 39 and 57 μg/m^3 from 2013 to 2017, respectively. The annual mass ratio of PM$_{2.5}$/PM$_{10}$ ranged from 0.69 to 0.78, with a mean of 0.74. Compared with 2013, the levels of PM$_{2.5}$ and PM$_{10}$ were 37.1% and 30.5% lower in 2017.

Several previous studies have conducted PSCF analyses based on 24-h PM$_{2.5}$ or PM$_{10}$ samples in Shanghai, and backward trajectories were usually calculated every 6 h each day, thus obtaining four backward trajectories per day (Li et al., 2012; Zhao et al., 2015). These four daily

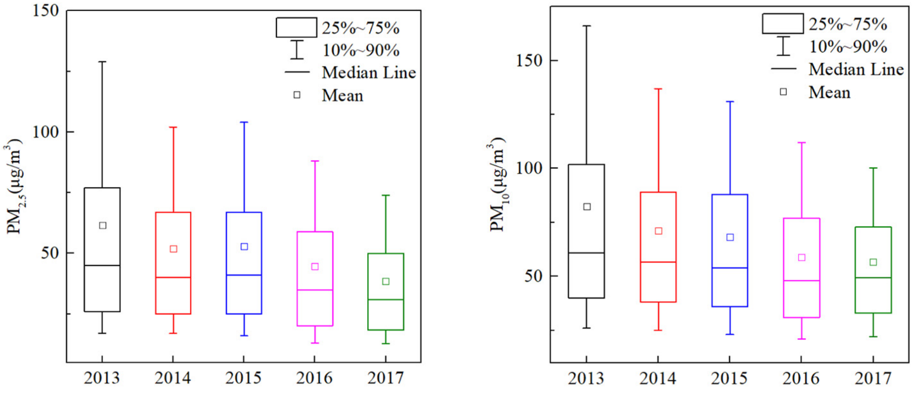

Fig. 1. Distribution of hourly PM$_{2.5}$ and PM$_{10}$ concentrations in Shanghai during 2013–2017.

backward trajectories correspond to the same $PM_{2.5}$ or PM_{10} concentration, i.e. the averaged 24-h $PM_{2.5}$ or PM_{10} concentration (Li et al., 2012; Zhao et al., 2015). In the current work, the high time resolution (1 h) of the $PM_{2.5}$ and PM_{10} data reduced the uncertainty of PSCF and CPSCF analysis. There is a one-to-one correspondence between the hourly $PM_{2.5}$ (or PM_{10}) concentrations and the backward trajectories (24 per day) in this study.

3.1.2. Health information and exposed population

We used the resident population at the year-end, instead of the household registered population, as the exposed population because many residents are not registered as part of the household population in a mega city like Shanghai. The annual exposed population in Shanghai was 24.15, 24.26, 24.15, 24.20, and 24.18 million, from 2013 to 2017, respectively (NBSC, 2014–2018). Table 2 lists the incidence rate of various health endpoints in Shanghai from 2013 to 2017. We assumed that the incidence rate of health endpoints in 2017 was the same as that in 2016 when the corresponding data were not updated in 2017. The total mortality rate in Shanghai from 2013 to 2017 was 5.24‰, 5.21‰, 5.07‰, 5.00‰ and 5.30‰ (NBSC, 2014–2018). Accidental death (which is not correlated with $PM_{2.5}$ pollution), including death caused by traffic accidents, accidental poisoning, accidental falls, accidental mechanical asphyxia, fire, drowning, electric shock, suicide, and homicide, accounted for 6.30%, 6.13%, 6.05% and 6.08% of total deaths in Chinese cities during 2013–2016, respectively (NHFPC, 2014–2017). Thus, we used these data to estimate total non-accidental mortality in Shanghai from 2013 to 2017 as 4.91‰, 4.89‰, 4.76‰, 4.70‰ and 4.98‰, respectively.

