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Overview of Urban $PM_{2.5}$ Numerical Forecast Models in China

Nianliang CHENG[1,2*], Hongxia LI[3], Fan MENG[4], Fahe CHAI[4]

1. College of Water Sciences, Beijing Normal University, Beijing 100875, China; 2. Beijing Municipal Environmental Monitoring Center, Beijing 100048, China; 3. Institute of Advanced Technology, Sun Yat-sen University, Guangzhou 510275, China; 4. State Key Laboratory for Environmental Criteria and Risk Assessment, Chinese Research Academy of Environmental Sciences, Beijing 100012, China

Abstract This paper made an overview and introduction of urban $PM_{2.5}$ numerical forecast models in China, and mainly introduced air quality simulated forecast system of Beijing, Shanghai, and Nanjing. On this basis, it discussed development direction and existing problems of urban $PM_{2.5}$ forecast models in China. Besides, it revealed significance of numerical models for air quality forecast. In a heavy air pollution of Beijing - Tianjin - Hebei in October 6 – 12 th of 2014, the forecast results indicated that pollutants was transported from south to north, so the regional transport exerts great influence on concentration of $PM_{2.5}$.

Key words $PM_{2.5}$, Air quality, Pollution forecast

1 Introduction

In recent years, with rapid development of national economy, acceleration of urbanization, and expansion of industrial scale, the situation of air pollution is increasingly serious[1-2]. Air pollution resulted from fine particulate matter $PM_{2.5}$ greatly threatens public health and its negative influence has been paid more attention to by human beings[3]. $PM_{2.5}$ is named fine particulate matters in air, consisting of primary particulates and secondary particulates with diameters less than or equal to 2.5 microns in size, about 1/20 of hair diameter[4]. The new *Ambient Air Quality Standard* (GB3095 – 2012) included $PM_{2.5}$ into conventional ambient air quality evaluation, which is the first $PM_{2.5}$ standard in China.

In January 2013, 10 provinces in central China and east China experienced serious haze pollution, arousing wide attention of government and the public. In the period of Twelfth Five-Year Plan, it is very necessary and urgent to launch urban $PM_{2.5}$ forecast and prediction, develop suitable urban air quality system, and provide accurate, timely, and comprehensive information for administrative department.

Air quality forecast is a complex system work and it is a hot spot and difficult problem of present environmental science[6]. According to methods of forecast, urban air pollution forecast can be divided into potential forecast, statistical forecast, and numerical simulation forecast. With perfect theoretical foundation, reasonable model design, and forecast effect of regular time and quantity, the numerical forecast has become development trend of air pollution forecast. Compared with potential forecast and statistical forecast, the numerical forecast involves multiple criteria (city and weather), many pollutants (chemical reaction of dozens of substances), consideration of many processes (pollutant transfer, diffusion, chemical transport and removal), and high spatio-temporal resolution[7].

The aerosol model is an essential part of air quality forecast and it was developed in the 1980s[8]. Using models to simulate aerosol size and changes of chemical composition is much more complex than to simulate changes of gaseous pollutants. When processing aerosol, it is necessary to consider how to characterize total particulates, total mass, distribution of particulates, and chemical component of different size of particulates, as well as major physical and chemical processes of particulates[9]. Fig. 1 illustrated aerosol simulation process.

