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Research Article

A Parameterized Method for Air-Quality Diagnosis and Its Applications

J. Z. Wang,[1] S. L. Gong,[1,2] X. Y. Zhang,[1] Y. Q. Yang,[1] Q. Hou,[1] C. H. Zhou,[1] and Y. Q. Wang[1]

[1] *Center for Atmospheric Composition Observing & Service, Chinese Academy of Meteorological Sciences, Beijing 100081, China*
[2] *Air Quality Research Division, Science & Technology Branch, Environment Canada, 4905 Dufferin Street, Toronto, ON, Canada M3H 5T4*

Correspondence should be addressed to X. Y. Zhang, xiaoye@cams.cma.gov.cn

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A parameterized method is developed to diagnose the air quality in Beijing and other cities with an index termed (parameters linking air-quality to meteorological elements PLAM) derived from a correlation between PM_{10} and relevant weather elements based on the data between 2000 and 2007. Key weather factors for diagnosing the air pollution intensity are identified and included in PLAM that include atmospheric condensation of water vapour, wet potential equivalent temperature, and wind velocity. It is found that the poor air quality days with elevated PM_{10} are usually associated with higher PLAM values, featuring higher temperature, humidity, lower wind velocity, and higher stability compared to the averaged values in the same period. Both 24 h and 72 h forecasts provided useful services for the day of the opening ceremony of the Beijing Olympic Games and subsequent sport events. A correlation coefficient of 0.82 was achieved between the forecasts and (air pollution index API) and 0.59 between the forecasts and observed PM_{10}, all reaching the significant level of 0.001, for the summer period. A correction factor was also introduced to enable the PLAM to diagnose the observed PM_{10} concentrations all year round.

1. Introduction

Meteorological elements, including water vapor content, surface wind speed, visibility, and the diurnal temperature range are important parameters to effect air pollutant concentrations [1]. Studies using data from seven air quality stations during the period of 2000 to 2008 in Taiwan area showed that PM_{10} and $PM_{2.5}$ concentrations were significantly controlled by the weather elements, resulting in high concentrations in spring and winter and low concentrations in fall and summer [2]. Even in summer when relatively low pollutant concentrations were found, the weather elements still had a large impact on air quality as the high temperature and humidity tended to increase PM_{10} and $PM_{2.5}$ concentrations, due to the formation of secondary pollution [3, 4]. Recently, substantial advances have been made in the studies of the impact of human activities on air quality caused by the increasing pollutant concentrations, especially ozone and particulate matters (PM) [5–9]. The concentration variations of different aerosols in various regions of China, as well as the impacts of aerosol concentration on sand/dust storms (SDS) and hazy weather in the Asia and North American were investigated [1, 10–14]. It is found that the variation of aerosol and gaseous concentrations is closely related to the changing weather elements [3, 8, 15–19]. The key weather elements influencing the air pollution include wind speed, wind direction, air pressure, temperature, humidity, precipitation, and atmosphere stability [20]. These factors control the dilution, transports, accumulation, and removal processes of air pollutants and hence dominate the air concentration of various pollutants under a given emission condition.

The relationship between the evolution of the general circulation and foggy/hazy weather systems was also examined to link the wind/cloud fields with low-visibility weather, indicating that atmospheric aerosols such as mist, fog, fume, smoke, smog, and haze can be formed from a condensation or nucleation process [21–25]. Studies also show that in the case of heavy pollution due to the increase of NO_2 and SO_2, significant differences in condensability were observed before

and after a hazy weather process. Before the haze onset, with the increase of SO_2 and NO_2 concentrations, condensability was increasing quickly. On the contrary, during a haze event, both SO_2 and NO_2 concentrations were decreased [19]. This was related to the consumption and washout of the nucleus in the haze formation. Atmospheric condensation is a key factor for diagnosing and forecasting the air pollution intensity in relation to weather conditions.

The above studies indicated that meteorological elements have a significant control over the accumulation and dilution of air pollutants. One of the most important scientific questions is how to quantify the meteorological impacts and use them to diagnose and forecast the air quality under the assumption that the time scale of emission changes is much longer than the meteorology changes.

Numerical prediction of air quality by 3D chemical transport models (CTM) has been implemented in a number of weather services around the globe with various degree successes [26–28] to forecast air quality. Due to the emission inventories used for the forecasts usually lagging behind the current date, this method has the limitation for an accurate forecast if the emission inventory is not updated to the current time for a region with ever changing industries such as in China. Through an analysis of observed PM and meteorological parameters, a parameterized method was developed and defined as the PLAM index. PLAM links the air pollution variations to the meteorological conditions. During the period of 2008 Beijing Olympic Games, PLAM was used to forecast the air quality in Beijing and achieved reasonable results.

2. Data and Methods

2.1. Data. For the sake of data comparison, analysis, and operational run, both PM_{10} and weather observations were collected simultaneously at the National Climate Observatory in Beijing (NCOB). PM_{10} is measured by a TEOM (Series 1400a Ambient Particulate Monitor). The instrument measures the PM_{10} mass concentrations every 5 minutes automatically. The mass transducer minimum detection limit is $0.01\,\mu$g. The precision for 10-minute and 1-hour averaged data is $5.0\,\mu\text{g}\,\text{m}^{-3}$ and $1.5\,\mu\text{g}\,\text{m}^{-3}$, respectively [29]. The daily mean PM_{10} data and weather observations were obtained after careful QA/QC processes. NCOB is one of the national climate observatories providing data for international exchange under Word Meteorological Organization (WMO) through World Weather Watch (WWW). The NCOB (N 39.8, E116.5, 32 m) station is in the suburban/rural area of Beijing. Compared with meteorological variables, PM measurements are substantially influenced by the local environment.

