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Air Quality over the Yangtze River Delta during the 2010 Shanghai Expo

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ABSTRACT

An air quality monitoring network consisting of 53 stations at 9 cities over the Yangtze River Delta (YRD) simultaneously measured gaseous and particulate pollutants (SO_2, NO_2, CO, O_3, $PM_{2.5}$ and PM_{10}) during the six-month Shanghai World Expo in 2010. The regional distribution of air pollutants showed that Shanghai was a low-SO_2-PM_{10} zone over the YRD during the Expo, owing to the effective controls that were applied to power plants, industrial activities and construction works. However, Shanghai also became a high-NO_x-CO-O_3 zone in the YRD, partly due to the large number of vehicles in Shanghai, and also the expected increase in transportation emissions due to the tremendous number of visitors during the Expo. Monthly variations in the major pollutants generally presented similar patterns, with lower values in the middle of the Expo, i.e., from July to September, and higher values in May, June and October. The magnitudes of pollutant precursor (SO_2 and NO_2) concentrations and meteorological conditions (e.g., wind speed, directional wind from X vector, and mixing layer height) were investigated, and found to play important roles in the monthly variations. Spatial correlations of air pollutants between Shanghai and the other 8 cities revealed the impact of regional transport on air quality in Shanghai, and vice versa. Intense air pollution episodes in Shanghai were mainly related to the regional/long-range transport from inland polluted regions. The high frequency of marine winds during the Expo had a positive effect on the air quality of coastal cities, while it had a negative effect on some inland cities in the YRD.

Keywords: Shanghai Expo; Air quality; Meteorology; Regional transport.

INTRODUCTION

Shanghai hosted the World Expo in 2010 from May 1 to October 31 and totally 73 million visitors attended this mega-event. It was the biggest international event in China after the 2008 Beijing Olympic Games. Shanghai is located on the eastern tip of the Yangtze River Delta (YRD), which owns the largest adjacent metropolitan areas in the world. The delta region comprises of the megacity Shanghai, and many other cities in Jiangsu and Zhejiang provinces. It is the most populous region in China, with 80 million people and about 63% were living in urban areas as of 2007. It is also one of the most industrial regions, contributing about 21.4% of the nation GDP (gross domestic production) in China. The GDP of Shanghai quintupled from 1996 to 2006 and the numbers of automobiles increased from 0.47 to 2.53 million during these years (UNEP, 2009).

The Shanghai municipal government has implemented a series of control strategies including stepwise, long-term, region-wide and emergency measures to achieve better air quality for the 2010 Expo. Since 2000, three rounds of Three-Year Environmental Action Plan have been taken to build a resource-efficient and environmentally friend city in Shanghai on the occasion of hosting the 2010 Expo. The growth of total energy consumption for the industrial, transport and building sectors was controlled and the energy efficiency has been improved a lot. Use of natural gas, installation of wind power facilities and imported electricity from neighboring provinces (e.g., Anhui province, and electricity generated by the Three Gorges Hydro Power Station) resulted in less coal combustion (UNEP, 2009). From 2007 to 2010, Shanghai closed 29 dirty and inefficient coal-burning units in 7 plants with a total capacity of 2,108 MW, which prevented 80,000 tons of SO_2 emission to be released into the atmosphere annually. Also, the Flue-Gas

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Desulphurization (FGD) technology aiming at cutting SO_2 emission from coal-fired power plants has been applied since 2005. By 2009, Shanghai installed FGD devices for coal-fired stations with more than 10GW capacities and 11 power plants were desulphurized, which summed a total capacity of 10,674 MW (UNEP, 2009). Regional joint control measures in YRD were enacted near the end of 2008 to minimize the effect of regional transport of air pollution. Shanghai, Zhejiang and Jiangsu provinces agreed to raise the environmental threshold for industry start-ups, standardizing emission standards, and strengthening region scale air pollution control and so on (SEPB, 2009). The specific measures included desulphurizing all coal-fire plants by 2010, using stricter emission standards for cars, prohibiting biomass burning in agricultural fields and etc.

Air quality improvement during the 2008 Beijing Olympics have been reported in many studies (Wang and Xie, 2009; Wang *et al*., 2009), however, the contribution of emission control or meteorological conditions to the improvement remains controversial (Zhang *et al*., 2009; Wang *et al*., 2010b; Wang *et al*., 2011). During the 2008 Beijing Olympic Games, strict air pollution control measures were enforced such as closing construction facilities, restricting high-emission private and government vehicles, and the even-odd day driving rules for Beijing's 3.3 million private cars (Wang *et al*., 2010a). Emissions from both local Beijing and its neighboring provinces were considerably reduced, which was the so called "great shutdown". However, the same control policy was impossible to be directly applied for the Expo. The duration of Expo was 184 days, lasting much longer than the Olympics. Long-term temporary shutdown of industrial activities and other human activities was not realistic as economy growth was always the priority for the local government. Also, the joint control of the regional transport in YRD may be not as efficient as the Olympics. Finally, the Expo expected much more visitors than the Olympics, and it was harder to control the numbers of visitors to the Expo. Thus, more challenges were expected to achieve clean air during the Shanghai Expo. However, compared to Beijing, Shanghai possesses more advantages in its topography and meteorological conditions. It is close to the East China Sea, surrounded by Yangtze River estuary, East China Sea, and Hangzhou Bay. With the flat topography and the marine monsoon subtropical climate, the air quality in Shanghai is generally better than some inland urban cities. For instance, the particle and gas concentrations were lower in Shanghai compared to Beijing though the emissions of black carbon and NO_x were 2–3 times higher (Chan and Yao, 2008). The Yangtze River Delta is located in a typical Eastern Asian monsoon region, with warm and humid conditions in summer while cold and dry weather in winter. Significant relationship between urban air quality and monsoon and ENSO was indicated (Kim *et al*., 2013). And the La Niña events could significantly affect the Meiyu rainfall over the YRD region (Wang *et al*., 2012). Extreme synoptic events such as tropical cyclone can even cause pollution with an expansion of PBL (Yang *et al*., 2012). In June of 2010, South China experienced persistent heavy rain while regions above the Yangtze River experienced less precipitation compared to the long-term mean values of 1981–2010, which were investigated to be related to anomalous monsoonal circulation (Yuan *et al*., 2012). The complex monsoon and synoptic weather may play an important role in air pollution transport and formation in the Yangtze River Delta region.

Air pollutant (e.g., NO_2, AOT (Aerosol Optical Thickness) and CO) reductions during the Expo period were observed from the view of space compared to the past three years, indicating the short-term emission control measures were effective (Hao *et al*., 2011). A long-term sun photometer measurement found out low levels of AOD (Aerosol Optical Depth) during the Expo (Jia *et al*., 2012). In this study, we presented air quality assessment during the Shanghai Expo period at nine cities in the Yangtze River Delta. Regional distribution and monthly variation of major air pollutants in YRD were analyzed. The major factors affecting the air quality of Shanghai during the Expo were determined. Regional transport and the effect of meteorological conditions on the air quality were finally discussed.

METHODS

During the 2010 Shanghai Expo, a joint air quality monitoring network of key cities in YRD was established, which included Nanjing, Suzhou, Nantong, and Lianyungang in Jiangsu province, Hangzhou, Ningbo, Jiaxing and Zhoushan in Zhejiang province, and the Shanghai metropolitan. Of the nine cities, Zhoushan is located on the island over the East China Sea and is regarded as the background site. Each city had several automatic monitoring stations, and totally 53 monitoring stations were included in this network. Locations of each station are plotted in Fig. 1, and the detailed information is summarized in Table 1. In China, SO_2, NO_2, and PM_{10} are required to be measured at all monitoring stations. SO_2 was measured by using API 200 (Teledyne Instruments, Advanced Pollution Instrumentation, Inc., US) or TE 43C (Thermo Electron Corporation Environmental Instruments Division, US). NO_2 was measured by using API 300 or TE 42C. O_3 and CO was measured by the Thermo Scientific 49i O_3 analyzer and 48i CO analyzer, respectively. PM_{10} and $PM_{2.5}$ was measured by TOEM 1400A 1400A and TOEM 1405D (Thermo Scientific, Inc., US), respectively. The PM instrument was operated at a temperature of 50°C to avoid the interference of moisture on the calculation of aerosol concentrations. The measurement of $PM_{2.5}$, O_3, and CO only operated at some specific monitoring stations and is noted in Table 1. All the pollutants were monitored with a time resolution of 10 seconds, and average concentrations at intervals of 1 hr were used in this study. The routine QA/QC included the daily zero/standard calibration, span and range check, station environmental control, staff certification, etc., were based on the guidelines established by (USEPA, 1998).

