



Measuring and Modeling Aerosol: Relationship with Haze Events in Shanghai, China

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ABSTRACT

Observation of surface concentration of particulate matter (PM₁₀, PM_{2.5}) and meteorological parameters, including visibility, relative humidity (RH), precipitation, and wind speed (WS) from 2008 to 2010 were analyzed in Shanghai, China. The haze events are identified as the following: (1) Severe haze (visibility < 2 km) occurs frequently when PM₁₀ and PM_{2.5} are above 181 and 115 µg/m³, respectively, with RH in between 78%–90% and WS ≤ 0.6 m/s; (2) Moderate haze (2 km ≤ visibility < 3 km) occurs frequently when PM₁₀ and PM_{2.5} are greater than 114 µg/m³ and 96 µg/m³, respectively, with RH of 67%–90% and WS ≤ 1.0 m/s; (3) Mild haze (3 km ≤ visibility < 5 km) happens when PM₁₀ and PM_{2.5} are greater than 96 µg/m³, 71 µg/m³, respectively, with meteorological conditions of 72% ≤ RH ≤ 90% and WS ≤ 1.0 m/s; (4) Slight haze (5 km ≤ visibility < 10 km) happens when PM₁₀ and PM_{2.5} are higher than 80 µg/m³, 54 µg/m³, with meteorological conditions of 66% ≤ RH ≤ 90% and WS ≤ 1.3 m/s. A typical haze event was analyzed during the MIRAGE-Shanghai field campaign (September, 2009). The results show that fine particles play very important role in haze formation. WRF-Chem, an on-line regional chemistry/transportation model was applied to simulate the haze event and its related meteorological conditions. The mass concentration of aerosol during the haze period of simulation agrees relatively well with that of observation, suggesting that the WRF-Chem model is reliable for aerosol forecasting over Shanghai. It also indicates that the implementation of combination criterion of PM_{2.5}, RH, and WS is a potential solution for numerical forecasting of haze event.

Keywords: Haze identification; WRF-Chem; Haze forecast.

INTRODUCTION

Shanghai locates on the east coast of China. It is one of the largest cities in the world with a population of about 23 millions. In the past two decades, Shanghai has undergone a rapid increase in economic development and urbanization. For instance, the GDP (gross domestic production) of 2010 is 22 times of 1990, accounting for more than 4% of the total GDP of China. The industrial gross output (IGO) has also rapidly increased (Shanghai Municipal Statistics Bureau, 1991, 1996, 2010).

Previous study indicated that direct emitted particles from human activities and secondary aerosols lead to significant reduction in visibility. As a result, haze events frequently occurred in large cities (Molina and Molina, 2002; Deng *et al.*, 2008).

Shanghai is suffering severe air pollution problems in recent years, such as high concentration of particulate matter (PM) and poor visibility, resulting in adverse effects upon people's lives (Tie *et al.*, 2006; Zhang *et al.*, 2006; Geng *et al.*, 2007). Low visibility caused by aerosol with relatively high humidity has been defined as "haze". This terminology is now commonly used to refer to aerosol pollution due to anthropogenic activities. The haze observation and prediction standard released by China Meteorological Administration (CMA) in January 2010 use the respirable particulate matter of PM_{2.5} and PM₁ mass concentration, aerosol extinction (sum of absorption and scattering) coefficients as parameters for haze identification. Several regional chemical and dynamic models have been applied to study air pollution and poor visibility. For example, Geng *et al.* (2007) and Tie *et al.* (2009) used the WRF-Chem model (Weather Research & Forecasting Model with chemistry) to study the variations of O₃, NO_x, VOCs, and other air pollutants in Shanghai. Wang *et al.* (2006b) used NAQPMS (Nested Air Quality Prediction Modeling System) to study East Asian

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cross-border transport of sulfur oxides. Hu *et al.* (2009) used an air quality forecasting system developed by Nanjing University to simulate the haze occurred in Nanjing.

Summarizing previous work, air quality and visibility was often discussed separately. Shanghai Meteorological Service (SMS) performs numerical forecasting of weather and air quality (O_3 , NO_x , PMS, etc.) and integrated measurements of meteorology and atmospheric chemistry. This capability offers a unique opportunity to understand haze formation. The modeling experience also provides useful tools for haze identification by the integration of numerical modeling results with meteorological observations (e.g., relative humidity, wind speed).

MEASUREMENT AND METHOD

Brief Introduction of Observational Data

The observational data used in this study are from two sources: 1) the operational observation carried out by SMS and 2) MIRAGE-Shanghai field campaign experiments. The meteorological parameters are measured by Vaisala MILOS 500 Automatic Weather Station, which consists of sensors, data collector, etc. Visibility, wind speed, precipitation, and relative humidity are observed by FD12P forward scattering visibility sensor, WAA511 photo-electronic anemometer, rain gauge, and HMP45D air temperature and relative humidity sensor, respectively. The precision of visibility is $\pm 10\%$ and $\pm 20\%$ for visibility ranges within 1–10 km and 10–50 km, respectively. In this study, the meteorological parameters were hourly averages from their original observational data. PM_{10} and $PM_{2.5}$ are measured by GRIMM-

180 Stationary Aerosol Monitor (GRIMM Technologies, Inc.) at Pudong site (Fig. 1), with precision of $1 \mu\text{g}/\text{m}^3$ and a flow rate of 72 l/h. In MIRAGE-Shanghai period from Sep. 1st to Sep. 22nd, aerosol chemical composition is measured on-line by the Monitor for Aerosols & Gases in Ambient Air (MARGA, Model ADI 2080, Metrohm Applikon BV) at the Fudan University campus which is about 10 km northwest from Pudong site (Fig. 1). The MARGA measures concentrations of inorganic aerosol species and their related gas phase components in ambient air (Li *et al.*, 2010). Its precision is greater than $0.1 \mu\text{g}/\text{m}^3$ for each species. More details about MIRAGE-Shanghai and MARGA are described in section “*Intensive Field Measurement: A Case Study*”.