According to the health data published by the Shanghai Municipal Commission of Heath and Family Planning (http://www.wsjsw.gov.cn/index.html), CVD causes the greatest number of deaths, followed by tumors and RD. The specific death rate for CVD in Shanghai in each year of the study period was 304.67, 320.14, 338.69, 343.12, and 350.85 per 10^5 population, accounting for 37.38%, 38.48%, 39.32%, 40.24%, and 40.40% of all deaths in each year, respectively. The specific death rate for RD in Shanghai was 78.61, 81.16, 81.53, 75.11 and 72.55 per 10^5 population, accounting for 9.65%, 9.75%, 9.47, 8.81% and 8.35% of all deaths in each year of the study period, respectively. Thus, the mortality rate for CVD and RD was 1.96‰ and 0.51‰ in 2013, 2.00‰ and 0.51‰ in 2014, 1.99‰ and 0.48‰ in 2015, 2.01‰ and 0.44‰ in 2016, and 2.14‰ and 0.44‰ in 2017 (Table 2).

The incidence rate of all-cause hospital admissions in Shanghai from 2013 to 2017 was 12.1%, 13.1%, 13.9%, 15.2%, and 15.2%, respectively (NHFPC, 2014–2017). The incidence rates of hospital admissions due to CVD and RD in the eastern Chinese cities (including Shanghai) in 2013 were used in this study (NHFPC, 2014–2017). Information on outpatient visits in Shanghai, including internal medicine and pediatric outpatient visits, was sourced from the National Health and Family Planning Yearbook (NHFPC, 2014–2017).

Table 2
Incidence rate of various health endpoints in Shanghai from 2013 to 2017.

Health endpoints	2013	2014	2015	2016	2017
Total non-accidental mortality (‰)	4.91	4.89	4.76	4.70	4.98
Mortality of CVD (‰)	1.96	2.00	1.99	2.01	2.14
Mortality of RD (‰)	0.51	0.51	0.48	0.44	0.44
Hospital admissions					
All-cause (%)	12.1	13.1	13.9	15.2	15.2[a]
CVD (‰)[b]	20	20	20	20	20
RD (‰)[b]	8.8	8.8	8.8	8.8	8.8
Outpatient visits					
Internal medicine (per 10^4 population)	3760.7	4071.5	4266.6	4275.9	4275.9[a]
Pediatrics (per 10^4 population)	1105.9	1170.8	1235.8	1227.8	1227.8[a]

[a] Refers to the data in 2016.

[b] Refers to the data in the eastern Chinese cities, including Shanghai in 2013, which is sourced from National Health and Family Planning Yearbook, 2017.

3.2. Contribution of transregional transport (CTRT)

The results of the PSCF analysis of $PM_{2.5}$ and PM_{10} in Shanghai during 2013–2017 are depicted in Fig. 2. The PSCF maps of $PM_{2.5}$ are similar and the significant potential source areas with PSCF values larger than 0.8 are mainly distributed in Anhui and the surrounding areas. In 2014, the significant potential source area extended to include Anhui, Henan, Jiangsu, Jiangxi, Zhejiang, and Fujian. The PSCF values for 2015 and 2016 were slightly lower than for the rest of the study period,