RESULTS AND DISCUSSION

Regional Distribution of Gaseous Pollutants and Aerosol in YRD

Fig. 2 plots the spatial distribution of gaseous and aerosol concentrations at 9 cities in YRD during the Expo. Generally, the regional distributions of pollutants over YRD were spatially heterogeneous. The mean SO_2 concentration ($\mu g/m^3$) at all sites (Fig. 2(a)) during the Expo followed the sequence of NJ (32.3 ± 3.3) > JX (32.1 ± 6.2) > LYG (29.0 ± 4.9) > SZ (27.3 ± 3.0) > NT (25.5 ± 4.3) > HZ (23.9 ± 4.7) ≈ NB (23.5 ± 5.5) > SH (21.4 ± 4.3) > ZS (12.3 ± 4.3). Fig. S1 shows the distributed power plants over YRD with their annual energy intensities. Generally, areas with more power plants showed higher SO_2 concentrations, e.g., southern Jiangsu and northern Zhejiang, where NJ, JX, and SZ showed higher SO_2 concentrations. Two cities (HZ and NB) in Zhejiang province presented relatively low SO_2 concentrations, partly due to the less high intensity power plants in Zhejiang and partly due to their locations close to the sea. The concentration of SO_2 in Shanghai surprisingly ranked the second lowest during the Expo and was only higher than that of Zhoushan (ZS), which is a background site offshore the coast, while SO_2 in Shanghai still ranked the highest among 16 cities in YRD in 2004 (Fig. 18 in Li *et al.* (2011)). Additional measures on the abatement of power plants emission and industrial emission during the Expo had been implemented. For instance, SO_2 emission from power plants was enforced to reduce 30.5%, 20.3%, 14.6%, 16.2%, and 5.85% on April 29, May 19, August 4, October

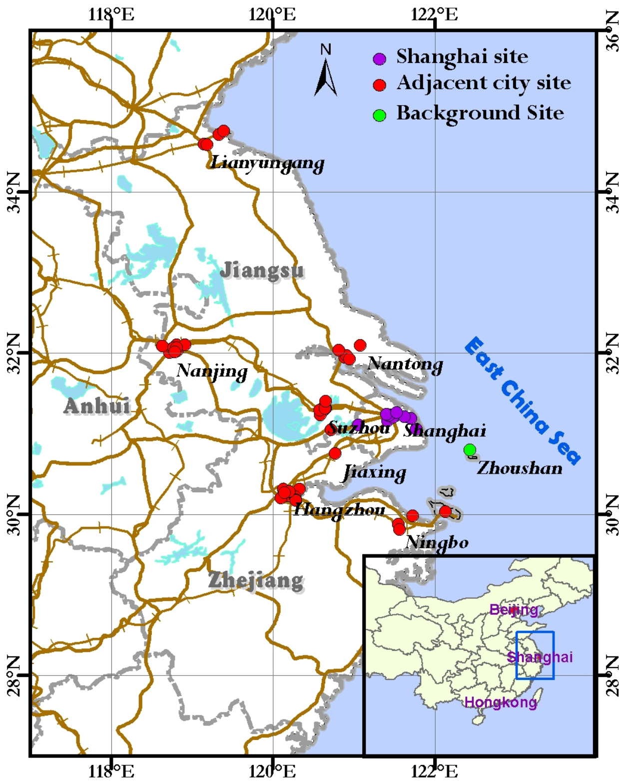

Fig. 1. The map of monitoring sites during the 2010 Shanghai Expo, including 11 sites in Shanghai, 41 sites in the adjacent cities, and 1 background site over the East China Sea. The lower right corner of the figure shows the area of the Yangtze River Delta region in China.

Table 1. Summary of the 9 monitoring city sites in the Yangtze River Delta region.

City[a]	Area[b] (km^2)	Pop[b] (10^5)	No.[c]	Latitude (°N)	Longitude (°E)	Air Pollutants Measured
Lianyungang (LYG)	1156	8.87	4	34.66	119.26	SO_2, NO_2, PM_{10}
Jiaxing (JX)	968	8.31	1	30.76	120.77	SO_2, NO_2, PM_{10}
Nanjing (NJ)	4723	54.60	9	32.06	118.78	SO_2, NO_2, PM_{10}, $PM_{2.5}$, CO, O_3
Nantong (NT)	1521	21.15	5	32.00	120.92	SO_2, NO_2, PM_{10}, CO, O_3
Suzhou (SZ)	1650	24.02	8	31.28	120.63	SO_2, NO_2, PM_{10}, $PM_{2.5}$, CO, O_3
Zhoushan (ZS)	1028	7.00	2	30.42	122.28	SO_2, NO_2, PM_{10}, CO, O_3
Ningbo (NB)	2462	22.18	3	29.89	121.61	SO_2, NO_2, PM_{10}, $PM_{2.5}$, CO, O_3
Hangzhou (HZ)	3068	42.94	10	30.24	120.21	SO_2, NO_2, PM_{10}, $PM_{2.5}$, CO, O_3
Shanghai (SH)	5155	133.17	11	31.20	121.48	SO_2, NO_2, PM_{10}, $PM_{2.5}$, CO, O_3

[a] Abbreviation of the city name are in parentheses
[b] Both Area and population refer to statistic of municipal district from China City Statistical Yearbook (2010)
[c] Numbers of the monitoring stations in one city

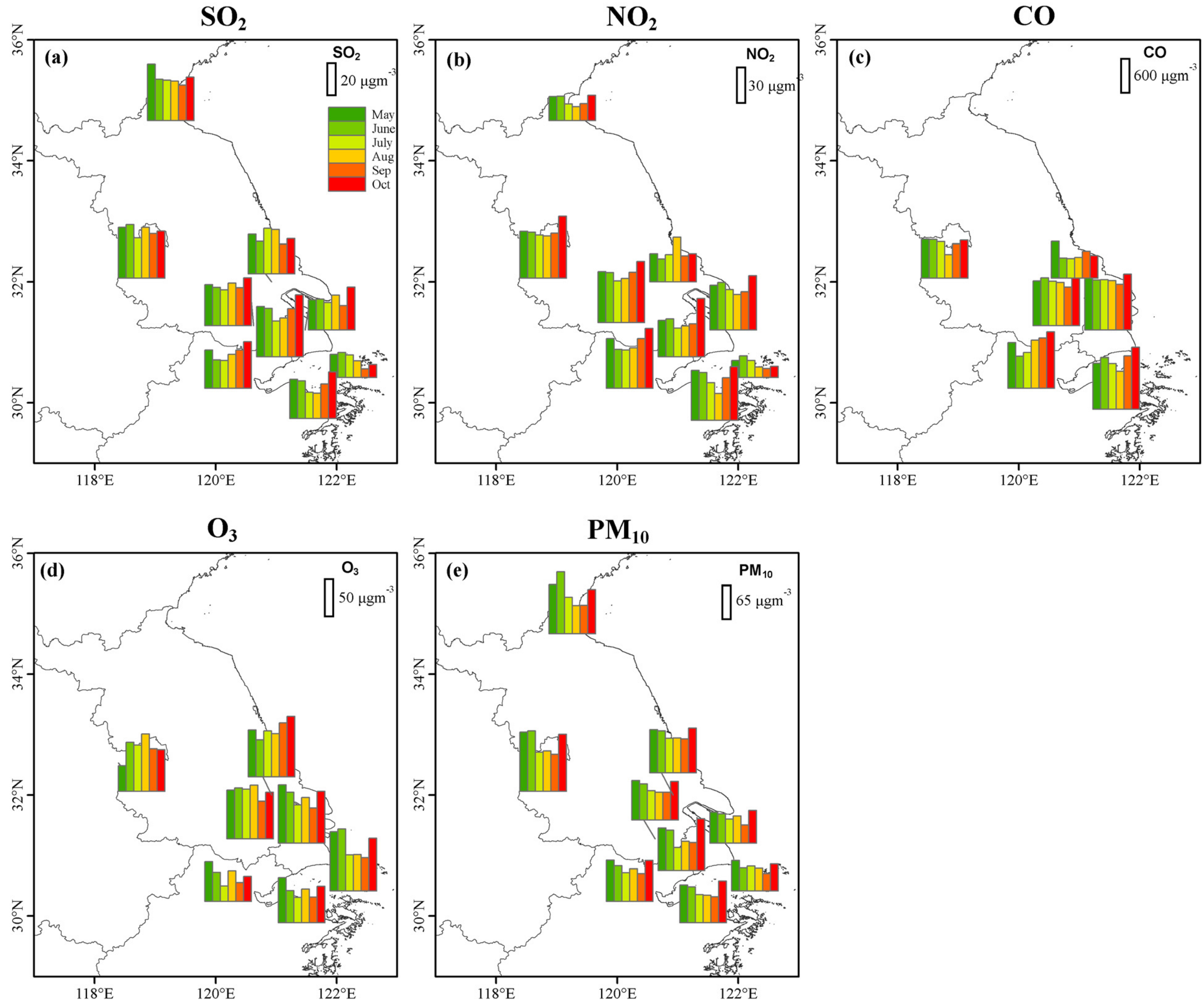

Fig. 2. The regional distribution and monthly variation of SO_2, NO_2, CO, O_3 and PM_{10} concentrations at each city over the Yangtze River Delta during the Expo.