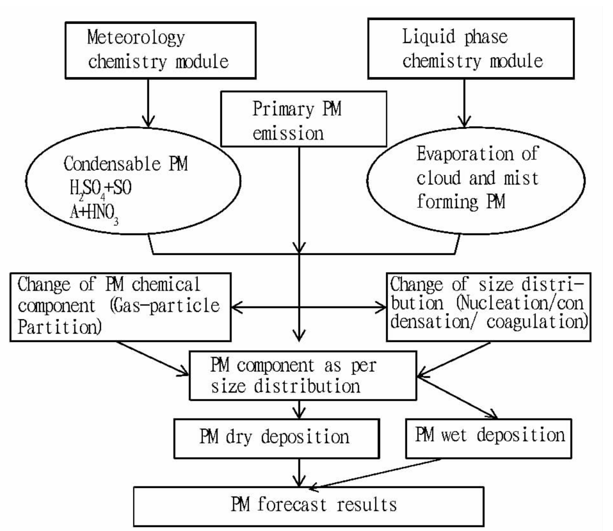

Fig. 1 Aerosol simulation process

Urban air quality numerical model has already had decades of development history in north America and Europe. In foreign countries, common models include American CMAQ and CAMx, Canadian MC2-CALGRID, Germany EURAD, and England Your Air system. China's air quality forecast starts later and fundamental research basically remains passive trace state[5]. In the 1980s, Beijing, Shenyang, Lanzhou, Tianjin and Nanjing started to pre-

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* Corresponding author. E-mail: 15001195306@163.com

dict urban air quality using statistical method. In the 1990s, numerical forecast model of urban air quality obtained certain development. From 2000, China National Environmental Monitoring Center organized 47 key environment protection cities to launch urban air quality forecast, but only few cities made numerical forecast. The CAPSS urban air pollution numerical forecast system recommended in *Environment and Development*[2000] *No.* 231 does not rely on list of urban pollution source emission and adds forecast of ozone, but it is still unable to simulate forecast of $PM_{2.5}$. Since entry to the 21st century, air pollution forecast and pre-warning get wide attention of both domestic and foreign experts and government officials. The *Action Plan for Air Pollution Prevention and Control* (National Development[2013] No. 37) issued in 2013 clearly requires environmental protection department to strengthen cooperation with relevant departments and establish heavy pollution monitoring and pre-warning system.

2 Classification of forecast models

Development of numerical model experiences three stages: Gauss mist-plume model, Euler model, and Air Quality Integrated Index model. We mainly introduced 4 common air quality numerical models.

2.1 NAQPMS NAQ PMS (Nested Air Quality Forecast Modeling System) was developed by Institute of Atmospheric Physics in Chinese Academy of Sciences (IAP of CAS) mainly includes Meso-Scale Weather Forecast subsystem and Air Quality Forecast subsystem, suitable for urban and regional air quality forecast. We used aerosol thermodynamic model (ISORROPIA1.7) to calculate component state of inorganic aerosol, adopted an advanced sand dust uplifting mechanism, and added secondary organic aerosol module. This model considers two types of artificially emitted precursors (toluene and other aromatic hydrocarbons) and four types of biologically emitted precursors (isoprene and monoterpenes), and the process of generation of secondary organic matter SOA through photochemical reaction. The heterogeneous chemical reaction model of aerosol surface mainly focuses on influence of sulphides and nitrides. At present, NAQPMS has basically realized parallelization and business of model system, and obtained wide approval. This model is already applied in many provinces and has obtained better effect[10].

2.2 CMAQ CMAQ is a multiple module integrated multi-scale nested grid three-dimensional Eulerian, issued by EPA in 1998, suitable for regional multi-scale environment simulation and evaluation. CMAQ model has perfect chemical mechanism and aerosol module and has the ability of predicting secondary pollution. Aerosol process of CCTM chemical reaction mechanism involves removal of dry deposition, mutual reaction of aerosol and cloud droplet, wet removal, homogeneous nucleation process of sulphuric acid / vapor system, organic aerosol component generated from gaseous precursor, particle condensation and coagulation growth[11]. The aerosol model is evolved from regional particulate model (RPM) established by Binkowski and Shanker (1995), while the RPM is based on Regional Acid Deposition Model (RADM)[12]. Aerosol particulates are divided into fine and coarse particulates. Based on thermodynamic balance principle, we calculated chemical composition of inorganic aerosol, and then calculated gaseous and aerosol composition and balance concentration of components after inorganic matters such as H_2SO_4, NH_3, HNO_3, sea salt, and H_2O reach thermodynamic balance in gaseous and aerosol phase. Secondary inorganic aerosol mainly considers mixture of NH_3-H_SO_4- HNO_3- H_2O, secondary organic aerosol (SOA), calculated using Pandis organic aerosol output efficiency method[13].