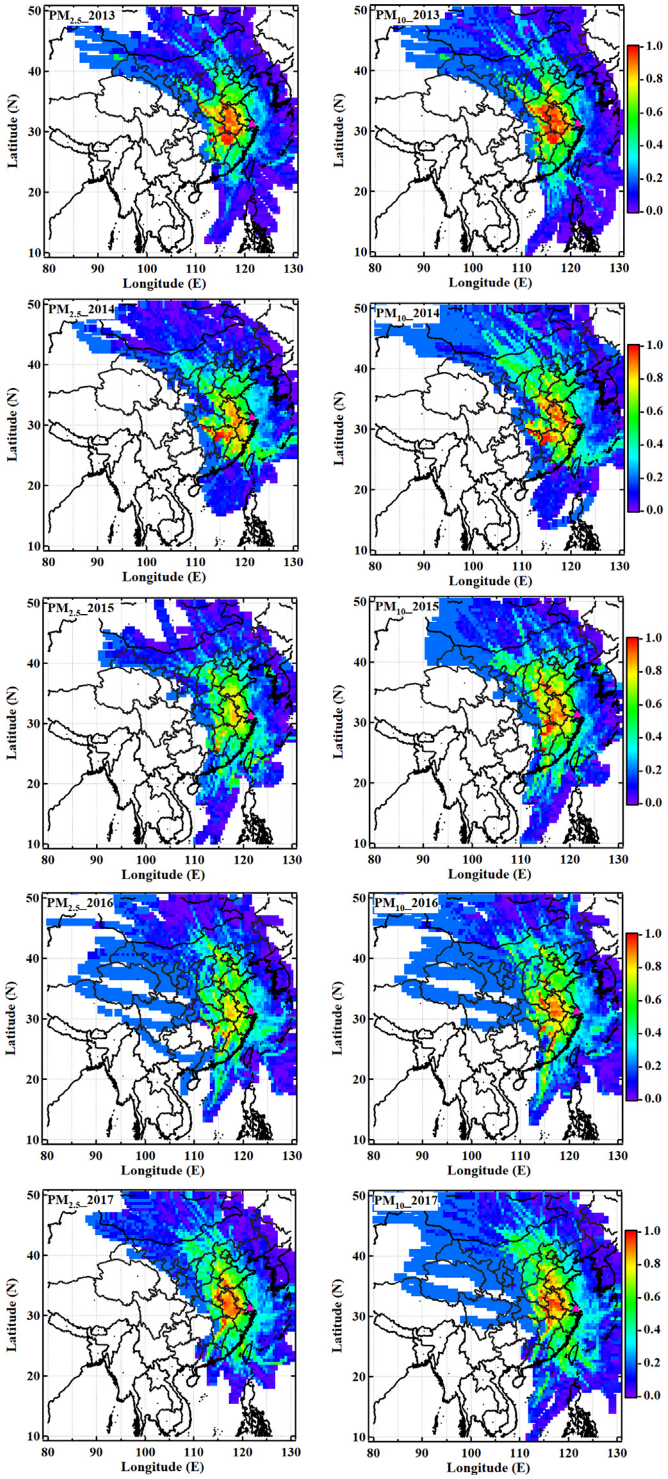

Fig. 2. Spatial distribution of PSCF (potential source contribution function) values of hourly $PM_{2.5}$ (left) and PM_{10} (right) in Shanghai from 2013 to 2017.

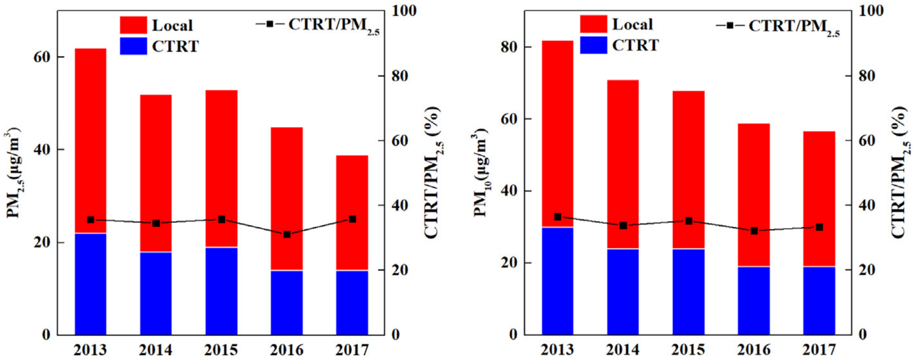

Fig. 3. CTRT (contribution of transregional transport) to $PM_{2.5}$ and PM_{10} in Shanghai from 2013 to 2017 based on CPSCF (conditional potential source contribution function) analysis.

whereas the significant potential source areas extended to Hebei, Shandong, and Shanxi. Moderate potential source areas of $PM_{2.5}$ in Shanghai involved large areas of the North China Plain, central China, and the Yangtze River Delta, with PSCF values larger than 0.6.

The PSCF maps of PM_{10} are similar to those of $PM_{2.5,}$ but cover a wider potential source area. Despite the inter-annual variation in the PSCF maps of $PM_{2.5}$ and PM_{10}, Anhui made the greatest contribution to $PM_{2.5}$ and PM_{10} levels in Shanghai over the study period.

From the CPSCF analysis, the mean concentrations of $PM_{2.5}$ in the PS condition were 140, 105, 106, 91 and 74 μg/m^3 during 2013–2017, respectively, and these values were 90–126% higher than their mean concentrations. The mean number of days under the PS condition in each year was 57.6, 61.0, 62.5, 55.0, and 70.5 for $PM_{2.5}$. Similarly, the mean concentrations of PM_{10} under the PS condition were 186, 141, 131, 106, and 96 μg/m^3, with 58.3, 60.5, 66.6, 63.8, and 70.5 days under the PS condition each year.