17, and October 29, respectively due to the heavy pollution (SEMC, 2011). Hence, these additional control measures partly explained the relatively low SO_2 concentration in Shanghai

The regional distribution patterns of NO_2 and CO (Fig. 2(b) and Fig. 2(c)) differed a lot from that of SO_2. The mean NO_2 concentration (μg/m^3) at all sites during the Expo followed the sequence of SZ (46.4 ± 6.3) > NJ (44.3 ± 6.9) > HZ (43.0 ± 8.0) > SH (40.5 ± 6.4) > NB (40.2 ± 9.2) > JX (35.3 ± 10.0) > NT (27.6 ± 7.1) > LYG (19.0 ± 4.7) > ZS (13.5 ± 4.5). For CO, it followed the sequence of SH (1005.6 ± 73.8) > NB (983.7 ± 160.0) > HZ (881.8 ± 181.9) > SZ (878.5 ± 69.0) > NJ (692.3 ± 116.6) > NT (483.5 ± 131.6). Bigger cities with more vehicle stocks, such as Shanghai, Hangzhou, Suzhou, Ningbo, and Nanjing, evidently showed higher NO_2 and CO concentrations. The five cities above contained the largest vehicle stocks in YRD, with shares of 26%, 12%, 11%, 8%, and 8%, respectively (Li *et al*., 2011). Lower concentrations of NO_2 and CO were observed in some smaller and less developed cities such as Lianyungang, Nantong and Zhoushan with smaller vehicle stocks. In addition, more than 73 million visitors visited Expo, which would surely increase the demand for the transport infrastructures in and around Shanghai than the normal times (UNEP, 2009). Also, most visitors tended to visit some famous resorts in Suzhou and Hangzhou before or after they visited the Expo in Shanghai, which was the so-called "Expo chain effect". This explains the relatively high concentrations of NO_2 and CO in Suzhou and Hangzhou.

The mean O_3 concentration (μg/m^3) at all sites (Fig. 2(d)) during the Expo followed the sequence of SZ (71.3 ± 8.3) ≈ NT (71.0 ± 12.4) ≈ SH (69.4 ± 13.1) ≈ ZS (69.1 ± 19.2) > NJ (65.1 ± 15.5) > NB (49.2 ± 10.9) > HZ (39.3 ± 12.9). Obviously, a relatively high O_3 zone was formed along the coast areas of Eastern China. And the similar concentrations between the costal sites (i.e., ZS and NT) and the urban cities suggested the intrusion of pollutants from the urban areas to the suburban and rural areas. The low O_3 concentrations in NB and HZ should be due to the chemical titration by NO_x as was commonly observed in the VOC limited regime of YRD (Geng *et al*., 2009).

The mean PM_{10} concentration (μg/m^3) at all sites (Fig. 2(e)) during the Expo followed the sequence of NJ (103.8 ± 23.7) > LYG (88.5 ± 27.7) > NT (82.1 ± 10.6) > JX (75.8 ± 23.0) > HZ (73.5 ± 12.3) > SZ (70.0 ± 11.8) > NB (69.8 ± 13.9) > SH (57.8 ± 11.1) > ZS (51.3 ± 9.3). Cities in Jiangsu province evidently had the highest concentrations. As stated above, gaseous pollutants emitted from power plants and vehicles both showed higher concentrations in Jiangsu province, thus resulting in higher aerosol concentrations. As similar as SO_2, PM_{10} in Shanghai also ranked the second lowest among all the cities and only higher than Zhoushan. It is interesting to note that Shanghai had become a low PM_{10} core surrounded by cities with higher PM_{10} concentrations. While before 2010, Shanghai was still a high pollution center in YRD (Li *et al*., 2011). The municipality had implemented various measures to reduce construction and roadside dust pollution, which was an important source of PM_{10} composition (Shu *et al*., 2001; Wang *et al*., 2006). These control measures included requirements on the covering or containment of idle soil, cement, and construction waste. Additionally, a large number of construction sites were temporally shut down during the Expo to avoid the suspended dust (SEMC, 2011). Despite the great achievement of emission control on PM_{10}, the concentration of fine particles, i.e., $PM_{2.5}$, was still the biggest problem in Shanghai and other cities in YRD. The mean ratio of $PM_{2.5}$ in PM_{10} reached 0.70 in Shanghai, indicating the dominant contribution of fine particles in particles. The average $PM_{2.5}$ concentrations at Nanjing, Ningbo, Hangzhou, Suzhou and Shanghai were 71, 44, 58, 48, and 40 μg/m^3, respectively. Although Shanghai presented the lowest $PM_{2.5}$ level among the five cities above, its $PM_{2.5}$ level was still almost triple of the U.S. National Ambient Air Quality Standard (NAAQS) annual average of 15 μg/m^3. Additionally, almost 50% of the Expo days exceeded the daily $PM_{2.5}$ standard of 35 μg/m^3 set by U.S. EPA.

Monthly Variation of Gaseous Pollutants and Aerosol in YRD

Fig. 2 also illustrates the monthly variations of the air pollutants at each city. Generally, concentrations of air pollutants followed a curve pattern with lower concentrations in the mid-term of the Expo, i.e., July, August and September, while with higher concentrations at the beginning and the end of the Expo, i.e., May, June and October at all cities except Shanghai. For SO_2, its concentration in Shanghai remained steady at around 19–20 μg/m^3 from May to July, while SO_2 in the other cities generally showed higher concentrations in May and/or June. The inconsistent monthly variations between Shanghai and the other cities suggested that some special control measures were implemented to lower the SO_2 emission in Shanghai during the early periods of the Expo. In May, to ensure the relatively good air quality, SO_2 emission from power plants in Shanghai was enforced to reduce as discussed above, thus resulting in the relatively low SO_2 concentration in May. In August, we noticed that SO_2 increased about 3–5 μg/m^3 compared to the previous months, which was investigated to be the problems with power plants (CAI-Asia, 2010). At Zhoushan, it was found that the monthly average SO_2 concentration was about 80% of that in Shanghai during May to June, while this ratio decreased to about 30–50% in the last four months. The relatively close concentration between Shanghai and Zhoushan during the first two months probably indicated the regional transport from inland to the sea coast. As shown in Fig. 3 that will be discussed below, the non-negligible winds from the west and northwest in May and June tended to transport the inland pollutants eastward and Zhoushan was probably influenced by the inland outflow. While in the next several months, Zhoushan was more impacted by the ocean breezes, and that's why there was great divergence between the background site and the other urban sites.

As for NO_2, it showed similar monthly variation as SO_2. Its highest monthly concentration occurred during October at all the large cities (Fig. 2(b)), when Expo visitor number reached the highest in this month with expected enhanced anthropogenic activities. Compared to the variation magnitude of monthly NO_2 concentration, CO didn't vary so distinctly (Fig. 2(c)). For instance, during July and August when NO_2 were relatively low, CO was still high and comparable to the first two months. As the Expo period just covered the harvest season of Eastern China from late spring to summer, biomass burning probably accounted for part of the CO emission (Li *et al*., 2010; Huang *et al*., 2012). Fig. S2 shows the monthly accumulated carbon emission from biomass burning over Eastern China derived from the FLAMBE (Fire Locating and Monitoring of Burning Emissions) emission inventory (Reid *et al*., 2009). It could be seen that the most intense biomass burning periods during the Expo occurred from May to August while almost negligible during the last two months. During May, most intense fires occurred in the northern Zhejiang province, resulting in the relatively high CO in Hangzhou and Suzhou (Fig. 2(c)). In June, although intense biomass burning existed in the upper domain, the cities evaluated in this study were probably less influenced due to the prevailing southeast winds (Fig. 3). For instance, Nantong and Hangzhou both showed the lowest CO concentrations in June (Fig. 2(c)). One exception was for Ningbo where CO was elevated. It was noticed that intense local fires occurred around the Ningbo area, thus explaining its high CO concentrations there. In July and August, biomass burning was the most intense during the Expo and mainly distributed in the northern Zhejiang province. Facilitated by the south and southeast winds (Fig. 3), Shanghai should be greatly influenced by the biomass burning plumes and thus its CO concentration stayed as high as compared to the previous two months. Some other inland cities such as Hangzhou, Suzhou, and Lianyungang were also influenced to different extent while Nanjing was probably not influenced much as its CO level was the lowest in August. Although Ningbo was located in the intense fire area, its CO level was relatively low, which was probably due to the clean effect of sea breezes. During September and October, the impact of biomass burning on the air quality of YRD could be almost neglected as shown in Figs. S2(e)–2(f). Thus, the relatively high CO concentration during the last two months of the Expo should be due to the enhanced anthropogenic emission, and also the unfavorable meteorological conditions.