CMAQ model is universal, flexible and developable, rapid development in recent years has made it become one of the air quality simulation systems with widest application[14]. At present, NOAA and EPA have developed nationwide air quality forecast (NAQF) system using Eta-12 model and CMAQ. David G Streets also simulated the air quality of 2008 Beijing Olympic Game stadium using CMAQ model. China has made extensive researches on CMAQ numerical simulation forecast. In national 973 project "air, water and soil environment pollution and control mechanism for capital Beijing and surrounding areas", Liu Yu *et al* transplanted new generation air quality model CMAQ to Sunway supercomputer of State Meteorological Administration and realized professional air quality simulation of north China. Later, researches transplanted it to IBM supercomputer of National Meteorological Center, and took MM5 numerical forecast products as meteorological field to connect numerical business system of meteorological center, to provide reference for national and provincial level air quality forecast[9]. Feng Yerong *et al*[15] successfully applied CMAQ/MM5/SMOKE air quality model in south China areas and made analysis on haze weather generated from tropical cyclone in Delta of the Pearl River. Compared with NAQPMS, this model is already widely applied in simulation and forecast evaluation researches of many provinces and cities.

2.3 CAMx Developed by ENVIRON Company on the basis of UAM-V model, CAMx model is used to make comprehensive evaluation of gaseous and particle state air pollutants in urban and regional scale. The most distinctive benefits of CAMx include two-way nesting and elastic nesting, Plume-in-Grid (PiG) module, Ozone Source Apportionment Technology (OSAT), and Particulate Matter Source Apportioning Technology (PSAT), *etc.* Besides, vertical layer structure is defined externally, so the height of each layer can be defined as function of any space or time. Such flexibility in defining horizontal and vertical grid structure makes CAMx adapt to meteorological model used to provide input field for environmental model, so it is widely applied in China[16].

2.4 WRFCHEM WRFCHEM model is the Weather Research and Forecasting (WRF) model coupled with Chemistry recently developed by the United States. It integrates atmospheric chemistry into WRF developed by National Center for Atmospheric Research (NCAR). The largest benefit of WRFCHEM is complete coupling of meteorological model and chemical transport model in time and space resolution and realizes real online feedback. This model remains preliminary application stage in China and the forecast application is relatively few[17].

3 Application of models

In provinces and cities already implementing air quality forecast, the technical framework generally consists of statistical model, numerical model, and subjective revision. According to the *Notice about Printing Implementation of Air Quality Forecast in Provinces and Cities of China* (No. 2014.02) issued by China National Environmental Monitoring Center[18], 11 provincial stations launched air quality forecast, including Beijing, Tianjin, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Hubei, Hunan, Shaanxi and Qinghai, 9 provincial capitals (Taiyuan, Shenyang, Nanjing, Hangzhou, Jinan, Wuhan, Guangzhou, Chengdu, and Xi'an), and 2 cities under direct planning by the state (Qingdao and Shenzhen). There are 15 provincial stations, 13 provincial capitals and 3 cities under direct planning by the state having forecast capability establishment plan. Table 1 listed implementation of part of cities already implementing air quality numerical forecast system. It shows that Beijing, Shanghai, Nanjing and Guangzhou started early and the development level is relatively higher, while some cities and provinces are still at preparatory stage. The models they select are basically CMAQ, CAMx, NAQPMS, and WRFChem. In this study, we made a brief introduction using data of Beijing, Shanghai, and Nanjing air quality numerical forecast models.