WRF-Chem Model

The Weather Research and Forecasting (WRF) Model is a meso-scale numerical weather forecast system designed for both operational forecasting and atmospheric research (Klemp, 2004). The WRF is non-hydrostatic, with several dynamic cores and many different choices for physical processes. This allows the model to be applicable on many different scales. The dynamic cores include a fully mass- and scalar-conserving flux form mass coordinate version with two dynamic cores (Advanced Research WRF and Non-hydrostatic Meso-scale Model) and two vertical coordinates (Eulerian height coordinate and Eulerian mass coordinate). The detailed description of the parameters used in the WRF model, such as the planetary boundary layer (PBL) scheme, the land surface scheme, the microphysics scheme, and the cumulus cloud scheme can be found in the WRF web-site (<http://www.wrf-model.org/>).

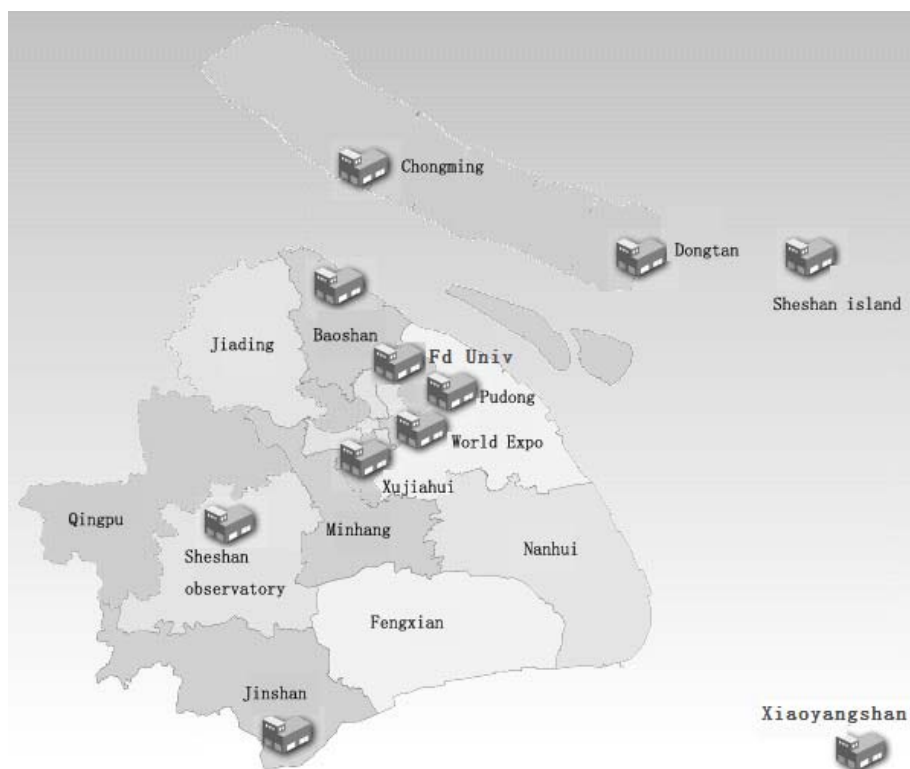


Fig. 1. Atmospheric component observation stations over Shanghai area.

In addition to dynamic calculations, a chemical model is fully coupled with the WRF model (WRF-Chem, Grell *et al.*, 2005). WRF-Chem includes on-line calculation of dynamical inputs (winds, temperature, relative humidity, boundary layer, clouds etc.), transport (advective, convective, and diffusive), dry deposition (Wesely, 1989), wet deposition, gas phase chemistry (Chang *et al.*, 1989), radiation and photolysis (Madronich and Flocke, 1999; Tie *et al.*, 2003), and surface biogenic emission. More detailed description of WRF-Chem can be found in Grell *et al.* (2005). Modifications in the chemical scheme can be found in Tie *et al.* (2007).

RESULTS AND DISCUSSION

Haze Identification by Historic Data Analysis

Historical PMs and meteorological data of haze days since August 2008 to August 2010 were analyzed in this study. When visibility is less than 10 km and relative humidity is less than 90% for two hours in one day, it is defined as a haze day. Snow, rain, dust storms, and other special weather phenomena are excluded for haze identification (Wu *et al.*, 2005). There are 445 haze days in Shanghai from August 2008 to August 2010. Most of haze days are slight or mild ($3.0 \text{ km} \leq \text{visibility} \leq 10.0 \text{ km}$). Moderate or severe (visibility $< 3.0 \text{ km}$) haze days account for about 23% of the total haze days (Fig. 2). Haze is highly correlated with PM concentrations, especially fine particulate matter ($\text{PM}_{2.5}$). Exceedance of $\text{PM}_{2.5}$ standards ($35 \mu\text{g}/\text{m}^3$, 24-hour average) occurs in 58%, 66%, 80%, and 76% of slight, mild, moderate, and severe haze events, respectively. As shown in Fig. 3, there is obvious correlation between visibility and $\text{PM}_{2.5}$ concentration. It shows that the visibility generally decreases as $\text{PM}_{2.5}$ concentration increases. During the study period, visibility shows moderate anti-correlation to $\text{PM}_{2.5}$, with a fitting curve of $y = 45.97x^{-0.57}$ and R^2 of 0.279. The correlation is significant at the 0.01 level of significance. The power in the fitting curve, -0.57 , is close to $-2/3$, the theoretical value in the relationship between visibility and particulate mass concentration assuming the relative humidity and the

physical and chemical properties of the particles are stable. The relationship between visibility and $\text{PM}_{2.5}$ concentration suggested that elevated concentration of fine particulate matter would result in reduced visibility.