The CTRT results for $PM_{2.5}$ and PM_{10} are plotted in Fig. 3. The CTRT to $PM_{2.5}$ ($PM_{2.5\_CTRT}$) in Shanghai was 22, 18, 19, 14, and 14 μg/m^3, accounting for an average of 36%, 35%, 36%, 31%, and 36% of total $PM_{2.5}$ per year (Fig. 3). Similarly, transregional transport contributed 30, 24, 24, 19, and 19 μg/m^3 of PM_{10} (PM_{10_CTRT}), respectively, accounting for 32–37% of total PM_{10} in Shanghai (Fig. 3). The mass ratio of $PM_{2.5\_CTRT}/PM_{10\_CTRT}$ ranged from 0.73 to 0.79, with a mean of 0.75.

For a typical severe haze episode, local or regional transport could be the dominant contributor, depending on the meteorological conditions. For example, up to 70% of $PM_{2.5}$ in Shanghai was attributable to regional transport during a winter time case study (Fu et al., 2016). Wang et al. (2014) reported a local contribution of 80% during a Shanghai haze event in which the $PM_{2.5}$ concentration exceeded 140 μg/m^3, which was closely related to the weak wind (<0.5 m/s). The same study attributed 85% of $PM_{2.5}$ mass to regional transport in a typical severe pollution episode ($PM_{2.5} > 170$ μg/m^3) with a moderate wind speed of 2 m/s and air masses originating from the upwind adjacent regions (Wang et al., 2014). Stronger and more frequent transregional transport in winter than in summer was reported in three mega cities (Beijing, Shanghai, and Chongqing) due to the very different meteorological conditions in the two seasons (Ying et al., 2014). In addition, different chemical compositions of $PM_{2.5}$ in Shanghai showed large differences in the dominant contributor: local sources contributed 81% of the elemental carbon concentration in urban Shanghai, whereas regional transport made a much greater contribution to sulfate, nitrate, and ammonium concentrations over the whole of Shanghai during autumn haze episodes (Wang et al., 2014).

3.3. $PM_{2.5}$-related health effects attributable to transregional transport

As discussed in Section 3.2, $PM_{2.5\_CTRT}$ represents a dominant fraction of PM_{10_CTRT}. To avoid double calculation, the health effects related to $PM_{2.5\_CTRT}$ in Shanghai were highlighted in this study. Concentrations of $PM_{2.5\_CTRT}$ correspond to *c* in Eq.(4) to calculate the health effects associated with $PM_{2.5\_CTRT}$. The health effects attributable to $PM_{2.5\_CTRT}$ exposure in Shanghai from 2013 to 2017 are listed in Table 3. The number of deaths attributable to $PM_{2.5\_CTRT}$ each year was 1039 (95% CI, 573, 1530), 852 (469, 1254), 871 (480, 1282), 636 (350, 936), and 673 (371, 991), accounting for 8.2‰, 6.7‰, 7.1‰, 5.3‰, and 5.3‰ of the total deaths in Shanghai, respectively. The number of CVD deaths related to $PM_{2.5\_CTRT}$ each year was 652 (364, 939), 548 (305, 789), 572 (319, 824), 428 (238, 616), and 455 (253, 656), accounting for 62.8–67.6% of total non-accidental deaths. RD mortality accounted for 16.6–19.5% of annual $PM_{2.5\_CTRT}$-related deaths. Each year, 9764 (9251, 10,277)–12,190 (11,549, 12,830) cases of all-cause hospital admissions were attributable to $PM_{2.5\_CTRT}$ in Shanghai, among which CVD and RD hospital admissions accounted for 15.9–20.0% and 7.9–9.2%, respectively. Internal medicine outpatient visits related to $PM_{2.5\_CTRT}$ ranged from 70,684 (39,009, 100,829) to 97,380 (53,788, 138,793) cases, and pediatric outpatient visits ranged from 23,185 (8302, 37,173) to 32,702 (11,726, 52,361) cases. Internal medicine and pediatric outpatient visits associated with $PM_{2.5\_CTRT}$ accounted for 3.9–5.4‰ of the total population of Shanghai in each year of the study period.