Table 1 Development of air quality forecast models of domestic cities

City	Forecast organization	Time of launching the forecast	Forecast model
Beijing	Beijing Municipal Environmental Monitoring Center	2001: API forecast; 2013: AOI forecast	CMAQ + CAMx + NAQPMS
Shanghai	Shanghai Environmental Monitoring Center	September 2013: formal forecast	CMAQ + CAMx + NAQPMS + WRF-CHEM
Guangzhou	Guangzhou Environmental Monitoring Center	August 2013: in-house formal forecast	CMAQ + CAMx + NAQPMS
Tianjin	Tianjin Environmental Monitoring Center	November 2013: formal forecast	AUROAR
Chongqing	Chongqing Environmental Monitoring Center	Preparatory stage	CMAQ + CAMx + NAQPMS
Jinan	Jinan Environmental Monitoring Center	December 2013: formal forecast	CUACE
Shijiazhuang	Air Warning Center	Preparatory stage	NAQPMS
Hangzhou	Hangzhou Environmental Monitoring Center	December 2013: formal forecast	WRFCHEM
Nanjing	Nanjing Environmental Monitoring Center	2001: API forecast; 2013: AOI forecast	CMAQ + CAMx + WRFCHEM
Shenyang	Shenyang Environmental Monitoring Center	November 2013: formal forecast	No

3.1 Air quality forecast system of Beijing As early as 2001, Beijing launched the air quality numerical forecast. Later, taking 2008 Olympic Game as an opportunity, it realized system upgrade of Beijing air quality forecast technology framework, mainly including development and application of dynamic statistical forecast system, construction and application of comprehensive forecast platform, and setup of numerical forecast models. The numerical forecast system includes NAQPMS model, CMAQ model, and CAMx model. It adopts unified model region setting, unified pollution emission list and SMOKE model to dispose emission sources, and it is driven by unified meteorological model MM5. Besides, the grid region is provided with four layer nesting: the first layer covers all regions of China, the second layer covers north China, the third layer covers Beijing, Tianjin and Hebei, and the fourth layer covers Beijing. Fig. 2 illustrated frame structure of this numerical forecast system.

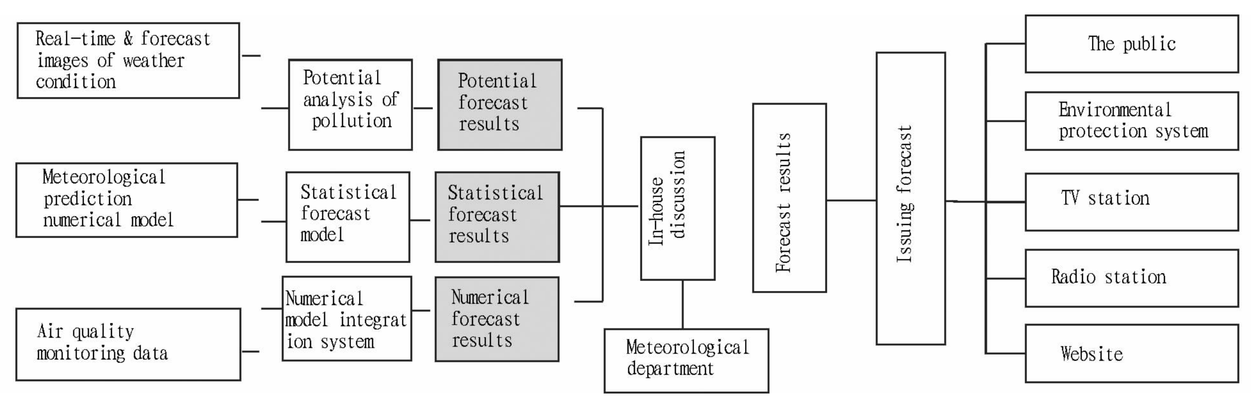

Fig. 2 The framework of air quality forecast model system of Beijing[19]