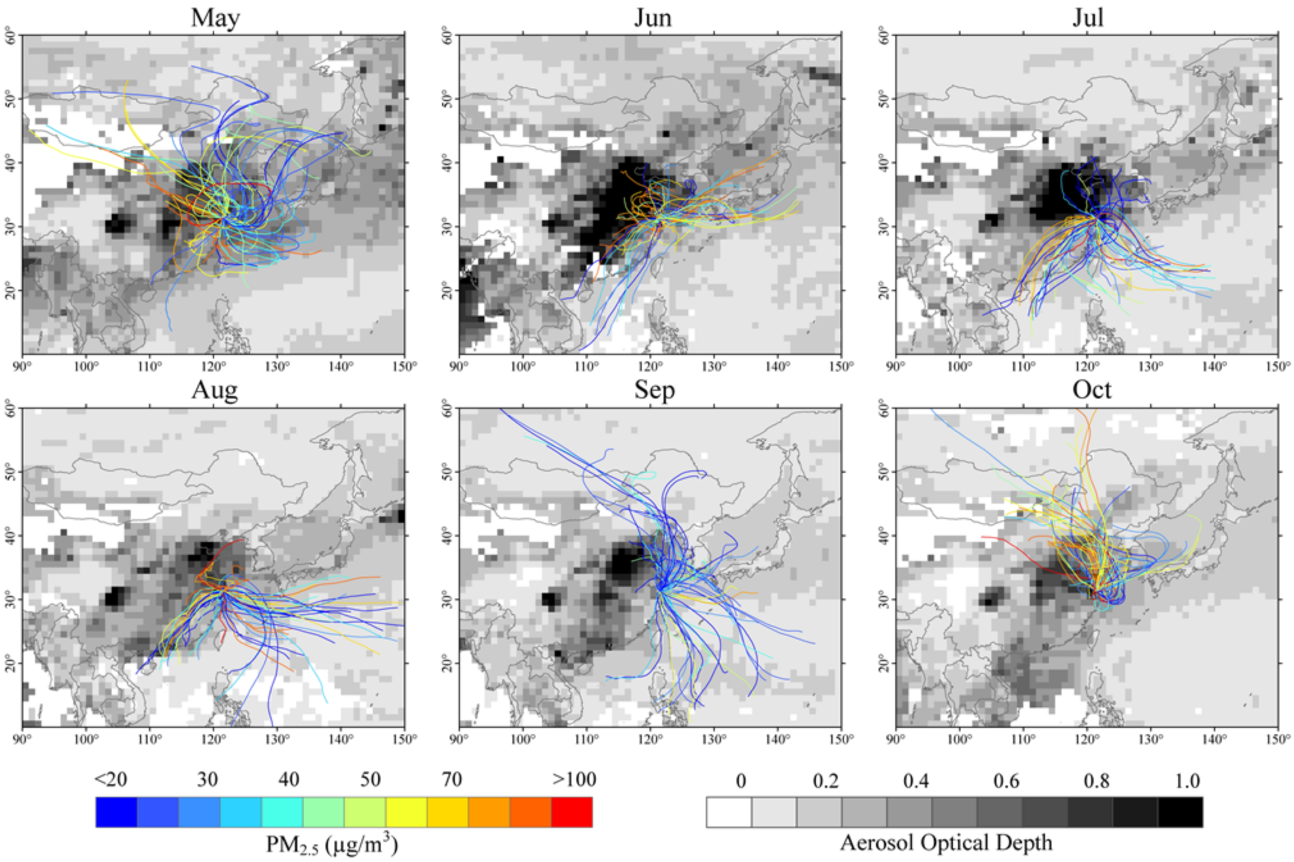

Fig. 3. The monthly clusters of three-days back trajectories ending at Shanghai. Back trajectories were computed at 8:00 and 20:00 LST (Local Standard Time) each day by using the NOAA HYSPLIT model. Individual trajectory is color-coded with its corresponding $PM_{2.5}$ concentration of Shanghai at the same time. The monthly aerosol optical depth (AOD) at the wavelength of 550nm with 1° × 1° resolution derived from MODIS are overlaid with the trajectories.

As for O_3, its monthly variation showed different behaviors at various cities (Fig. 2(d)). The competition between local NO_x and VOCs emission should be the major factor determining the magnitudes of O_3 concentrations. For Shanghai and Zhoushan, O_3 in May, June, and October were much higher with average concentrations around 78–90 μg/m^3 than the other three months. We believed that the high O_3 concentrations in these three months were probably due to the enhanced VOC emission from vehicle as Shanghai was a VOC limited region (Geng *et al*., 2009). Monthly PM_{10} presented similar variations with higher concentrations during May, June and October over YRD except in Shanghai. For instance, the average PM_{10} concentration at the other sites from July to September decreased about 30% compared to the previous two months. However, PM_{10} of Shanghai remained around 60 μg/m^3 during the first four months. This similar monthly pattern as SO_2 further corroborated that intense control measures had been implemented during the early periods of the Expo in Shanghai.

Major Factors Affecting the Air Quality during Expo

Meteorological conditions are important factors affecting the air pollution formation and atmospheric transport. Monthly mean temperature and dew point showed very consistent monthly profile with peak values in July and August and relatively lower values in the other months. As for the monthly wind speed, it didn't show distinct monthly variation with relatively constant values of 3.7–3.9 m/s while the lower wind speed was found in July with the value of 2.9 m/s. The time-series of mixing layer height computed from the NCEP Global Data Assimilation System (GDAS) model (http://ready.arl.noaa.gov/READYamet.php) is shown in Fig. S3. It was observed that the occurrence of precipitation events generally corresponded to lower mixing layer heights. For example, the Meiyu rainfall season from June 24 to July 16 was associated with the lowest mixing layer heights during the whole study period. Overall, the Expo was the most precipitate period during the whole year in Shanghai. During the Expo, the frequency of rainy days reached 36%. Thus, the daily and monthly mixing layer heights are considered to be greatly related to those events. Fig. S3 also shows the time-series of atmospheric stability which is expressed as the temperature difference of $\Delta T/\Delta z$ (unit: °C/100 m). Strong negative correlation was observed between these two parameters. The more negative atmospheric stability meant the more unstable atmosphere, hence induced stronger convection and higher mixing height. Generally, the atmosphere was more stable in the first three months of the Expo. Then the atmosphere became more unstable starting from August and reached the highest in October.

The total precipitation amount during the Expo was 709.2 mm, lower than the average level (823.3 mm) during the past ten years (2000–2009).

The correlations between hourly $PM_{2.5}$ and pollutant gases and meteorological parameters in Shanghai were investigated to understand the relative importance of chemical processes and meteorology on the aerosol formation. Table 2 shows the Pearson's correlation coefficients between $PM_{2.5}$ and various parameters. The gaseous pollutants, i.e., SO_2, NO_2, and CO exhibited the most significant correlations with $PM_{2.5}$. Among them, NO_2 and CO had more significant relationship with $PM_{2.5}$ than SO_2. In Shanghai, mobile sources constituted a major part of NO_x and CO emission while stationary emissions (e.g., power plants, fugitive emission from industry) constituted the majority of SO_2 emission (Li *et al*., 2011). The correlation analysis above indicated that the mobile emission contributed more to aerosol formation than the stationary source. Regarding the temporal variation of correlation coefficients from May to October, the correlation between pollutant precursors and particles generally showed higher correlations in May, June and October, while lower from July to September. As will be discussed in the Section "Source identification from seasonal back trajectories", July to September were the months when meteorological conditions were most favorable for the dispersion of particles, thus the aerosol precursors played a less important role. It was noted that $PM_{2.5}$ had a moderate correlation with O_3 in addition to its significant correlations with the other gases in July and August with correlation coefficients around 0.4–0.5. July and August were the hottest months during the whole year. Intense solar radiation caused strong photochemistry in the atmosphere, which could be one possible reason for the moderate correlation between O_3 and $PM_{2.5}$ via the homogeneously photochemical processing. In addition, July and August were the most active biomass burning periods around the Shanghai area as shown in Fig. S2. Facilitated by the south winds (Fig. 3), Shanghai was impacted by the biomass combustion during this period. Thus, we believed that the moderate correlation between O_3 and $PM_{2.5}$ could also be partly due to biomass burning, as biomass burning were important sources for particles and trace gases such as O_3, CO, CO_2 and etc (Andreae and Merlet, 2001). During the other months, very weak or almost no correlations were observed between O_3 and $PM_{2.5}$, indicating that secondary photochemical formation didn't act in a major role.