To obtain the short-term health effects of total $PM_{2.5}$ in Shanghai from 2013 to 2017, we calculated the health impact caused by $PM_{2.5}$

Table 3
Health effects attributed to $PM_{2.5\_CTRT}$ in Shanghai from 2013 to 2017, mean value (95% CI).

Health endpoints	2013	2014	2015	2016	2017
Total non-accidental mortality	1039 (573, 1530)	852 (469, 1254)	871 (480, 1282)	636 (350, 936)	673 (371, 991)
Mortality of CVD	652 (364, 939)	548 (305, 789)	572 (319, 824)	428 (238, 616)	455 (253, 656)
Mortality of RD	202 (106, 298)	166 (87, 245)	165 (86, 242)	112 (58, 165)	112 (58, 165)
Hospital admissions					
All-cause	12,190 (11,549, 12,830)	10,851 (10,281, 11,421)	12,097 (11,461, 12,732)	9772 (9258, 10,286)	9764 (9251, 10,277)
CVD	2438 (2121, 2755)	2005 (1744, 2266)	2107 (1832, 2381)	1556 (1354, 1759)	1555 (1353, 1758)
RD	1213 (1027, 1445)	997 (844, 1188)	1048 (887, 1249)	774 (655, 923)	774 (655, 922)
Outpatient visits					
Internal medicine	97,380 (53,788, 138,793)	86,737 (47,888, 123,676)	95,484 (52,724, 136,134)	70,743 (39,041, 100,912)	70,684 (39,009, 100,829)
Pediatrics	32,702 (11,726, 52,361)	28,488 (10,207, 45,644)	31,587 (11,320, 50,601)	23,204 (8308, 37,204)	23,185 (8302, 37,173)

originating from local emissions in Shanghai. On average, 40, 34, 34, 31, and 25 μg/m^3 of $PM_{2.5}$ per year originated from local sources ($PM_{2.5\_LC}$). Correspondingly, 1883 (1039, 2766), 1603 (885, 2357), 1553 (857, 2284), 1402 (774, 2062), and 1199 (661, 1764) deaths were related to $PM_{2.5\_LC}$ exposure. Thus, a total of 2922 (1612, 4296), 2455 (1354, 3611), 2424 (1337, 3566), 2038 (1124, 2998), and 1872 (1032, 2755) deaths were related to short-term $PM_{2.5}$ exposure, accounting for 2.4%, 1.9%, 2.0%, 1.7%, and 1.5% of total deaths.

Comparisons among previous studies on the health impact of $PM_{2.5}$ are difficult because they use different population data, short-term or long-term assessment, and threshold concentrations (Wang et al., 2015a). For example, according to the Global Burden of Disease Study, the threshold concentration ranged from 5.8 μg/m^3 to 8.8 μg/m^3 (Burnett et al., 2014; Lim et al., 2012). World Health Organization Air Quality Guidelines (10 μg/m^3) are also widely used as the threshold $PM_{2.5}$ value (Jahn et al., 2011). Only a few studies that evaluated the mortality in Shanghai using a similar method can be compared. Kan and Chen (2004) evaluated the impact of PM_{10} on human health and the subsequent economic costs in Shanghai in 2001. They attributed 4780 (2950, 6610) deaths to PM_{10}, using the natural background level (73.2 μg/m^3) as the PM_{10} threshold concentration. Wang et al. (2015a) investigated short-term $PM_{2.5}$-related mortality in the Yangtze River Delta and reported 2415 (1974, 2854) deaths in Shanghai in 2010, with no threshold concentration. Voorhees et al. (2014) reported that between 39 and 1400 cases of all-cause mortality a year were avoided in Shanghai during 2010–2012. In Voorhees's study, the $PM_{2.5}$ concentration was estimated as 58% of the PM_{10} concentration and the threshold $PM_{2.5}$ concentration was 35 μg/m^3. Our results are similar to those of Wang et al. (2015a), and both studies used the same threshold concentration of $PM_{2.5}$.