Each air quality model has its own characteristic in different station simulation effect. To optimize air quality forecast results, arithmetic geometric average and weight integration methods were used to issue numerical forecast results, and various statistical parameters were calculated to test the level of this air quality numerical forecast. Application research indicates that the accuracy rate of this forecast model results is higher than 80%. Considering no pollution forecast method has absolute predominance, we made comprehensive integration of various forecast methods, namely potential pollution forecast → statistical numerical forecast → heavy pollution day indicator criterion → comprehensive forecast results → heavy pollution day warning issue. We established technical procedure for heavy pollution warning of Beijing based on Meso-Scale meteorological forecast products, to more accurately recognize and forecast time and cause of heavy pollution process.

3.2 Air quality forecast system of Shanghai Shanghai built air quality forecast system with the aid of Expo 2010 Shanghai and made improvement in recent years. This system consists of meteorological model, integrated numerical forecast model, statistical model, and various observation and information tools.

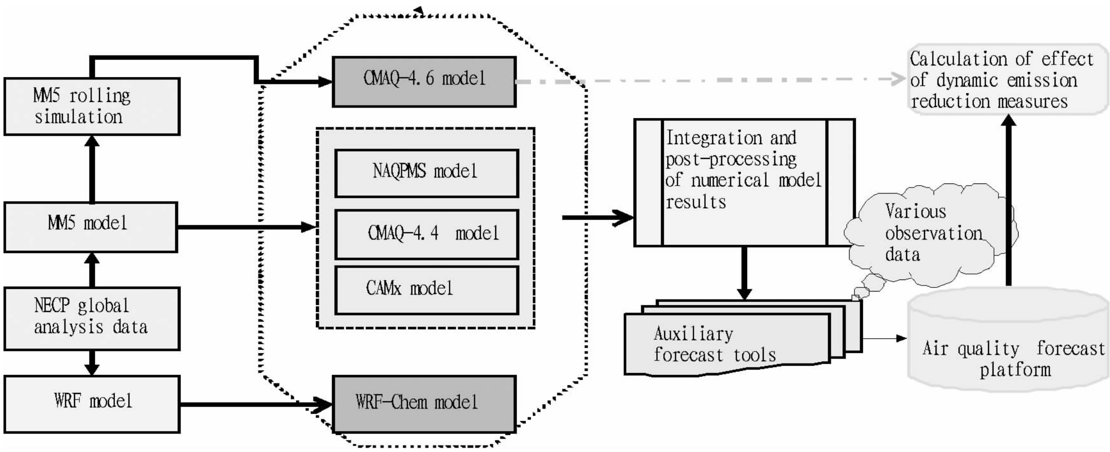

Fig. 3 The framework of air quality forecast model system of Shanghai[20]

Air quality forecast of Shanghai is jointly implemented by Environmental Atmosphere Monitoring Office and Information Technology Department of Shanghai Environmental Monitoring Center. In 2013, it established Yangtze River Delta Air Quality Forecast and Prediction Center. On August 1, 2013, it made in-house trial forecast. From September 1, 2013, Shanghai Environmental Monitoring Center started to issue AQI forecast to the public. The air quality forecast and warning system of Shanghai is further optimized and improved on the basis of Expo 2010 Shanghai. Integrating with technologies newly added in recent years, the system consists of multi-model integrated forecast system, straw burning warning system, automatic alarming system, and joint consultation system.

3.3 Air quality forecast system of Nanjing To welcome Nanjing 2014 Youth Olympic Games and establish urban air quality forecast ability, Nanjing built air quality and haze day forecast methods. Methods mainly include potential forecast, statistical forecast and numerical forecast. Potential forecast is to make qualitative or semi-quantitative prediction of future atmosphere environment condition taking weather condition and meteorological element indicators as basis. Statistical forecast mainly adopts BP neural network method, and the topology includes input layer, hidden layer and output layer. BP network structure is determined through determining number of network layers, number of nodes in each layer, transfer function, initial weight coefficient, and learning algorithm. Numerical forecast is mainly based on WRF-CHEM, RF-CMAQ, RegAEMS, and NJU_CAQPS, and provided with necessary improvement, to build urban/regional haze day and air quality forecast system. Nanjing Environmental Protection Bureau formally issued air quality forecast on November 1, 2014 on its website. It mainly forecasts air quality condition, grade, and primary pollutants from zero hour to 24 hour of the same day, and the statistical accuracy is about 70%.