2.2. Correlation Analysis. Previous study has indicated that a positive correlation of PM_{10} observations with maximum temperature (t_m) and relative humidity (rh) was found for the period from July to September in 2000–2007 at NCOB [30]. It was suggested that for a better signal analysis and forecasts, the peak PM_{10} values could be identified on a daily basis in the same month.

In this study, for the forecasting purpose, the observed PM_{10} (y) with preceding 24 h weather elements $x_i(p, t_m, w, \text{rh}, e, \text{etc.})$ was used with daily average meteorological data for period from 1 July to 31 September 2000–2007 (total 736 days) managed by the National Climate Centre of China. The elements of p, t_m, w, rh, evaporability, water vapour, dew point, wind direction, wind speed, cloudiness, rainfall, and so forth were included in the dataset. Figure 1 presents the correlations of PM_{10} values measured at NCOB with the maximum temperature, relative humidity, water vapor observed 24 hours before and with the evaporability at the same time. The evaporability is to describe the evaporation capacity of the atmosphere with a unit of mm. The correlations of PM_{10} with t_m, rh, air pressure, water vapor amount and evaporability are given in Table 1. Positive correlations of PM_{10} observations were found with the maximum temperature, relative humidity, and water vapor with preceding 24 hours, and negative correlations were found with evaporability from July to September in 2000–2007 at NCOB. The correlation coefficients are 0.6039, 0.6246, 0.5458, and −0.2557, respectively, reaching a significant level over 0.001 [31].The correlation of PM_{10} with air pressure is also noted (Table 1).

Based on the analysis, a set of weather sensitive parameters signalling a forthcoming hazy event are identified, which can be observed *several hours before* the hazy weather occurs. Among these elements, high temperature, high humidity, moderate wind, and high stability will dominate the poor air-quality in the summer of Beijing. The effects of seasonal changes of meteorological elements on the PLAM will be discussed in next section. Therefore, the PLAM is established as a function of the following parameters:

$$\text{PLAM } (F) \in f(p, t, w, \text{rh}, e, s, c', \ldots), \tag{1}$$

where p, t, w, rh, e, s, and c' represent air pressure, air temperature, winds, relative humidity, evaporability, stability, and effect parameter associated with the contribution of air pollution $\beta(c')$, respectively.

2.3. Parameterization Method for Air-Quality Diagnosis. Some studies [32–34] have showed that the microprocesses in cloud physics can be described in a parameterization scheme with large-scale observations. It was also found that the stabilized summer weather with high air temperature, high relative humidity, moderate winds, and stability might create a microenvironment for a high PM_{10} concentration in August over Beijing [30], corresponding to a static dynamic forcing (baroclinicity) and thermal forcing (equivalent potential temperature (θ_e) gradient) in the atmospheric moist adiabatic processes [35]. It is shown that the lowest diffusion efficiencies occur more than 90% in moderate winds and stable conditions during the time for the summer period of July and August. Part of the temperature profile ranges between the adiabatic lapse rate (neutral stability) and the isothermal lapse rate [36]. The condensation is also a key factor for diagnosing pollution intensity under given weather conditions in the atmospheric moist adiabatic processes. Apparently, the final PLAM can be attributed to two