Further statistical analysis of RH, WS, $\text{PM}_{2.5}$, PM_{10} in the two years (Table 1) shows that 1) for slight haze, the averaged RH and WS are 66.5% and 1.3 m/s, PM_{10} and $\text{PM}_{2.5}$ are 80.2 and $54.3 \mu\text{g}/\text{m}^3$, respectively; 2) the averaged RH and WS of mild hazes are 71.7% and 1.0 m/s, PM_{10} and $\text{PM}_{2.5}$ are 96.4 and $70.6 \mu\text{g}/\text{m}^3$; 3) moderate haze occurs frequently when averaged PM_{10} and $\text{PM}_{2.5}$ are 114.4 and $95.9 \mu\text{g}/\text{m}^3$, and RH and WS are 75.9% and 1.0 m/s, respectively; 4) severe haze occurs frequently when averaged PM_{10} , $\text{PM}_{2.5}$ are 181.4 and $114.8 \mu\text{g}/\text{m}^3$, and RH and WS are 77.9% and 0.6 m/s. Therefore, particulate matter concentration, relative humidity, and wind speed have obvious impact on visibility. Visibility significantly decreases with the combination of high concentration of particulate matter, high relative humidity, and low wind speed. That is, high humidity and stable meteorological conditions promote haze formation.

The influence of humidity on visibility is attributed to the hygroscopic nature of aerosols. Previous studies show that there are high levels of water soluble ions in aerosols in urban Shanghai. For example, Ye *et al.* (2003) reported that secondary inorganic species (the sum of SO_4^{2-} , NO_3^- , and NH_4^+) accounted for 41.6% of the $\text{PM}_{2.5}$ mass in Shanghai. The annual average of the SO_4^{2-} , NO_3^- , and NH_4^+ in $\text{PM}_{2.5}$ are 10.4, 3.8, and $6.2 \mu\text{g}/\text{m}^3$, respectively (Wang *et al.*, 2006a). It is also reported that there is distinct growth of aerosol with high relative humidity (Ye *et al.*, 2011). These results indicated that there might be interactive effects of $\text{PM}_{2.5}$ concentration and RH on visibility. Fig. 4 shows detailed relationship of RH, $\text{PM}_{2.5}$ concentration, and visibility. It can be seen that visibility generally decreases with increasing relative humidity at given $\text{PM}_{2.5}$ level. Meanwhile, it also decreases with increasing of $\text{PM}_{2.5}$ at given RH level. As a result, the worse visibility generally occurs when both RH and $\text{PM}_{2.5}$ level are high (top-right area in Fig. 4). Visibility is substantially improved when RH

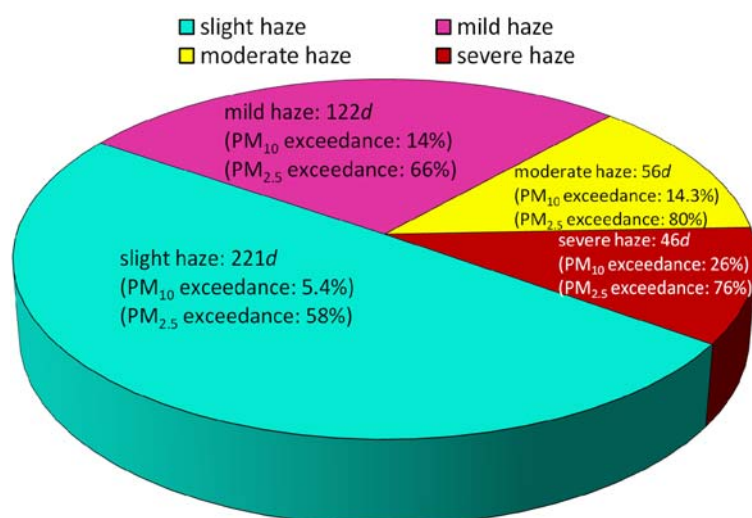


Fig. 2. Statistical analysis of Shanghai haze day and aerosol exceedance ratio from August 1, 2008 to August 31, 2010.

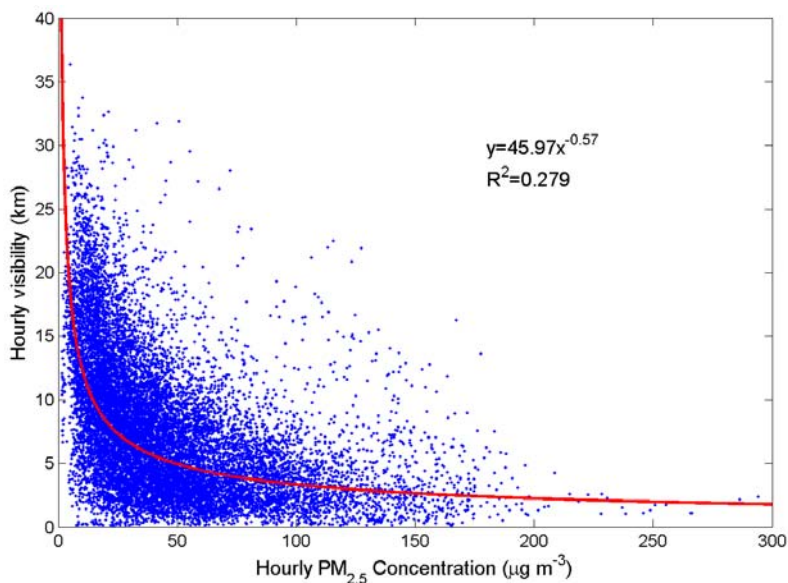


Fig. 3. Correlation analysis of visibility and $PM_{2.5}$.