4 Case analysis

On October 6-12th, 2014, Beijing-Tianjin-Hebei was attacked by a heavy pollution. The air quality level in October 8-10 th was heavy pollution; on October 11 th, it reached hazardous pollution and the average daily value $\rho(PM_{2.5})$ was up to 329 $\mu g/m^3$. Fig. 5 depicted spatial distribution of $PM_{2.5}$ concentration in Beijing-Tianjin-Hebei at 20:00 after linear interpolation using CAMx model (the grid resolution is 6 km), which was basically consistent with measured value (http://113.108.142.147:20035/emcpublish/). On October 6 th, the air quality of Beijing-Tianjin-Hebei was excellent; on October 7 th, Beijing-Tianjin-Hebei changed to area of high barometric pressure and southerly air current flowed to north and then to Beijing with high concentration of air pollutants; on October 8 th and 9 th, air diffusion condition became worse and regional pollution was further deteriorated; $PM_{2.5}$ concentration was high and evenly distributed, and the level reached hazardous pollution; on October 10 th, in the action of higher southerly wind, pollutants gradually gathered due to influence of terrain of Taihang Mountain; at night of October 11 th, cold air attacked Beijing, the $PM_{2.5}$ concentration of Beijing dropped sharply from 200 $\mu g/m^3$ to 10 $\mu g/m^3$, the air quality became excellent, while southeast of Heibei Province was still at moderate pollution level; on October 12 th, influenced by cold high barometric pressure moving eastward and southward, pollutant concentration gradually declined from north to south, and air quality of most areas of Beijing-Tianjin-Hebei turned excellent.

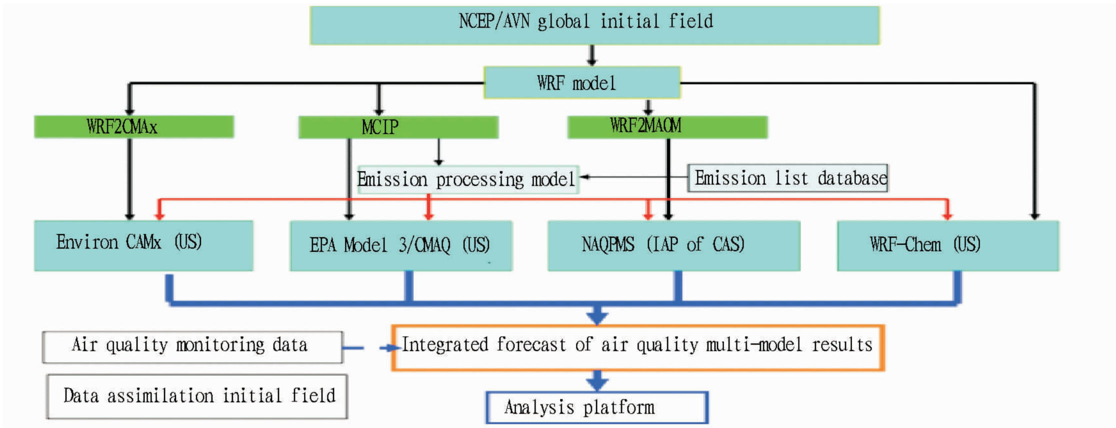

Fig. 4 The framework of air quality forecast model system of Nanjing[21]