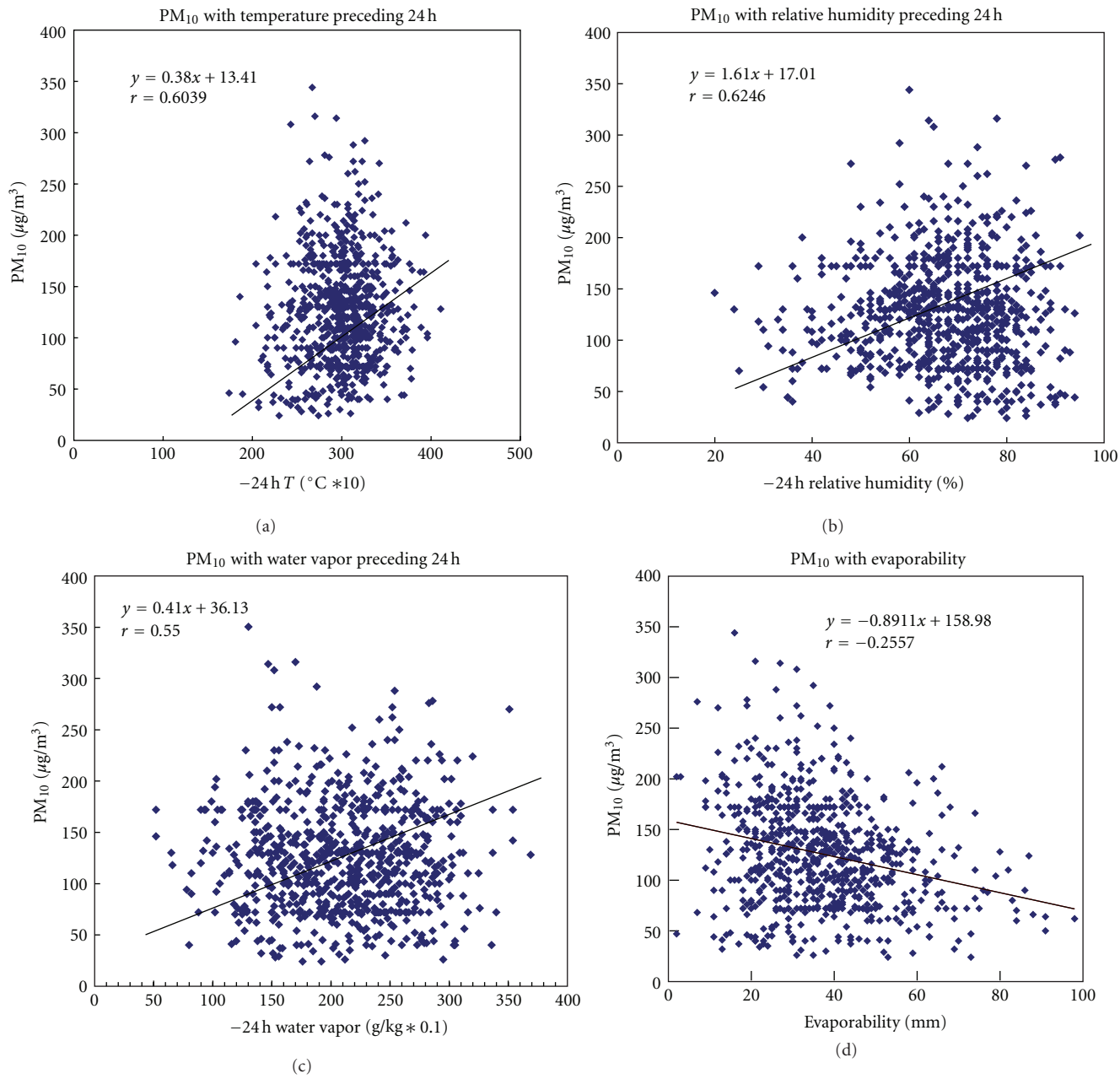

Figure 1: Correlation of PM_{10} with temperature (a), relative humidity (b), water vapor observed (c), and evaporability (d) preceding 24 h.

Table 1: Correlation analyses for PM_{10} with meteorological elements x_i.

Element	b_0 (Slop)	b_1	Correlation coefficient	Significant level	Period	N
t_m	0.38	13.41	0.6039	>0.001	pre 24 h	736
rh	1.61	17.01	0.6246	>0.001	pre 24 h	736
w (water vapor)	0.41	36.13	0.5458	>0.001	pre 24 h	736
p	−0.02	0.01	0.6481	>0.001	Synchronization	736
Evaporability	−0.89	158.98	−0.2557	>0.001	Synchronization	736

$Y_i = b_0 X_i + b_1$.

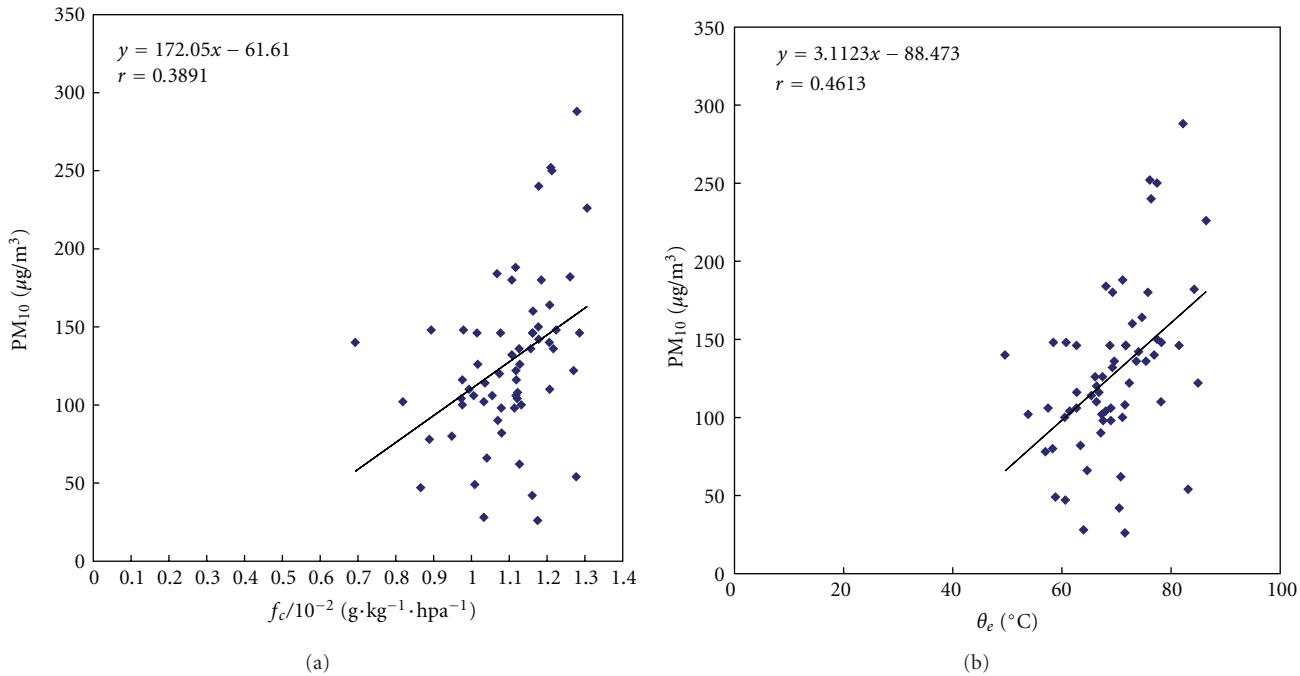

Figure 2: Correlation of PM_{10} with f_c (a) and θ_e (b) for July–August 2007.

separate factors: (1) initial meteorological conditions $\alpha(m)$ associated with the atmospheric condensation processes and (2) a dynamic effect parameter associated with the initial contribution of air pollution $\beta(c')$ such as

$$\mathrm{PLAM} = \alpha(m) \times \beta'(c). \tag{2}$$

In the following sections, these two terms are derived and discussed in details.