In terms of the relation between various meteorological parameters and $PM_{2.5}$, wind speed showed the most significant correlations with $PM_{2.5}$. They were negatively correlated with moderate correlation coefficients around 0.3–0.4 during the whole Expo period. The average wind speed during the Expo reached relatively high value of 3.7 m/s and was beneficial for the dispersion of air pollutants. In regard of the correlation between $PM_{2.5}$ and wind direction, we separated the wind into its X and Y vectors and correlated them with $PM_{2.5}$, respectively. As shown in Table 2, the winds from the X vector were moderately negatively correlated with $PM_{2.5}$ while those from the Y vector almost had no correlations with $PM_{2.5}$. This indicated that winds from east (positive value from the X vector) were beneficial for lowering the aerosol concentration while winds from the west (negative value from the X vector) had negative effects, which corroborated with the discussion in Section "Source identification from seasonal back trajectories". As for temperature and dew point, their correlations with $PM_{2.5}$ varied among different months. From May to August, temperature and dew point both had moderately positive correlations with $PM_{2.5}$, indicating higher temperature had positive effects on aerosol formation. However, in the last two months there were no such positive correlations, while instead slightly negative correlations were found as shown in Table 2. Mixing layer height was also moderately negatively correlated with $PM_{2.5}$ during all months with higher correlations observed in the summer. Higher temperature increased the atmospheric convection and elevated the mixing layer height, thus would be more favorable for the dispersion of air pollutants. As for relative humidity (RH), we didn't find strong correlation between it and $PM_{2.5}$. The average RH during the whole Expo reached a considerably high value of 78.9% with a standard

Table 2. The correlation coefficients between hourly $PM_{2.5}$ concentration and pollutant gaseous (i.e., SO_2, NO_2, CO and O_3) and various meteorological parameters on a monthly basis during the Expo period in Shanghai.

$PM_{2.5}$	SO_2	NO_2	CO	O_3	WS[a]	X-vector[b]	Y-vector[b]	TEMP[c]	DEWP[d]	MLH[e]	RH[f]
May	0.60**	0.75**	0.76**	−0.06	−0.29**	−0.33**	0.12**	0.33**	0.26**	−0.15*	−0.14
Jun	0.54**	0.72**	0.75**	−0.05	−0.37**	−0.35**	−0.16**	0.38**	0.31**	−0.26**	−0.08*
Jul	0.60**	0.71**	0.68**	0.40**	−0.40**	−0.42**	0.12**	0.22**	0.32**	−0.29**	−0.25**
Aug	0.49**	0.60**	0.69**	0.48**	−0.39**	−0.35**	0.11**	0.22**	0.27**	−0.37**	−0.20**
Sep	0.50**	0.65**	0.70**	0.06	−0.34**	−0.30**	0.11**	−0.16**	−0.07	−0.33**	0.16**
Oct	0.63**	0.72**	0.83**	−0.09*	−0.37**	−0.25**	−0.24**	−0.06	−0.12**	−0.25**	−0.12

**Correlation is significant at the 0.01 level (2-tailed).
*Correlation is significant at the 0.05 level (2-tailed).
[a] Wind speed.
[b] The wind speeds along the X and Y vectors, respectively.
[c] Temperature.
[d] Dew Point.
[e] Mixing Layer Height (source: NCEP Global Data Assimilation System (GDAS) model).
[f] Rleatively Humidity.

deviation of 12.8%. The ratio of standard deviation vs. average RH was relatively low of 0.16, indicating the temporal variation of RH was not intense. Thus, we couldn't find strong correlation between RH and $PM_{2.5}$ as RH stayed within a narrow range.

Source Identification from Seasonal Back Trajectories

In order to explicitly explore the effect of regional and/or long-range transport on the air quality during the Expo, air mass back trajectories computed by the NOAA's HYSPLIT model (Draxler and Rolph, 2003) were analyzed. Fig. 3 shows the monthly clusters of three-days back trajectories ending at Shanghai. Back trajectories were computed at 8:00 and 20:00 LST (Local Standard Time) each day, and individual air trajectories were color-coded with the corresponding $PM_{2.5}$ concentration of Shanghai at the same time. Additionally, the monthly aerosol optical depth (AOD) at the wavelength of 550nm with 1° × 1° resolution over East Asia was derived from MODIS (Moderate-resolution Imaging Spectroradiometer). Generally, Fig. 3 shows that most of the high pollution episodes were related to air masses originating from inland with heavy pollution, whereas reduced levels of aerosol were observed for trajectories coming from the ocean and less polluted continental regions. Table 3 calculates the average $PM_{2.5}$ concentration in Shanghai from eight different directions. Back trajectories from west and southwest evidently had much higher $PM_{2.5}$ concentrations than from the other directions. Distinct monthly characteristics of the regional/long-rang transport patterns were observed. During May, almost half of the back trajectories that reached Shanghai originated from inland China. Eastern and Central China with higher AOD evidently exerted adverse effects on the air quality of Shanghai. During June, winds started to shift from the ocean with average $PM_{2.5}$ around 35 μg/m^3. However, winds from the East China Sea were still characterized of relatively high particle concentration occasionally (Fig. 3). As shown in Fig. S4, the marine vessel activities derived from the EDGAR (Emissions Database for Global Atmospheric Research) global emission inventory were very busy over the Eastern China Sea. Thus, the marine vessel emission was probably partly responsible for the relatively high aerosol concentration from the ocean in summer. It was noted that most pollution events still originated from inland with relatively short trajectories, which were the typical synoptic stagnant environment for the formation of haze. From the spatial distribution of aerosol optical depth (AOD), June was the most polluted month with large areas of high AOD hot spots extending from the North China Plain to the Southern China. Thus, the regional transport could be an important cause for the high $PM_{2.5}$ concentrations in Shanghai during June.

The transport patterns were similar between July and August to some extent. Back trajectories dominantly came from the southeast to southwest (Fig. 3), while seldom from Northern or Eastern China. $PM_{2.5}$ from southeast was around 30 μg/m^3 and even less, while air masses from south, southwest and west were 15–20 μg/m^3 higher (Table 3). Different from previous months, September had considerable amounts of winds from northeast, north, southeast and south. Table 3 shows that winds from the north to southwest were accompanied with $PM_{2.5}$ lower than 30 μg/m^3, while much higher from the west and northwest. During October, $PM_{2.5}$ concentrations at Shanghai were the highest as discussed in Section "Monthly variation of gaseous pollutants and aerosol in YRD". Back trajectories dominantly originated from the northwest, north and northeast (Fig. 3). As shown in Table 3, air masses were associated with high aerosol concentrations except from northeast and southeast. Local enhanced emission during this period was the main reason for the elevated particle concentrations. Also, heavy pollution in northern China obviously contributed to the bad air quality over Shanghai via long-range transport. Overall, heavy air pollution episodes of Shanghai were usually related to the regional/long-range transport from inland polluted regions such as Central, Eastern China and North China Plain. However, as a considerable amount of back trajectories traveled over the ocean during the Expo period, the overall air quality was still good. Favorable meteorological conditions should be a significant driving force for the relatively good air quality during the Expo.

Effect of Regional Transport on the Distribution of Air Pollutants

To further explore the potential regional transport among the cities in YRD, we analyzed the linear relationship of air pollutants between Shanghai and the other cities during the six months, respectively (Fig. 4). It was found that air pollutants of Shanghai were most correlated with those of Suzhou, Ningbo, Nantong, and Jiaxing (see locations in Fig. 1). The correlation coefficients ranged from 0.5 to 0.8. The moderate relationship between Shanghai and those

Table 3. Monthly $PM_{2.5}$ concentrations (with one standard deviation, unit: μg/m^3) in Shanghai from eight directions based on the cluster analysis of backward trajectories.