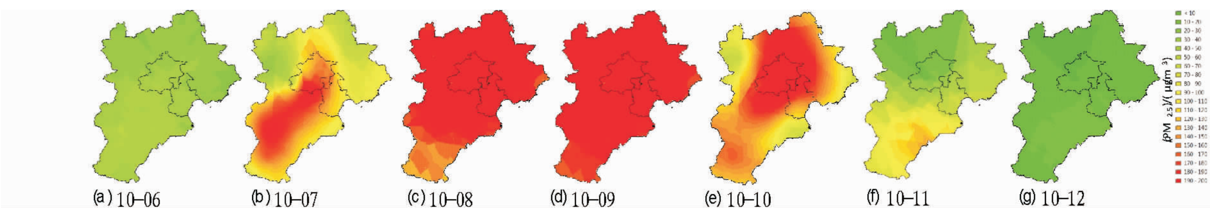

Fig. 5 Forecast of $PM_{2.5}$ spatial distribution at 20:00

Fig. 6 illustrated $PM_{2.5}$ regional transport rate of Beijing, Tianjin and Shijiazhuang in this time of heavy pollution caculated by PAST technology, showing the regional transport rate had significant temporal change with pollution degree. Before and after the heavy pollution, the outer source transport rate was below 20%; with deterioration of pollution, the outer source transport rate rose; through calculation, the average outer source transport rate of $PM_{2.5}$ in Beijing, Tianjin and Shijiazhuang during October 7-10 th was 57%, 48% and 27% respectively, so regional transport plays a great role in $PM_{2.5}$ concentration of Beijing.

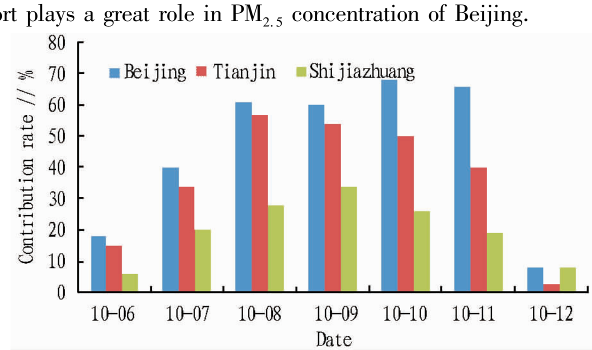

Fig. 6 Contribution rate of outer sources to $PM_{2.5}$ concentration of different cities during heavy pollution

Streets *et al*[22] using CMAQ model simulated the contribution of Hebei Province to $PM_{2.5}$ concentration of Beijing in the action of steady south wind reached 50-70% during 2008 Olympic Games; Wang *et al*[23] using CAMx model calculated the contribution rate of outer source to $PM_{2.5}$ concentration of Shanghai, the result was close to 50%; Wu *et al*[24] using CAMx model calculated sources of $PM_{2.5}$ concentration of Guangzhou in spring and found 31.7% came from regional transport; Xue Wenbo *et al*[25] using CAMx model simulated and calculated average $PM_{2.5}$ concentration of Beijing-Tianjin-Hebei, Yangtze River Delta, and Pearl River Delta regions and the contribution rate reaches 22%, 37%, and 18% separately, and the contribution rate of outer source to $PM_{2.5}$ concentration of Shandong reached 41%.

Forecast results of this study are comparable with other studies, while there are still differences for following reasons: (i) lack of studies on different regions and long time trans-regional transport rules of $PM_{2.5}$ and major component; (ii) different space resolution, emission source list, parameter setting and calculation methods.

5 Problems and prospects

At present, China's air pollution forecast model system has considerable development, but compared with foreign countries, there are still problems of inadequate pollution source list and low accuracy of forecast. China is still faced with challenges of atmospheric environment, we must further improve atmospheric environment numerical model.

(i) Establishing perfect pollution forecast system. There are problems of large error of pollution sources, few forecast items, limited coverage, and low forecast accuracy in domestic forecast models. Test of model forecast results is also an essential part of urban air quality forecast system. Thus, it is feasible to develop evaluation model to evaluate consistency with spatial distribution and time change of measured values, so as to improve fine forecast effect in the process of heavy pollution.