2.3.1. Initial Meteorological Conditions $\alpha(m)$. According to Gao et al. [37], the meteorological dynamical identification for haze and humid weather in summer Beijing indicated that, in general, the obvious variation of wet-equivalent potential temperature (θ_e) may be observed, which is associated with the releasing of latent heat by adiabatic condensation processes.

Initial meteorological contribution can be expressed as the variation of wet-equivalent potential temperature (θ_e):

$$\alpha(m) = \frac{d\theta_e}{dt} = \theta_e \frac{f_c}{C_p T}, \tag{3}$$

where the condensation function f_c is described by [19, 38]

$$f_c = \frac{f_{\mathrm{cd}}}{\left[\left(1 + \left(L/C_p\right)\left(\partial q_s/\partial T\right)\right)_p\right]}, \tag{4}$$

Where C_p is the heat capacity of air, L is the latent heat for condensation or evaporation of water vapor, and q_s is the specific humidity. f_{cd} is the dry condensation function as defined below:

$$f_{\mathrm{cd}} = \left[\left(\frac{\partial q_s}{\partial P}\right)_T + \gamma_p \left(\frac{\partial q_s}{\partial T}\right)_p\right]$$
$$\gamma_p = \frac{R_d}{C_p}\frac{T}{P}, \tag{5}$$

where R_d is the gas constant. In order to analyze the statistical relationship between air quality and meteorological parameters for the special period during the 2008 Beijing Summer Olympic Games (July to August, 2008), the data for July to August 2007 were used in calculating the correlation of PM_{10} with f_c and θ_e in (3). Figures 2(a) and 2(b) show the correlations of the condensation function f_c (4) and wet-equivalent potential temperature θ_e with the observed PM_{10} for July to August, 2007. It is seen that these two meteorological parameters are correlated with the PM_{10} and can be used for forecasting short term variations of PM due to changes in meteorology.

The f_c and θ_e only account for the meteorological contributions to the PM. In reality, the PM concentrations are effected by emissions, meteorology, and atmospheric processes such as nucleation, condensation, and dry/wet depositions.

2.3.2. Relative Dynamic Affect Parameter. In order to quantify the relative impact of weather conditions on air pollution and eliminate the effect of total aerosol concentration change, a ratio of the initial weather conditions to the

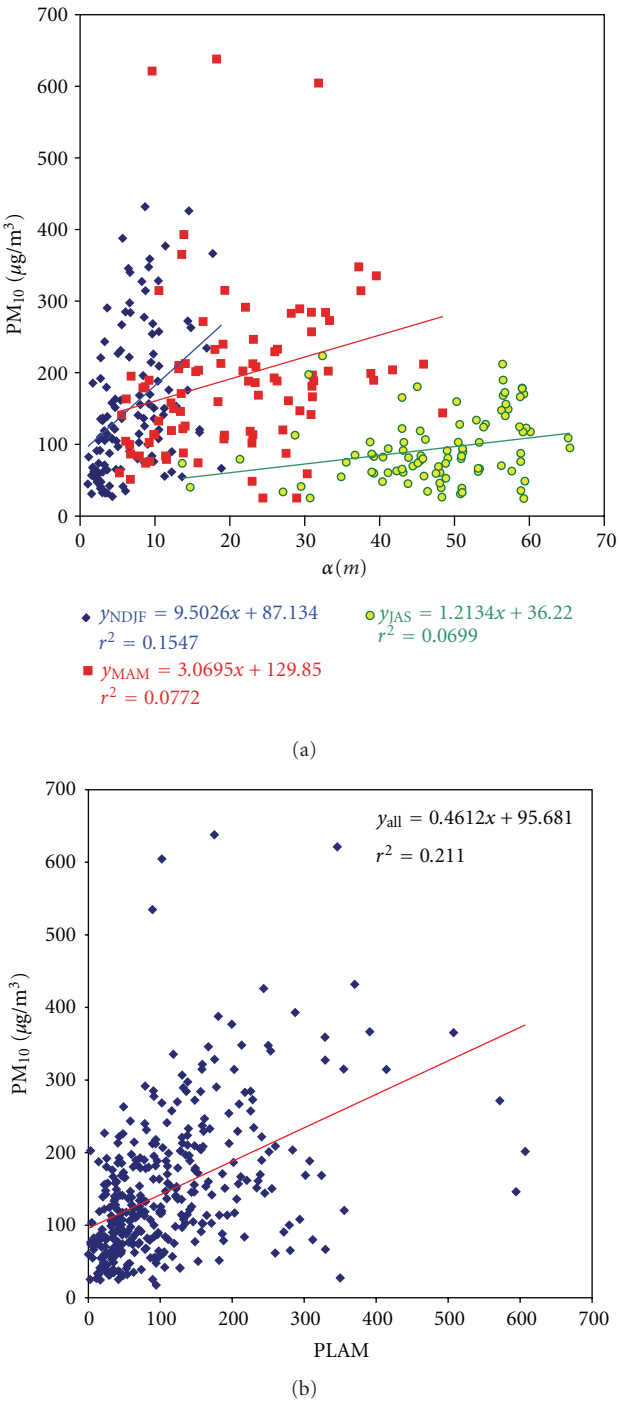

Figure 3: Correlations of $\alpha(m)$ and PLAM with PM_{10} observations for a year.

observed PM concentrations is introduced as the relative dynamic affect parameter μ:

$$\mu = \frac{\alpha(m)}{c'}, \tag{6}$$

where μ denotes the meteorological contribution increment per unit PM concentrations. Initial contribution of air pollution (c') implicitly contains the information of all the processes on PM before a forecast, including the emission contributions.