Direction	May	Jun.	Jul.	Aug.	Sep.	Oct.
N	41.9 ± 14.9	56.2 ± 32.0	28.8 ± 27.7	30.8 ± 22.2	24.2 ± 15.7	47.1 ± 30.8
NE	35.2 ± 16.4	51.6 ± 29.0	27.4 ± 22.6	37.0 ± 20.5	19.7 ± 11.1	36.7 ± 29.0
E	32.6 ± 19.0	34.9 ± 24.6	25.0 ± 17.7	25.3 ± 25.0	27.2 ± 11.7	51.6 ± 27.0
SE	34.8 ± 20.8	36.8 ± 30.5	22.4 ± 22.1	31.8 ± 28.8	19.7 ± 12.5	38.3 ± 21.7
S	40.3 ± 14.8	68.6 ± 32.2	46.9 ± 27.0	45.2 ± 32.3	19.0 ± 14.0	53.9 ± 23.4
SW	65.5 ± 32.1	69.2 ± 40.3	53.9 ± 28.9	55.7 ± 22.9	16.5 ± 9.6	47.6 ± 15.1
W	63.3 ± 29.4	56.3 ± 26.0	49.1 ± 33.9	54.6 ± 24.8	39.4 ± 14.3	67.8 ± 25.9
NW	37.2 ± 18.4	52.3 ± 31.5	44.2 ± 40.2	56.1 ± 23.4	39.5 ± 16.9	58.4 ± 27.1

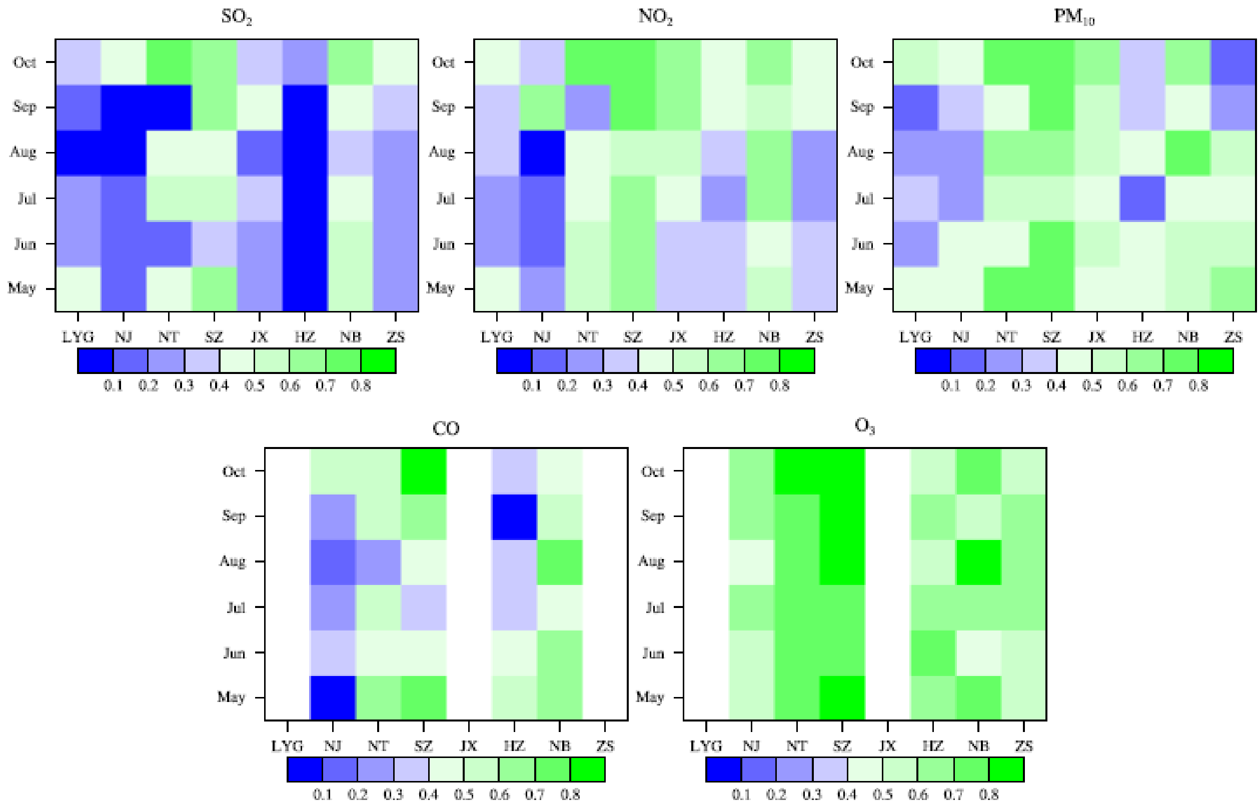

Fig. 4. The spatial correlations of hourly SO_2, NO_2, CO, O_3, and PM_{10} concentrations between Shanghai and the other eight sites in YRD. Correlation coefficients of the linear regressions between Shanghai and each site are calculated for every month of the month. Refer Table 2 to the abbreviations of city names.

cities (i.e., Suzhou, Ningbo, Nantong, and Jiaxing) indicated the regional transport was more prominent among them than the other cities since these cities were geographically close to Shanghai. However, the exception was found for Hangzhou, which showed weak or almost no correlations with Shanghai at most times although these two cities are closely located. The topography of Hangzhou was subject to be isolated from regional atmospheric circulation as Hangzhou is a mountainous city with most areas located in the valley. The other cities such as Nanjing and Lianyungang, are located to the northern and western part of Jiangsu province. Weak correlations between them and Shanghai were found with correlation coefficients generally less than 0.5, indicating that these cities exerted less impact on Shanghai.

Correlations of SO_2 between Shanghai and the other sites seemed to be the lowest. As SO_2 mainly derived from point sources (e.g., power plants and industrial boilers), the regional distribution of SO_2 was more dependent on the local source emission. For NO_2, CO and PM_{10}, their correlations between cities improved compared to SO_2. Vehicle emission accounted for a considerable amount of NO_2, CO concentrations and re-suspended particles. The more widespread transportation than the point emission was the major reason for the higher correlations of NO_2 and CO between cities. The most significant correlations were observed for O_3 between Shanghai and all the other cities, regardless of the distances. This pattern probably indicated that O_3 formation had become a regional problem for the whole YRD region. In regard of the monthly variation of the linear relationship, we found that correlations were usually higher during the high pollution periods, i.e., May, June, and October, which meant that regional transport contributed to relatively high pollution in both Shanghai and other urban sites. Less precipitation during these months may be also one of the reasons that facilitated the regional transport due to less wet scavenging. The anomalous monsoonal circulation has been investigated to account for the dry climate over the regions north of the Yangtze River in June 2010 (Yuan *et al.*, 2012). From July to September when pollution was relatively lighter, correlations were generally lower. Stronger correlation between meteorological conditions and air pollutants during these months as discussed in Table 2 was one cause for lowering the extent of regional transport. In addition, intense and uneven distribution of wet precipitation (Fig. S5) probably impacted the regional transport and lowered the correlations among cities.

The effect of meteorological conditions on the regional transport was quantitatively assessed in Fig. 5. In Shanghai, winds from the ocean (i.e., from north, northeast, east and southeast) dominated during the Expo and accounts for 73% of all the wind directions. The average PM_{10} concentration reached 53.0 $\mu g/m^3$, about 10 $\mu g/m^3$ lower than from inland. Also, the frequencies of low aerosol concentrations occurrences (designated as hourly PM_{10} concentration less than 30 $\mu g/m^3$) from the ocean were much higher than from

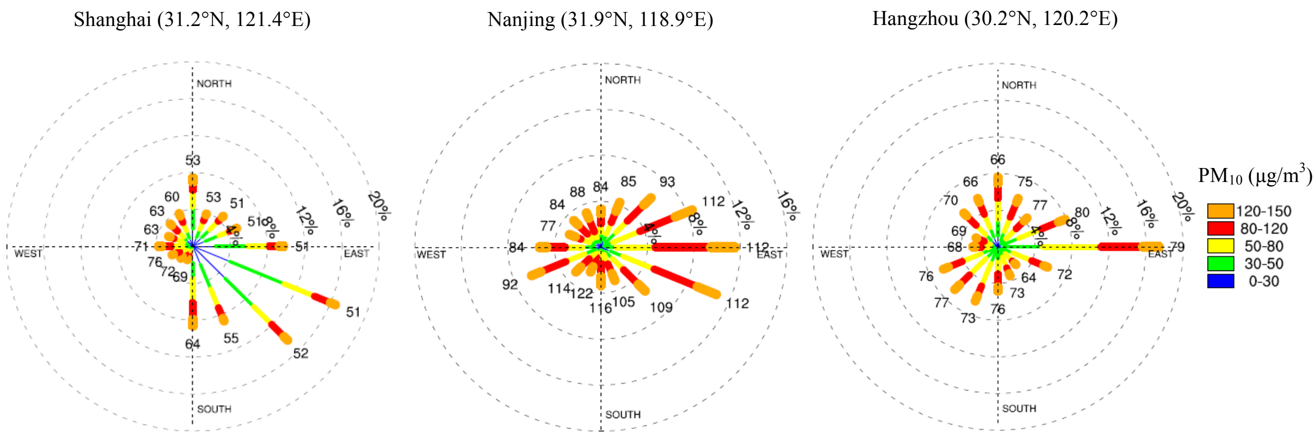

Fig. 5. The wind rose plot of hourly PM_{10} concentrations (μg/m^3) during the whole Expo period at three cities of Shanghai, Nanjing, and Ningbo, respectively. Each circle represents the percentage of the winds from a particular direction, and different colors represent the ranges of PM_{10} concentrations. The mean PM_{10} concentrations are plotted at the end of each directional line. The surface meteorological data is from the National Climatic Data Center (NCDC) supported by the NOAA Satellite and Information Service.