Table 1. Statistical analysis of Relative humidity (%), Wind speed (m/s), $PM_{2.5}$ ($\mu\text{g}/\text{m}^3$), and PM_{10} ($\mu\text{g}/\text{m}^3$) during haze events from August 2008 to August 2010.

	Visibility < 2 km				2 km ≤ Visibility < 3 km				3 km ≤ Visibility < 5 km				5 km ≤ Visibility < 10 km			
	RH	WS	$PM_{2.5}$	PM_{10}	RH	WS	$PM_{2.5}$	PM_{10}	RH	WS	$PM_{2.5}$	PM_{10}	RH	WS	$PM_{2.5}$	PM_{10}
Mean	77.9	0.6	114.8	181.4	75.9	1.0	95.9	114.4	71.7	1.0	70.6	96.4	66.5	1.3	54.3	80.2
Maximum	80.0	0.7	148.3	201.1	84.0	2.2	121.5	168.2	91.1	1.9	121.0	173.1	85.0	2.3	131.2	186.4
Minimum	76.0	0.4	81.3	175.8	67.0	0.5	50.4	55.7	48.0	0.4	38.7	50.9	41.0	0.7	21.5	33.1

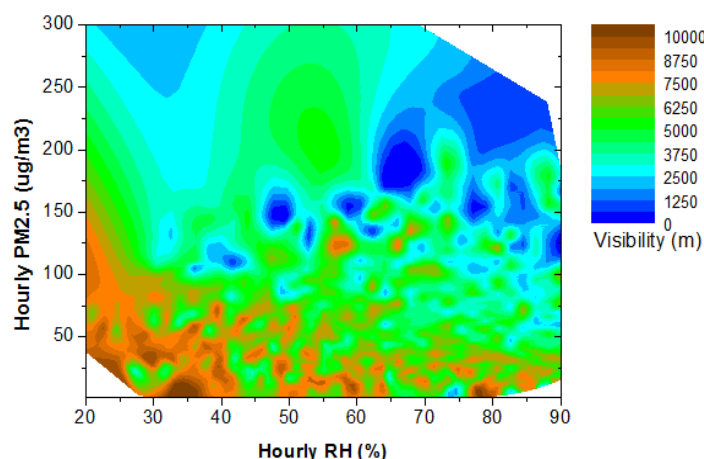


Fig. 4. Distribution of horizontal visibility related to relative humidity and $PM_{2.5}$ mass concentration. The time periods and data sources are the same as Fig. 2.

and $PM_{2.5}$ levels are both low (left-bottom area in Fig. 4). It should be noted that there are also some variations in the relationship, which is likely due to changes in the chemical composition and size distribution of $PM_{2.5}$ during the analysis time period. For some low visibility events, the physical and chemical properties of $PM_{2.5}$ may be different from those in usual conditions or other low visibility events. For example, substantial variations in the chemical composition of aerosol can be found during a haze event in September

2009 (in next section). Difference in chemical composition means the change of hygroscopic growth. Ye *et al.* (2011) found that the hygroscopic growth factor is also affected by aerosol size distribution in Shanghai. The extinction coefficient of aerosol is directly proportional to its surface area. Therefore, different size distribution results in different extinction as well as visibility.

In addition to high humidity, haze typically forms in relatively stable synoptic-condition, for example when cold

continental high pressure gets close to the region and warming conditions develop near the ground, usually with slight winds (1 to 2 m/s). Surface layer thermal inversion occurs frequently in autumn and winter, which promotes haze formation. The main features of inversion include reduced boundary layer, weak turbulent exchange, poor diffusion, and consequently accumulated aerosol particles and decreased visibility near the ground. These results are consistent with previous studies in the Yangtze River Delta and in Shanghai (Ye *et al.*, 2003; Tong *et al.*, 2007; Fu *et al.*, 2008; Chan and Yao, 2008; Di *et al.*, 2009; Feng *et al.*, 2009).

The above statistical analysis of particles and meteorological parameters can be used for haze identification. In the next sections, a case study will be introduced to validate the accuracy and usefulness of the methodology by intensive observations and modeling.

Intensive Field Measurement: A Case Study

In order to understand the air pollution in mega-cities, an intensive field experiment, Megacity Impacts on Regional and Global Environments (MIRAGE-Shanghai 2009, <http://www.acd.ucar.edu/mirage>), was conducted from September 1st to 22nd, 2009 in Shanghai. MIRAGE-Shanghai 2009 is a collaboration work between SMS and National Center for Atmospheric Research (NCAR), Texas A&M University, Fudan University, Peking University, and Institute of Earth Environment of Chinese Academy of Science. The goal of the campaign is to assess pollution and its precursors in preparation for future fieldwork. A comprehensive atmospheric dataset was obtained in the field study, providing an excellent opportunity for haze studies. During the experiment, an extremely low visibility event occurred in the evening of Sep. 11th, and continued through Sep. 12th. The hourly mean visibility, relative humidity (RH), precipitation is given in Fig. 5. Mass concentrations of PM₁₀, PM_{2.5} measured by Grimm180 instrument and aerosol chemical composition measured by

MARGA are given in Fig. 6. During the haze event (Fig. 5), the visibility ranges from 2.5 to 8 km, with average of only 4.5 km. Relative humidity is in the range of 65%–88%. At the same time, the mean concentration of PM_{2.5} is approximately 70 $\mu\text{g}/\text{m}^3$ and PM₁₀ about 100 $\mu\text{g}/\text{m}^3$. These values are in good agreement with statistical analysis in the previous section. The result indicates that combination of aerosol concentration and meteorological factors of RH and WS can be used to identify haze event in the real environment. Therefore, three parameters (PM_{2.5} mass concentration, RH, and WS) are selected for haze identification. By using the features of the WRF-Chem model, we will develop a method to identify and forecast haze event by numerical prediction. Details will be discussed in next section.