There exists a sharp seasonal variation in meteorological parameters. For example, the average temperature in Beijing can range from 28°C in summer to −8°C in winter, and relative humidity also varies a lot from summer to winter. The degree of the variation for $\alpha(m)$ with seasons is larger than that for PM_{10} observations. In order to derive a parameter applicable for a wider range of conditions, an adaptive function β', is introduced

$$\beta' = \frac{(1-\mu)^{i-1}}{\mu}, \tag{7}$$

which completes the definition of (2) for the PLAM.

For β' (μ, i), there exist several cases, depending on the size of the relative dynamic parameter value in this spectrum:

(1) $\mu \geq 1$, $i = 1$: favourable meteorological conditions for pollutants either to be diffused or to be maintained;

(2) $0.5 \leq \mu \leq 1$, $i = 2$: more adjustable weather conditions for pollutants to be accumulated;

(3) $\mu < 0.5$, $i = 3$: most favourable weather conditions for pollutants to be accumulated.

Figure 3 shows the correlations of $\alpha(m)$ and PLAM with PM_{10} observations for a year. The slope of the correlation and the magnitude of $\alpha(m)$ reflects the impact degree of meteorology on PM concentrations. In dry and cold season of Beijing and northern China area (NDJF), the observed concentration of PM_{10} can reach as high as $400 \sim 450\,\mu g\,m^{-3}$ and the initial meteorological influence parameter $\alpha(m)$ varies 0∼20. Figure 3(a) also indicates that the air pollution situation in the winter time of Beijing is very heavy. However, the influences and contributions of meteorological conditions on the high PM_{10} were not high (shown in blue dot). In hot and humid season of Beijing and northern China area (JAS), the concentration of PM_{10} observations is less than $200\,\mu g\,m^{-3}$. However, due to the hot and humid stabilizing weather conditions, $\alpha(m)$ is larger than that in the winter time, ranging from 40 to 70, which is the highest among all seasons (shown in green dot). In the transition season, that is, spring, (MAM), the concentration of PM_{10} observations can also reach as high as $400 \sim 600\,\mu g\,m^{-3}$ with a medium contribution and influence of initial meteorological $\alpha(m)$ (in red dot). The correlation coefficient (r) of PLAM for all season with PM_{10} observations reaches 0.46 ($R^2 = 0.2116$, Figure 3(b)), indicating that PLAM is a good indicator for air quality diagnosis.

Because the levels of air pollutants are usually controlled by a combination of meteorological variables within the stable air masses, the impacts of individual meteorological variables on air pollution may not be significant and/or may be cancelled each other, as they do not account for the interrelation between variables. PLAM, as an integrated index, considered the interactions among the meteorological variables such as the individual wind direction, temperature and hence reflected the better performance than any individual variable.

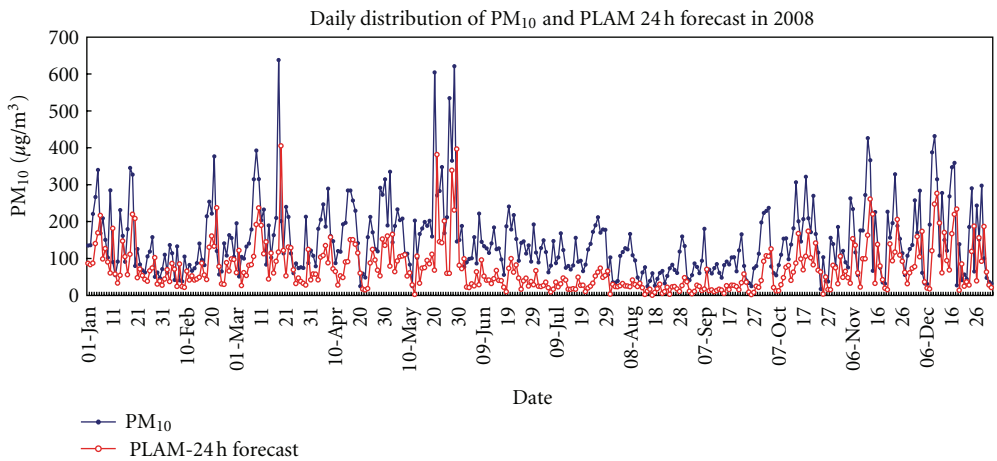

Figure 4: Daily PLAM distribution in 24 h forecasts, PM_{10} observed at NCOB from 1 January to 31 December 2008.

3. Annual Forecasts for 2008

To evaluate the performance of PLAM forecastability, an annual run was carried out to obtain the 24 hr forecasts of daily PLAM and compared with the observed PM_{10} at NCOB and the Air Pollution Index (API) defined by the Ministry of Environment of China taking into account of the air concentrations of NO_x, NO_2, SO_2, TSP, and PM_{10}. The API is calculated as follows:

$$I_i = \frac{\left(C_i - C_{ij}\right)}{\left(C_{ij+1} - C_{ij}\right)}\left(I_{ij+1} - I_{ij}\right) + I_{ij}, \tag{8}$$

where I_i is the API index for species i, C_i is the observed daily averaged concentrations for species i. C_{ij}, C_{ij+1} and I_{ij}, I_{ij+1} are the two standard daily averaged concentrations and API indices that are adjacent to the observed C_i and are determined from the lookup table (Table 2). The largest index for species i is regarded as the API index of the day. In China, SO_2, TSP, and PM_{10} are usually the major air pollutants and correlated very well [23].