Animal toxicity experiments have demonstrated that greater damage is caused by longer exposure to a moderate $PM_{2.5}$ concentration than by shorter exposure to a high concentration, with the same overall dose, which may indicate a greater hazard from long-term exposure to $PM_{2.5}$ (Hwang et al., 2005). We found two studies that used similar threshold concentrations of $PM_{2.5}$ to investigate the long-term health effects of $PM_{2.5}$ in Shanghai in recent years. Fang et al. (2016) used 5.8 μg/m^3 as the threshold value of $PM_{2.5}$ to assess the mortality effects in the 74 leading cities of China and reported >20,000 deaths (and <30,000) in Shanghai in 2013. Maji et al. (2018) investigated $PM_{2.5}$-related premature mortality in 338 Chinese cities and found that 17,740 premature deaths resulted from $PM_{2.5}$ exposure in Shanghai in 2016. That study used 5.9 μg/m^3 as the threshold concentration of $PM_{2.5}$. It is clear that the long-term $PM_{2.5}$-related health effects are much more serious (6.7–8.7 times) than the short-term effects (Fang et al., 2016; Maji et al., 2018). This implies that although $PM_{2.5}$ concentrations in Shanghai decreased from 62 μg/m^3 in 2013 to 39 μg/m^3 in 2017, long-term exposure to moderate $PM_{2.5}$ deserves more attention in future studies.

3.4. Uncertainty

There are two types of uncertainties in the current work. First, the CPSCF method may underestimate the CTRT because the transregional transport from moderate potential source areas (PSCF values < 0.8) could also affect the concentrations of pollutants in Shanghai. Thus, the results are likely to provide the lower limit of the CTRT to particulate matters in Shanghai. Jeong et al. (2017) reported that the uncertainty of the CPSCF method ranged from 22.6% to 38.2% in an investigation of the long-range transport contribution to PM_{10} in Seoul from 2001 to 2014. Second, the uncertainty of epidemiological references, incidences, and population data is difficult to quantify. The entire population of Shanghai was assumed to be exposed to the same $PM_{2.5}$ concentration when conducting the health impact assessment. In reality, $PM_{2.5}$ concentrations and the population of Shanghai exhibit large spatial variations. Models that consider the spatial distributions of the population and $PM_{2.5}$ concentration are recommended in future studies. $PM_{2.5}$ concentrations vary between seasons and between hazy and non-hazy days. Ho et al. (2018) investigated the spatiotemporal pattern of haze effects on the short-term mortality risk in Hong Kong and reported that the all-cause mortality risk was higher on a regular hazy day than on a day without haze, with an odds ratio of 1.029 (1.009, 1.049). In this study, we used the annual average concentrations of $PM_{2.5}$ to assess the health impact each year. This may be one of limitations of the current study.

4. Conclusions

This study aimed to quantify the CTRT to ambient particle concentrations and the consequent health effects (deaths, hospital admissions, and outpatient visits) in Shanghai from 2013 to 2017 based on hourly $PM_{2.5}$ and PM_{10} concentrations. Transregional transport contributed to 31–37% of the annual $PM_{2.5}$ ($PM_{2.5\_CTRT}$) and PM_{10} (PM_{10_CTRT}) in Shanghai over the five-year study period, which highlights the importance of both local emission and inter-regional emission control in the future. The number of deaths attributable to $PM_{2.5\_CTRT}$ ranged from 636 (95% CI, 350, 936) to 1039 (573, 1530) per year, accounting for 5.3–8.2‰ of all deaths in Shanghai during the study period. The results of the specific-cause morbidity analysis should remind people with CVD to take care on hazy days, as CVD-related deaths accounted for 62.8–67.6% of total deaths attributed to $PM_{2.5\_CTRT}$. For all-cause hospital admissions, 9764 (9251, 10,277)–12,190 (11,549, 12,830) cases were attributable to $PM_{2.5\_CTRT}$ in Shanghai each year, among which CVD and RD hospital admissions accounted for 15.9–20.0% and 7.9–9.2%, respectively. Outpatient visits (internal medicine and pediatrics) related to $PM_{2.5\_CTRT}$ accounted for 3.9–5.4‰ of the total population each year in Shanghai. Despite the limitations, the present study helps to explain the overall impact of transregional transport on air pollution and its health burden in a mega city with a high-density population.

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