Aerosol composition was also analyzed for this study. A MARGA analyzer with a PM₁₀ sampling inlet was used to conduct intensive measurements from Sep. 1st to Sep. 22nd, 2009. The MARGA data include mass concentrations of major water-soluble inorganic ions in aerosols (NH₄⁺, Na⁺, Ca²⁺, Mg²⁺, SO₄²⁻, NO₃⁻, Cl⁻) and trace gases (HCl, HONO, O₂, HNO₃, NH₃) at one hour resolution. For tracking changes in retention time and detector response for each sampling, the MARGA was continuously controlled by an internal calibration method using bromide for the anion chromatograph and lithium for the cation chromatograph over the whole observation period. There are significant differences in aerosol chemical composition between the haze periods and other times (Table 2, Fig. 6(b)). In the haze period, the averaged concentration of NO₃⁻ is 13.6 $\mu\text{g}/\text{m}^3$, which is about 5 times higher than in other times; SO₄²⁻ is 17.2 $\mu\text{g}/\text{m}^3$, about twice of other times; NH₄⁺ is 10.0 $\mu\text{g}/\text{m}^3$, about 5 times greater. The change of PM_{2.5} compositions is mainly due to the increases of NH₄NO₃, a common hygroscopic compound in PMs. This indicates that changes in aerosol composition led to the hygroscopic growth of aerosols, as suggested by Zelenyuk *et al.* (2006). Previous studies also found high ammonium nitrate

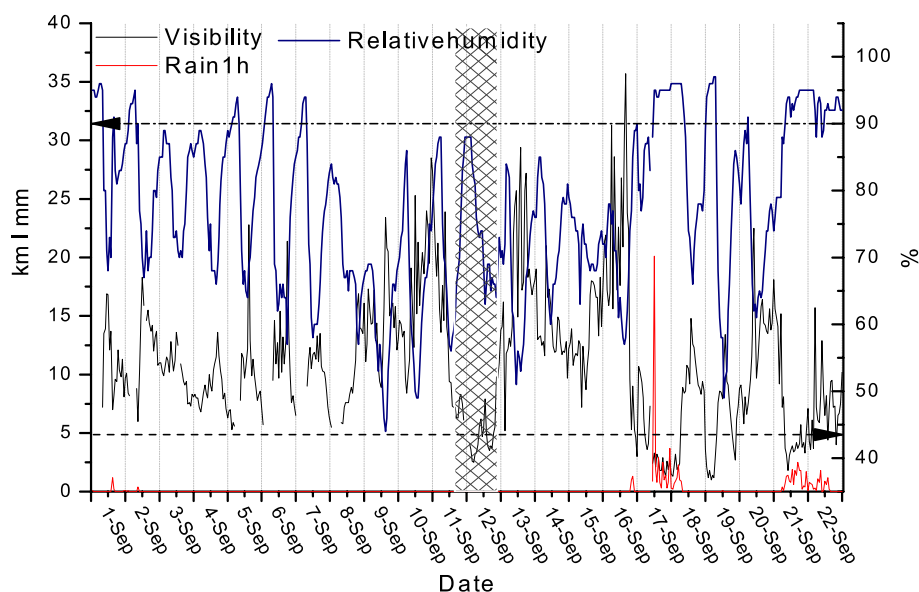


Fig. 5. Visibility, RH and precipitation during MIRAGE-Shanghai (Sep. 1st–22nd, 2009).