Figure 4 shows the daily PLAM distribution in 24 h forecasts from 1 January to 31 December 2008. A good agreement was found between the forecasted and observed, including the daily variations, peaks and lows. There were a number of heavy pollution days between March and May as well as in September and December with PM_{10} greater than 200 $\mu g\,m^{-3}$, among which there existed several extreme high pollution episodes around March 18, May 20–22, and May 27-28 with PM_{10} > 200–637, 280–604, and 200–450 $\mu g\,m^{-3}$, respectively. These high episodes were all captured by the PLAM index. The features of comparison between the PLAM index forecast and PM_{10} observations at NCOB from 1 June to 31 August 2008 during the 2008 Olympic Games will be discussed in Section 4. The correlations between forecasted PLAM index and observed PM_{10} and API are shown in Figure 5. A correlation coefficient was achieved for 0.85 between the forecasts and API and 0.43 between the forecasts and observed PM_{10} for whole of the year 2008. All reached the significant level of 0.001. During the summer season from mid-June to late September, that is, 2008 Beijing Olympic Games period, the air quality was relatively high with low PLAM indices forecasted. Detailed forecasts will be given Figure 6 in Section 4.

Comparing Figures 5(a) and 5(b), API is calculated from the average PM_{10} measurements at different sites in the Beijing metropolitan area, indicating that the PLAM has the better capability to capture the regional pollution rather than a single site.

4. Applications of PLAM

4.1. Olympic Applications from June to September in 2008. Figure 6 shows the time series of the PLAM index and PM_{10} observations at NCOB from 1 June to 31 August 2008. During this period of time, the averaged PLAM index was small (<50) with a declining rate of 35%, which signaled an improving meteorology for the period. However, a much larger declining rate of 83% for PM_{10} was observed. Under normal conditions, the variations of PLAM and PM_{10} should be rather consistent. The significant discrepancy of the variation trend should be caused by some nonmeteorological factors. It is well known that very active emission control measures were taken during the 2008 Olympic Games [3]. It is likely that the effective emission controls have contributed to the large declining rate for the PM_{10} in Beijing. Excluding the meteorological influence, that is, PLAM, the emission control may have contributed to a 43% reduction in PM_{10} from June 1 to August 31, 2008.

To evaluate the performance of the PLAM method, the correlative analysis has been made on the 24 h PLAM forecasts and observations (Figure 7). A correlation coefficient was achieved for 0.8209 between the forecasts and API and 0.5924 between the forecasts and observed PM_{10}. All reached the significant level of 0.001.

The good agreement of the forecasted PLAM index with the API and PM_{10} indicates the ability of PLAM as a criterion for diagnosing air quality problem. The high correlation illustrates that the meteorology has a dominant control over the variation of air quality in Beijing.

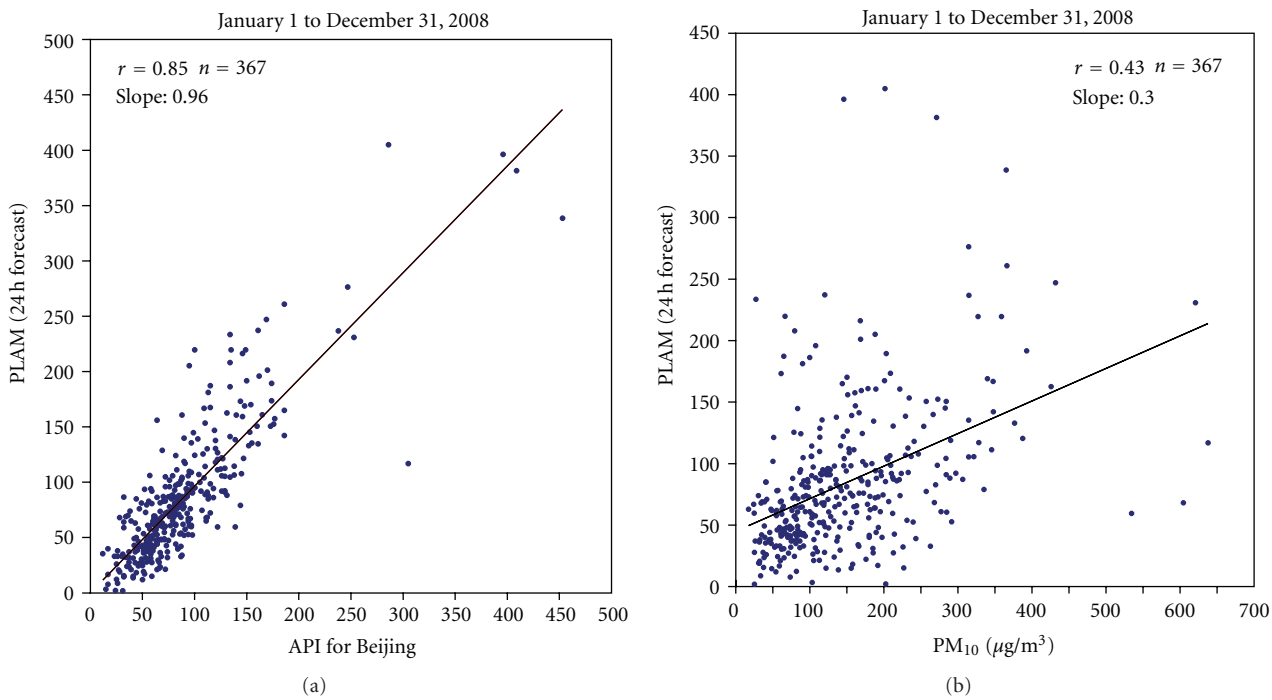

Figure 5: Correlations of 24 h PLAM forecast results with API of Beijing (a) and actual PM_{10} in Beijing (b) for the period from 1 January to 31 December 2008.