(ii) Constantly expanding new fields of studies of atmospheric environment simulation forecast. Some new research technologies and fields, such as multi-model integrated forecast technology, pollution source assimilation technology, and aerosol microphysical process studies also bring many new ideas and challenges.

(iii) Researching and developing graphical interface and forecast products. Diversified forecast models and products provide rich reference information and provide timely and accurate forecast warning basis for travel of the public and decision making of government.

(iv) Combining with other technologies, such as 3S and GIS technologies. Remote sensing technology takes space as information acquisition platform and has wide monitoring scope, rapid speed, and low cost. Besides, it is convenient for long-term dynamic monitoring and is able to find pollution source and diffusion state difficult to be revealed by conventional methods. Using GIS technology, it is able to see current air quality condition and forecast information of different time through clicking the corresponding region in website. Combination of forecast models with other technologies can provide better and more detailed references for warning and forecast and generate different forms of warning and forecast products for management department.

(v) Combining numerical forecast and subjective experience. Numerical forecast models automatically calculate forecast results already generated. This is mainly influenced by models themselves and their performance. Subjective experience guides forecast personnel to make forecast according to accumulated knowledge and other auxiliary data. Thus, there are many uncertain factors and may be accidental, but the forecast results are closer to actual situations. Finally, the forecast results are combination of subjective and objective forecast.

(vi) Improving corresponding regulations and requirements. Domestic urban air quality forecast has not established corresponding regulations and requirements and most works are implemented independently. In certain time and period, demands and concern have large fluctuation, and it is difficult to form constant motive force. Besides, meteorological department always strives for air quality forecast business. Demands and pressure rapidly expand, so environmental protection department must bring into play their subjective initiative, use their existing advantages, launch forecast of serving the public and management department. Standardized working methods and well-established assessment system are very necessary and need to be improved.

(vii) Combining forecast and management. The ultimate purpose of model forecast is to provide the public with air quality forecast and warning information services, provide information support for pollution prevention and control decisions of management department, and provide technical guarantee for joint prevention and control of air pollution and emergency response in key areas. This needs fine forecast of heavy pollution through combining forecast and management.

(viii) Strengthening construction of forecast team. It is recommended to strengthen construction of forecast team, consolidate in-house technical personnel to tackle key and difficult problems, and constantly deepen the strategic cooperation with relevant colleges and universities.

From January 1st, 2015, Ministry of Environmental Protection officially issued real-time monitoring data of all air quality monitoring stations at the third stage of new standard. In the 338 cities, there are 1436 monitoring stations and all of these stations will monitor air quality using new standard. Distribution of monitoring stations is not simple and it needs full consideration of feeling of the public. China is vast in territory, so it is impossible to establish perfect air quality monitoring network like the United States in short term. As an extremely effective research tool, the air quality forecast model can realize numerical simulation of multiple scale and multiple processes. Also, it is able to forecast $PM_{2.5}$ concentration and change trend in different seasons and different regions, obtain background concentration and forecast concentration of different stations, and obtain simulation results of point sources, non-point pollution and moving sources of different regions through analyzing sources of various pollutants. Through fully using monitoring and simulating forecast results, it is able to provide effective and comprehensive information for management department, so as to take necessary emergency measures to minimize adverse effect of $PM_{2.5}$ pollution. Combining $PM_{2.5}$ concentration of different regions in different meteorological conditions, government may promulgate highly restrictive and mandatory emission standards to improve regional air quality, and continue to do cooperation of emission reduction, rather than simply stressing $PM_{2.5}$ forecast.

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opportunity of potato staple food development, boost potato industry of Zhejiang Province, promote consumption, expand use of winter fallow field, increase farmers' income, and raise the grain self-sufficiency level of Zhejiang Province.

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