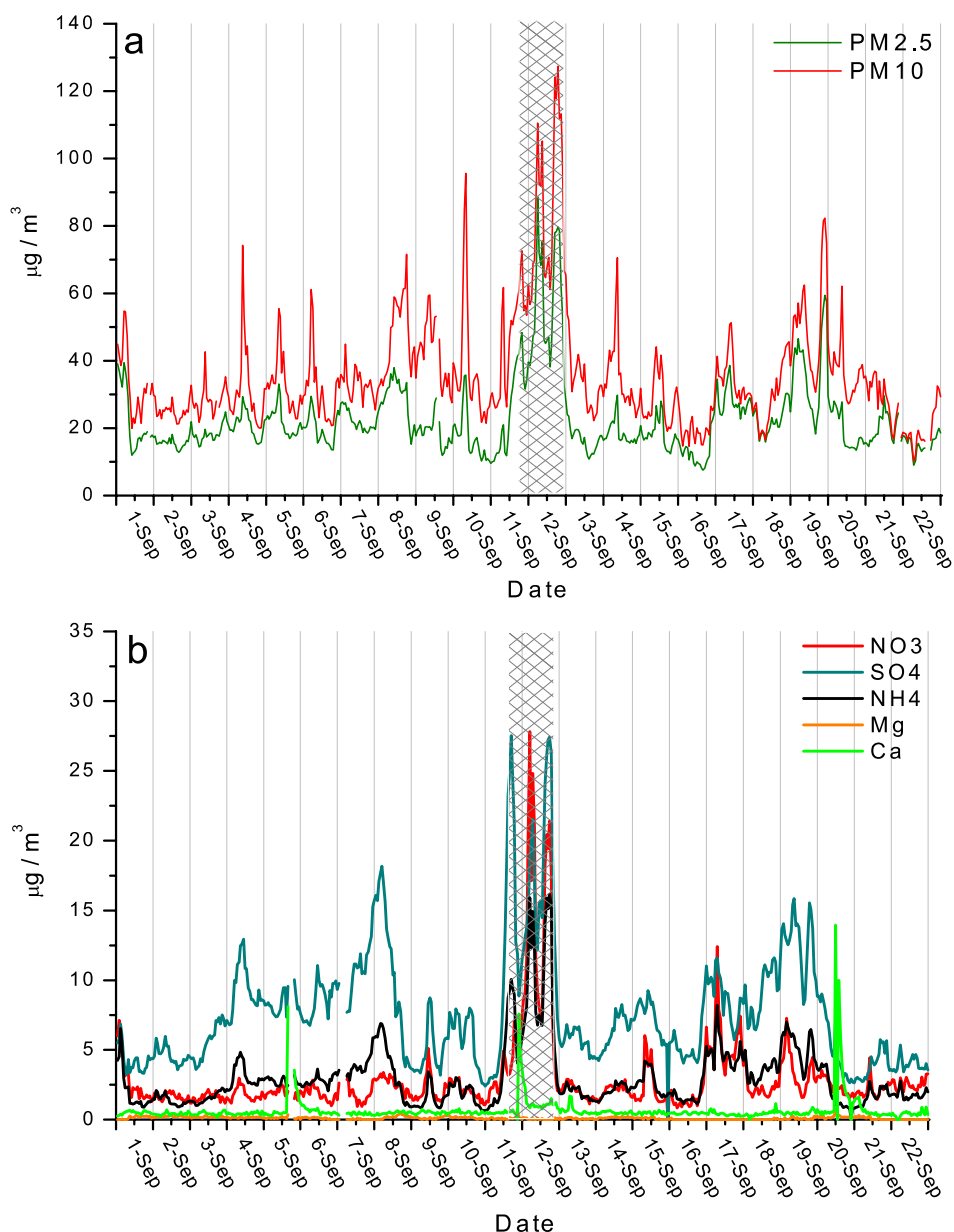


Fig. 6. PM mass concentration (a) and water-soluble ions (b) during MIRAGE-Shanghai.

Table 2. Variation in concentration of pollutants during haze and other times.

Averaged concentration of pollutants ($\mu\text{g}/\text{m}^3$)	Aerosol chemical composition				
	NO_3^-	SO_4^{2-}	NH_4^+	Mg^{2+}	Ca^{2+}
Haze period	13.6	17.2	10.0	0.2	1.7
Other times	2.6	6.8	2.3	0.1	0.6

concentration plays an important role in the formation of haze in the Shanghai area (Yang *et al.*, 2012). It is known that increase of ammonium nitrate concentration significantly enhances light scattering and decreases in visibility (Wu *et al.*, 2005; Ye *et al.*, 2011).

Numerical Simulation of the Haze Event by WRF-Chem Model

An important objective of this study is to use a regional

chemical/dynamical model (WRF-Chem model) and establish the methodology to identify haze event through numerical simulation/forecasting. WRF-Chem version 3.2 was used, which includes the impacts of aerosols on photolysis and gas phase chemistry (Tie *et al.*, 2007). The model was applied and evaluated in ozone study in Shanghai region (Tie *et al.*, 2009). In this study, The FNL version of NCEP reanalysis data was used for the initial condition and the lateral boundary layer condition of meteorology. Its resolution

is 1×1 degree horizontally, 6 hour interval temporally and 26 layers (1000, 975, 950, 925, 900, 850, 800, 750, 700, 650, 600, 550, 500, 450, 400, 350, 300, 250, 200, 150, 100, 70, 50, 30, 20, and 10 hPa) in the vertical. The chemical lateral boundary conditions are constrained by a global chemical transport model (MOZART, Model for Ozone and Related chemical Tracers, Emmons *et al.*, 2010). Anthropogenic emissions, based on the inventory of Streets *et al.* (2003, 2008) (Table 3), include 5 inorganic gases, 16 VOC species, and 7 aerosol species which include EC, OC, ammonia, sulfate and nitrate, etc. The emissions were updated using the land-use data (~ 30 m resolution) retrieved from Landsat-5 Thematic Mapper in 2008 and further adjusted using oil consumption data in 2008 and 2009 for the Shanghai chemical industry areas. The model resolution is 6×6 km horizontally, with a 900×900 km domain centered at Shanghai (121.4°E , 31.3°N). To decrease the effect of initial chemical condition, the simulation was started at 20:00 on Sep. 8th, 2009. The simulation was re-run from 20:00 on 10th by using the former result as the initial chemical condition.

As mentioned previously, particulate matter is one of the main factors that cause haze events. Thus, $\text{PM}_{2.5}$ was selected as one of indices for comparing model simulation and ground based observation. The results (Fig. 7) shows that modeled $\text{PM}_{2.5}$ concentrations generally agree with the observed levels, except for the values in the afternoon of Sep. 12th. The model captured the general trend and diurnal variation, especially from the noon of 11th to the noon of 12th. The peak in the 12th morning of the modeling agrees with that of observation, with a concentration of approximately $90 \mu\text{g}/\text{m}^3$. The averaged mass concentration of $\text{PM}_{2.5}$ in this period is about $60 \mu\text{g}/\text{m}^3$, which is in the range of mild or moderate haze. Meanwhile, in terms of meteorological factors, modeled results during this period meet the haze identification

meteorological conditions, with averaged RH of 74%, range from 58–89% and averaged wind speed of 2.1 m/s, slightly larger than the standards in Table 1. This result suggested the WRF-Chem model has the capability for describing the chemistry and meteorology of haze events. It should be noted that the model is biased low for the relative high $\text{PM}_{2.5}$ in 12th afternoon. Observation results showed the averaged wind speed during the two $\text{PM}_{2.5}$ peaks (06:00 and 18:00 LST) was only 1.4 m/s, indicating that transportation effect was fairly weak. While the modeled value reached 4.3 m/s, substantially over estimated the wind speed and therefore the effect of transportation. The backward trajectory (Fig. 8(b)) calculated by HYSPLIT model (Draxler and Hess, 1998) using the simulated meteorological field showed that the air parcel which reached Shanghai at 18:00 LST passed by the coast area in the last 12 hours, the low $\text{PM}_{2.5}$ region at 06:00 LST (Fig. 8(a)). Therefore the modeled $\text{PM}_{2.5}$ concentration was lower than the observed in 12th afternoon.