inland as shown in the figure. It can be concluded that the predominant winds from the ocean was one of the most important reasons for the good air quality during the Expo in Shanghai. During the summer monsoon, the air quality (e.g., higher visibility) was relatively better in costal cities such as Hong Kong (Kim *et al.*, 2013). A modeling sensitivity study evaluated the impact of Asian summer monsoon on surface $PM_{2.5}$ reduction could reach 50–70% (Zhang *et al.*, 2010). The wind rose pattern of PM_{10} in Nanjing was just opposite to Shanghai. A high frequency of 57% wind from the ocean was observed, however, higher PM_{10} concentration was also observed with average value of 110 μg/m^3. Compared to the other directions, PM_{10} with wind from the ocean were about 20–30 μg/m^3 higher. During the Expo, Nanjing was on the downstream pathway from regions more close to the sea via the prevailing winds from the ocean and thus could be regarded as a source receptor. A regional modeling study showed a significant cross-border transport of particle deposition between Shanghai and another 8 cities in YRD under certain meteorological conditions (Wang *et al.*, 2007). The comparison of wind rose patterns between Shanghai and Nanjing clearly demonstrated the meteorological conditions during the Expo had a positive effect on the air quality of costal cities while may exert a negative effect on some inland cities in YRD. Nanjing is now in preparation of the Youth Olympic Games in 2014, this finding highlighted the importance of regional transport on air quality improvement in YRD. Compared to Shanghai and Nanjing, wind directions of Hangzhou were more evenly distributed. And there was no distinct difference of the mean PM_{10} concentrations from each wind direction, which indicated less dependence of PM_{10} concentration on wind directions in Hangzhou. This finding corroborated the statement of the poor correlations of gases and aerosol between Hangzhou and Shanghai although they are closely located. To better evaluate the effect of meteorology, topography and regional transport on the air quality of Shanghai during the Expo, a chemical transport model is needed in the further study.

CONCLUSIONS

We investigated the air quality at 9 cities (total 53 ground stations) over the Yangtze River Delta (YRD) region during the six-month Shanghai World Expo in 2010. Regional distribution of air pollutants showed that Shanghai had become a low-SO_2-PM_{10} zone over YRD during the Expo, owing to the effective control measures such as the desulphurization and close of some dirty and inefficient power plants in the past few years, effective control of transportation emission and abatement of construction works during the Expo. However, Shanghai also became a high-NO_x-CO-O_3 zone in YRD, mainly attributed to the large vehicle stocks of Shanghai and the expected increase of transportation emission during the Expo. Monthly variations of all pollutants generally presented similar patterns with lower values in the middle of the Expo, i.e., from July to September, while presented higher values in May, June and October. Emission strengths and meteorological conditions were the major factors controlling the air quality in Shanghai. Correlation analysis found out that NO_2 and CO had higher correlations with $PM_{2.5}$ than SO_2, indicating that mobile sources (e.g., transportation emission) had played a more important role in aerosol formation than the stationary sources (e.g., coal combustion) in Shanghai. Wind speed, directional winds (X vector), mixing layer height were the most influential meteorological factors affecting the air quality. Cluster analysis of monthly back trajectories illustrated that most pollution episodes were related to the regional transport from the inland continent while relatively clean days were usually accompanied with trajectories from the ocean. Spatial correlations of air pollutants between Shanghai and the other eight cities revealed that nearer cities such as Suzhou, Ningbo, Nantong, and Jiaxing had more impact on Shanghai via the regional transport, and vice versa. The dominated marine winds during the Expo had a positive effect on the air quality of costal cities (e.g., Shanghai) while had negative effect on some inland cities (e.g., Nanjing) in YRD.

ACKNOWLEDGMENTS

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SUPPLEMENTARY MATERIALS

Supplementary data associated with this article can be found in the online version at http://www.aaqr.org.

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SUPPLEMENTARY MATERIALS

Air Quality over the Yangtze River Delta during the 2010 Shanghai Expo

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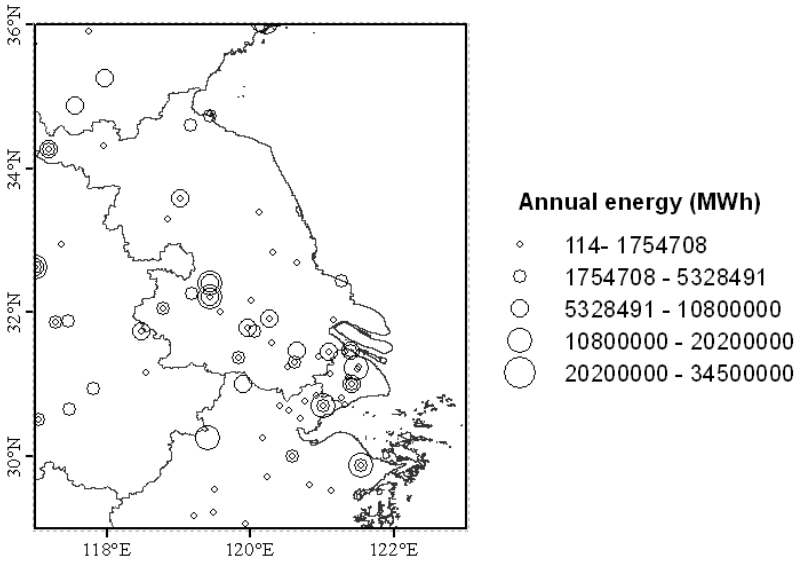

Fig. S1. The locations of coal-fired power plants with individual annual energy (indicated by the size of circle) over YRD (Data source: CARMA 2007: Carbon Monitoring for Action).

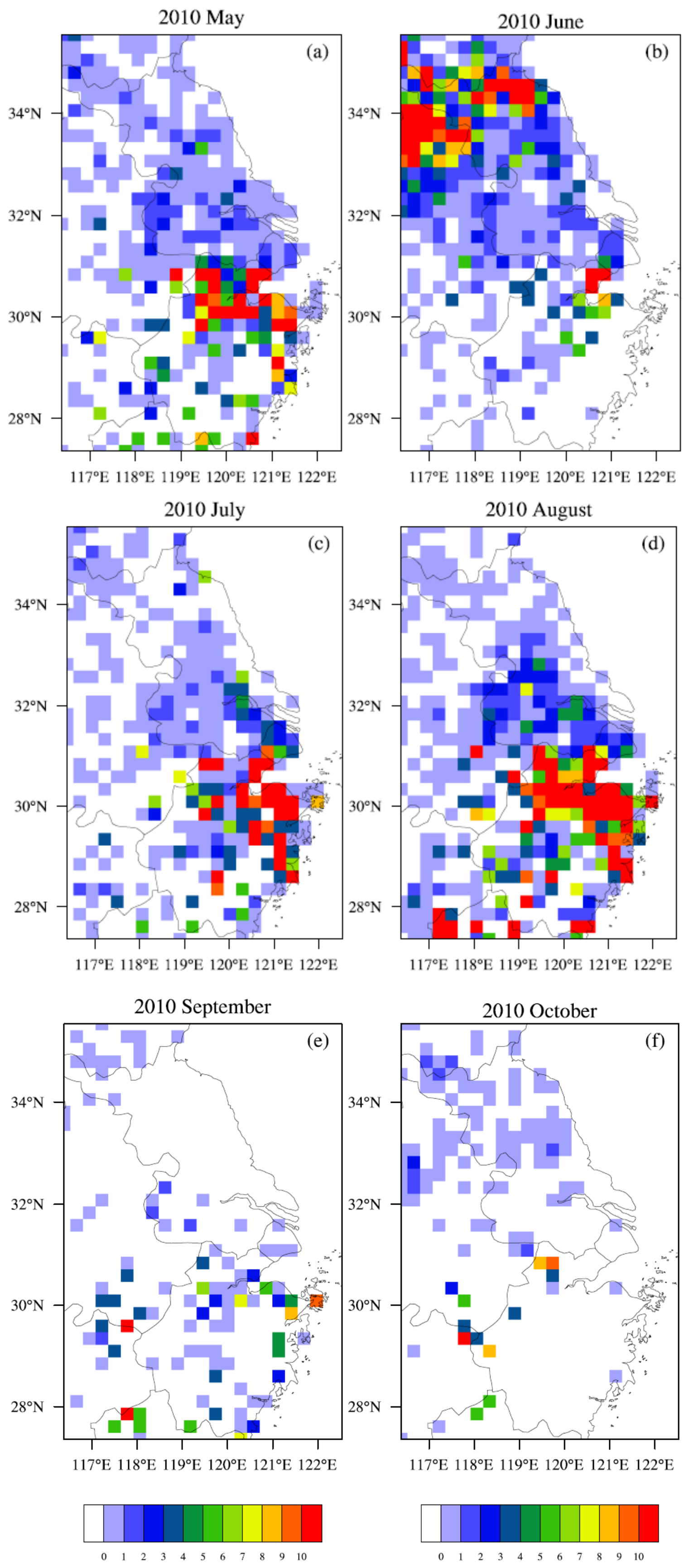

Fig. S2. Monthly accumulated carbon emission from biomass burning over Eastern China derived from FLAMBE emission inventory.