Table 2: Standard air pollutant concentrations and indices.

API		500	400	300	200	100	50
Pollutant concentrations (mg/m^3)	SO_2	2.62	2.100	1.60	0.80	0.15	0.05
	NO_x	0.94	0.750	0.565	0.15	0.10	0.05
	NO_2	0.94	0.750	0.565	0.28	0.12	0.08
	TSP	1.00	0.875	0.625	0.50	0.30	0.12
	PM_{10}	0.60	0.500	0.420	0.35	0.15	0.05

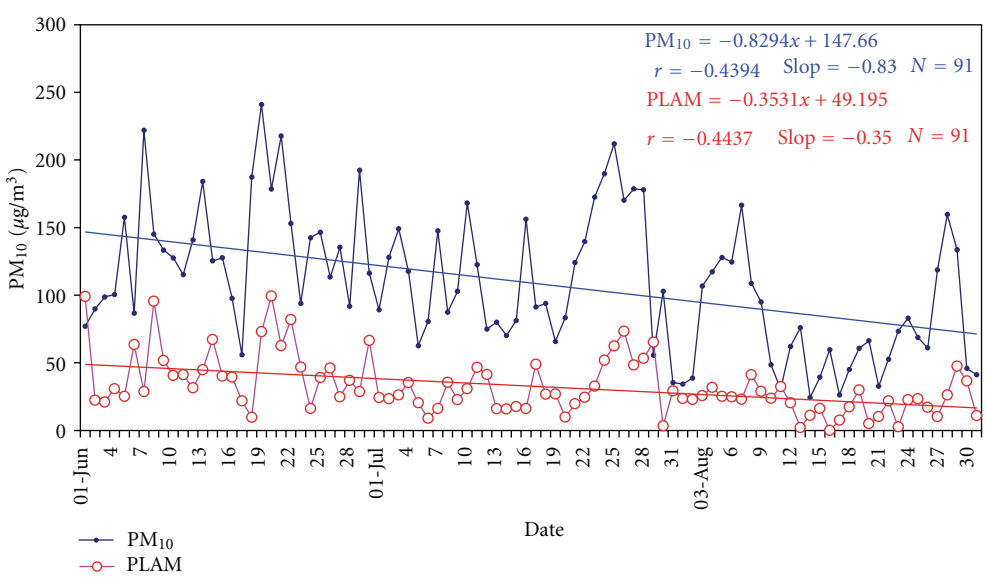

Figure 6: Daily PLAM distribution and PM_{10} observed in NCOB in Beijing.