The model also output the concentrations of aerosol species, including SO_4^{2-} , NO_3^- , NH_4^+ , element carbon (EC), organic (primary and secondary anthropogenic, and biogenic), and unresolved aerosol. Comparing to the observations from MARGA at the site of Fudan University (Fig. 9), the model simulated similar SO_4^{2-} and NH_4^+ temporal variations agree with the observations except in 12th afternoon, but with obviously lower concentrations; the modeled NO_3^- trend and concentration are both different from the observed. For other modeled aerosols, EC accounts for 17%, organic 26%, and unresolved 57%. So the simulation of aerosol composition is not satisfied, and visibility calculation based on model aerosol species, such as using Malm and Day (2001) algorithm, would results in substantial bias. This result also indicated that the current modeling system

Table.3 Emission inventory of SO_2 , CO, NO_x , VOCs, black carbon (BC), organic carbon (OC), fine particles excluding EC and OC (PMF), and coarse particles (PMC) in Shanghai Region used in the WRF-Chem model ($\text{Ton}/\text{Year} \times 10^6$).

SO_2	CO	NO_x	VOCs	BC	OC	PMF	PMC
1.08	14.53	0.40	1.57	0.10	0.47	0.63	0.18

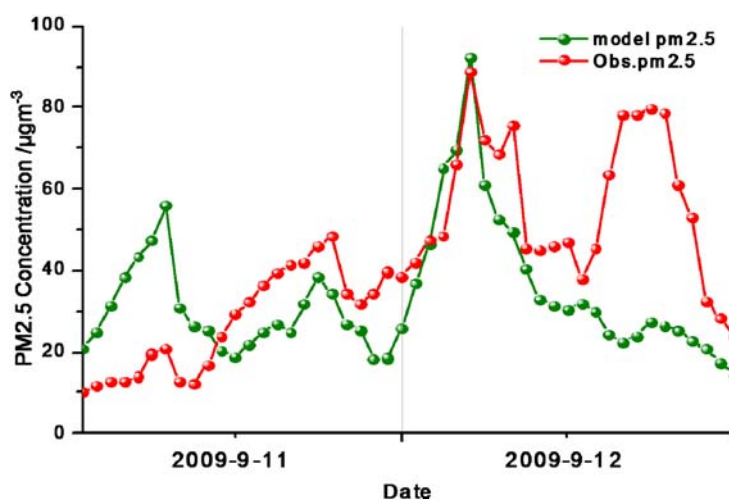


Fig. 7. Comparison of modeled and observed $\text{PM}_{2.5}$ mass concentration during the haze event.