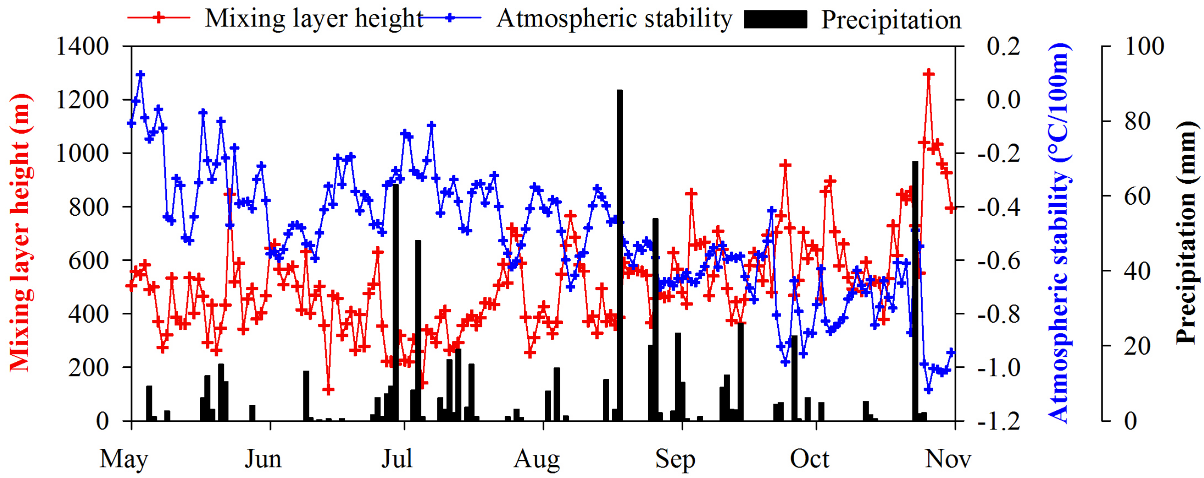

Fig. S3. Daily variations of mixing layer height (m), atmospheric stability (°C/100m) and precipitation (mm) during the Expo.

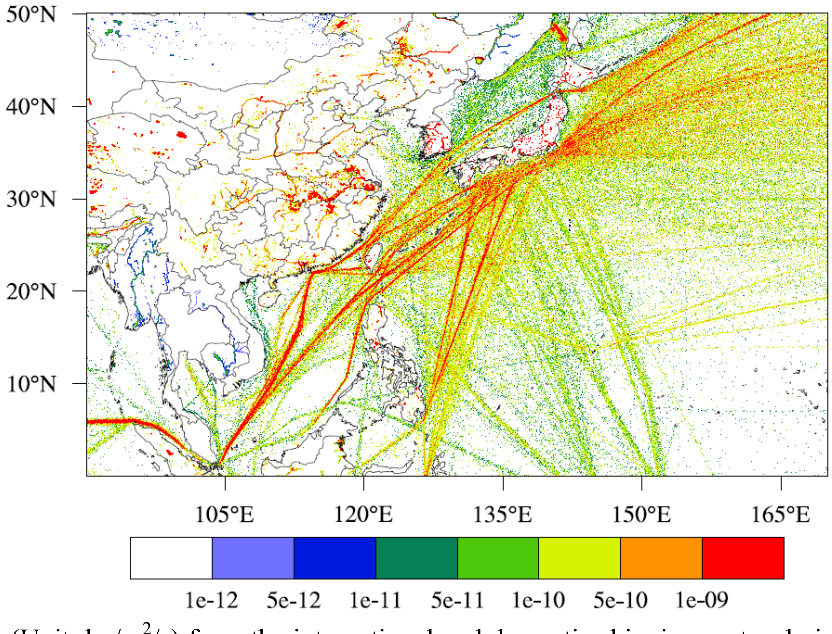

Fig. S4. PM emission (Unit: kg/m^2/s) from the international and domestic shipping sector derived from the EDGAR (Emissions Database for Global Atmospheric Research) global emission inventory.

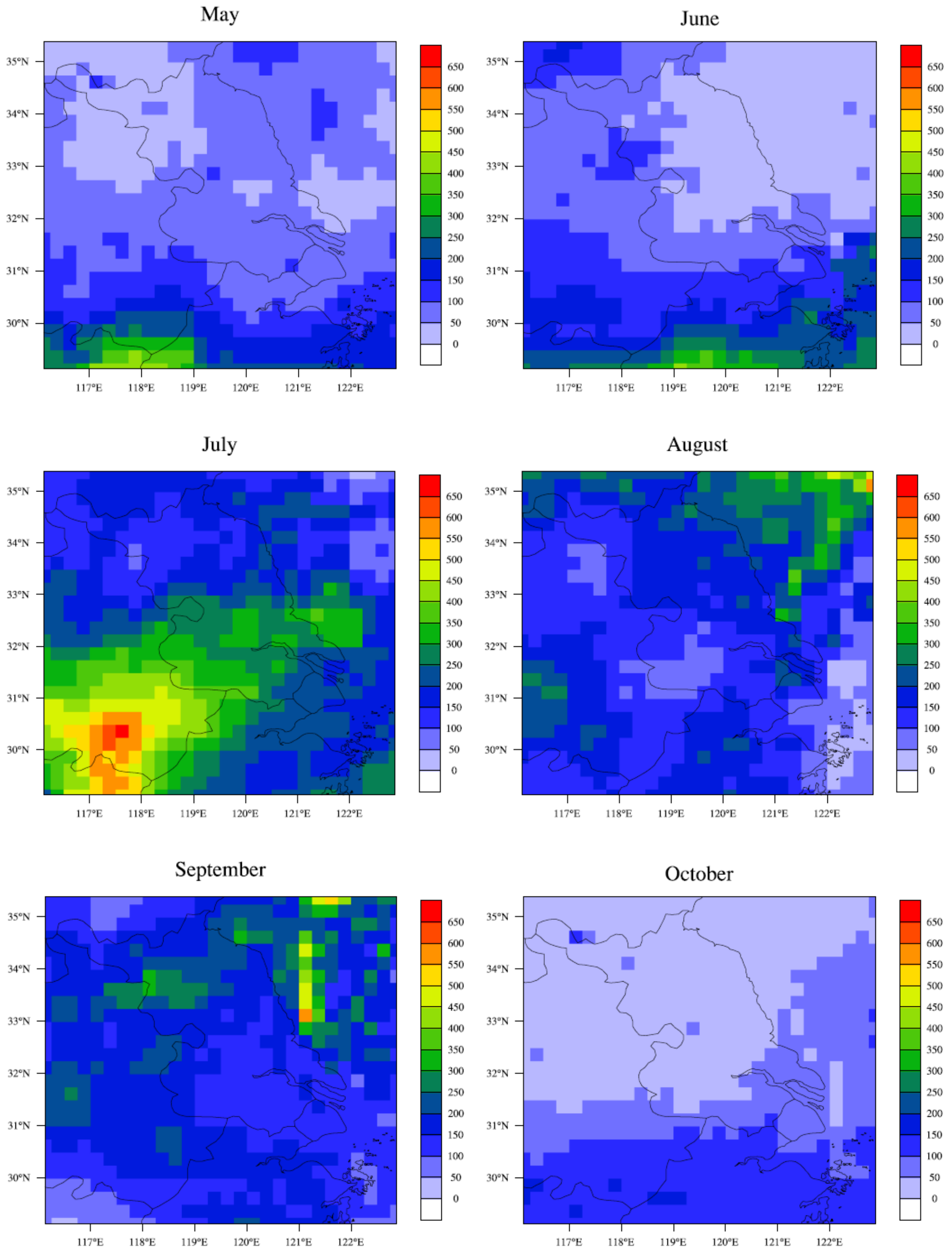

Fig. S5. Monthly accumulated rainfall (mm) from the TRMM (Tropical Rainfall Measuring Mission) PR satellite sensor.