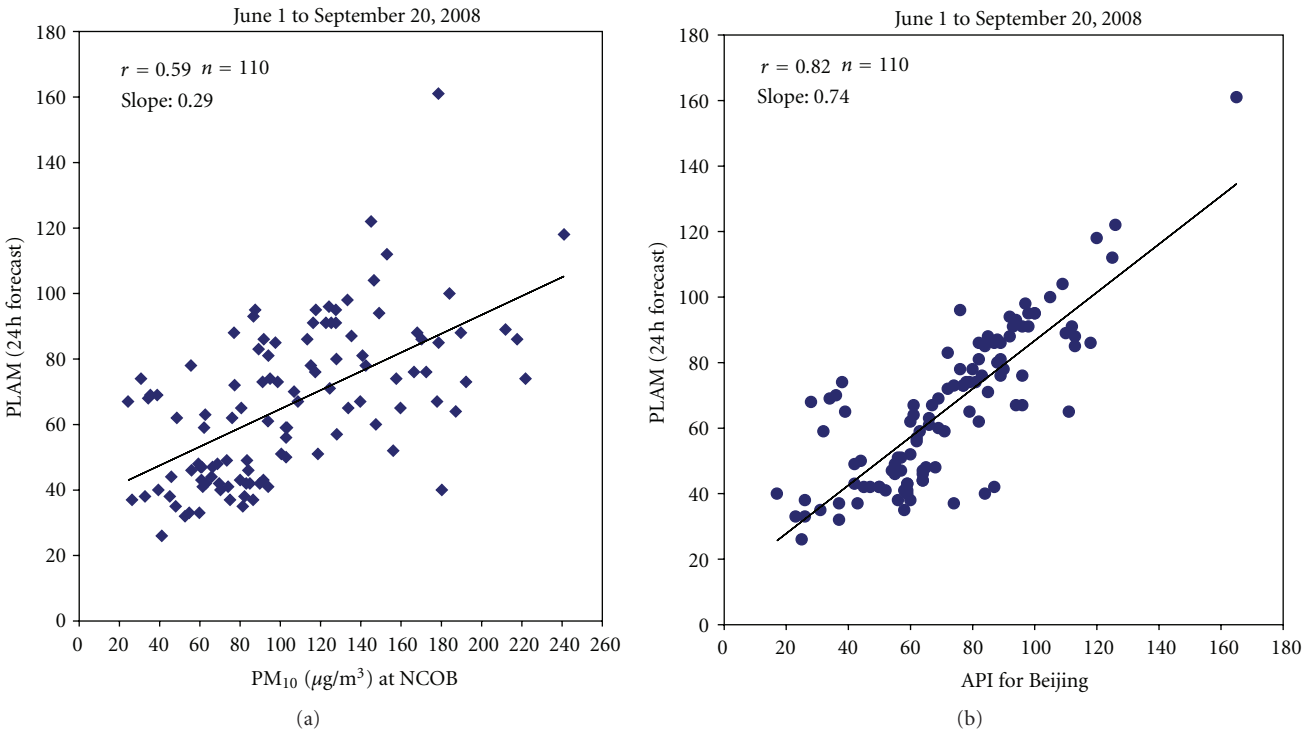

Figure 7: Correlations of 24 h PLAM forecast results with actual PM_{10} in Beijing Nanjiao (a) and API of Beijing (b) during the period of Beijing Olympic Game.

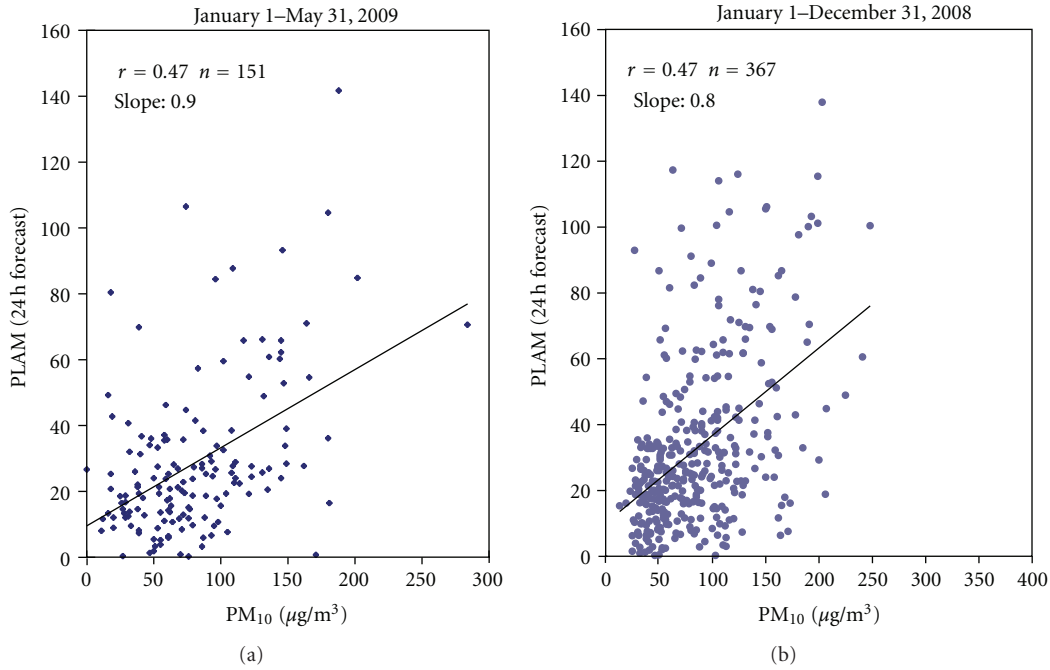

Figure 8: Correlation analysis between PLAM 24 h prediction and PM_{10} January 1–December 31, 2008 in Shanghai (a) and correlation analysis between PLAM 24 h prediction and of PM_{10} January 1–May 31, 2009 in Guangzhou (b).

4.2. PLAM Applications in Shanghai and Guangzhou. In order to check the applicability of the PLAM in various regions of China, two other cities were chosen, that is, Shanghai and Guangzhou, to evaluate the performance of the PLAM. Shanghai (31.1_N, 121.4_E, 8.2 m) is the largest city in Yangtze River Delta in East China with climatic characteristics different from North China and is located in the East Asian monsoon region with humid and rainy climate on the East coast of the Asian continent. Guangzhou (23.1,1_N 13.3_E, 7.3 m) located in the coast of South China has a subtropical climate features. Figure 8(a) shows correlation analysis between the PLAM 24 h prediction and PM_{10} during January 1–December 31 in 2008 in Shanghai. Figure 8(b) shows correlation analysis between the PLAM 24 h prediction and of PM_{10} during January 1–May 31 in 2009 in Guangzhou. From Figure 8 it can be seen that the PLAM also applies to eastern and southern areas of China for different climatic characteristics regions in China.

5. Conclusions and Discussions

A parameterized method has been developed to predict the air quality in BISA and used successfully during the 2008 Beijing Olympic Games. The following was found.

(1) Water vapor condensation (f_c), wet potential equivalent temperature (θ_e), air pressure, air temperature, relative humidity, and evaporability are found to be the key meteorological factors for diagnosing air pollution intensity.

(2) With the help of two independent data systems (PM_{10} values reported in API in Beijing and daily PM_{10} data collected by Beijing Nanjiao Observatory), the tests of PLAM performance showed that the forecasts have a cohesive correlation with them, reaching to a significant level.

(3) It is found that the correction factor β' enables the ability for PLAM to diagnose the observed PM_{10} concentrations all year round. The $24 \sim 72$ h forecasts by PLAM provided valuable services for the day of opening ceremony and subsequent events during the whole Beijing Olympic Games. PLAM also was applied to eastern and southern areas of China for different climatic characteristics regions in China.

Acknowledgments

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