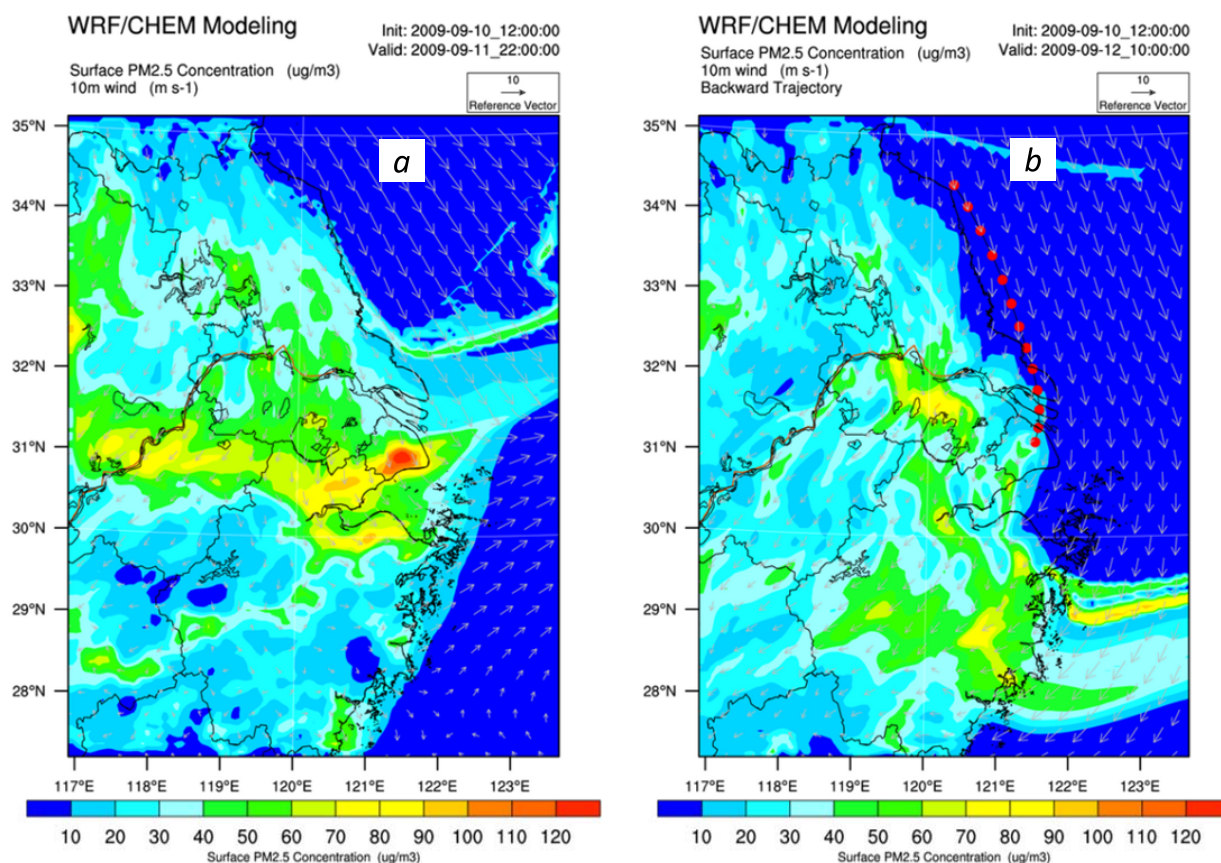


Fig. 8. Simulated $PM_{2.5}$ distribution and surface (10-meter) winds at 06:00 LST (a, left) and 18:00 LST (b, right) on Sep. 12th, 2009. Marked line on (b) is the backward trajectory.

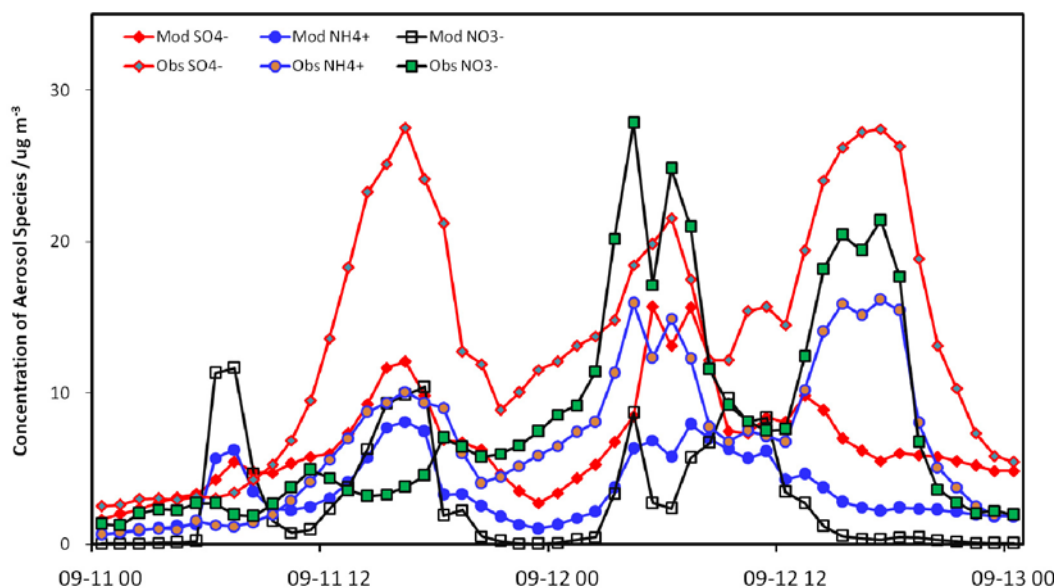


Fig. 9. Comparison of modeled and observed aerosol species concentrations during the haze event.

has better capability in simulation of $PM_{2.5}$ concentrations than aerosol composition, suggesting that the statistical method is more suitable for haze event forecasting when combined with WRF-Chem model.

The result of a case study in MIRAGE-Shanghai suggests

that the combination criterion of $PM_{2.5}$, RH, WS listed in Table 1 can be used to identify haze events. Numerical prediction of meteorological and chemical model, such as using WRF-Chem, could be a potential method to forecast haze event.

SUMMARY AND CONCLUSIONS

In this study, statistical analysis of aerosol and meteorological data obtained in Shanghai was applied to understand environmental conditions promoting haze formation. The result shows that haze in Shanghai occurs generally in relative stable synoptic situation with high RH and high concentrations of fine particles. Different level of haze can be identified using three key parameters of PM_{2.5}, RH and WS as: (1) Severe haze (visibility < 2 km) occurs frequently when PM₁₀ and PM_{2.5} are above 181 and 115 µg/m³, respectively, and with RH of 78%–90% and WS ≤ 0.6 m/s; (2) Moderate haze (2 km ≤ visibility < 3 km) occurs frequently when PM₁₀ and PM_{2.5} are greater than 114 µg/m³ and 96 µg/m³, respectively, with RH from 67% to 90% and WS ≤ 1.0 m/s; (3) Mild haze (3 km ≤ visibility < 5 km) happens when PM₁₀ and PM_{2.5} are greater than 96 µg/m³, 71 µg/m³, respectively, with meteorological conditions of 72% ≤ RH ≤ 90% and WS ≤ 1.0 m/s; (4) Slight haze (5 km ≤ visibility < 10 km) happens when PM₁₀ and PM_{2.5} are greater than 80 µg/m³, 54 µg/m³, with meteorological conditions of 66% ≤ RH ≤ 90% and WS ≤ 1.3 m/s. It is also shown that the influence of RH and PM concentration on visibility is interactive due to the hygroscopic growth of aerosol.

A typical haze event occurred in MIRAGE-Shanghai, a field campaign conducted in September 2009 in Shanghai was intensively analyzed. The observations show that ammonium nitrate is the most important components of aerosol during the event, suggesting that the hygroscopic growth of aerosols plays important roles in this event. It is also confirmed that statistical criterion is useful for the identification of haze events. Furthermore, a fully coupled on-line regional chemistry/transportation model, WRF-Chem, was applied to simulate the meteorology and chemistry of this haze event. The simulation result basically agrees with the observation in the haze event. The performance of the modeled haze case suggests that numerical tool combined with statistical results could be a useful tool for forecasting haze event.

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