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Review Article

National Environmental Meteorological Services in China

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The environmental meteorological services in China are concerned with atmospheric environmental quality, which is directly related to human activities and affects human health. In recent years, air pollution and other environmental problems have attracted nationwide attention in China, so the environmental meteorological services have been developed rapidly. To provide better meteorological monitoring and forecasting services, the Environmental Meteorological Centre of China Meteorological Administration was established in March 2014 by integrating the resources of various national service units. We review the development of China's national environmental meteorological services and highlight their current status including major technological capabilities. We also explore future trends of the national environmental meteorological services by analysing deficiencies, gaps in supply and demand, and capabilities of the current environmental meteorological services.

1. Introduction

Routine environmental meteorological services (EnMet services) by the China Meteorological Administration (CMA) include monitoring, forecasting, and early warning of variables such as fog, haze, and dust. These services are relatively mature. In recent years, fog, haze, and dust occur frequently. Air pollution, particularly high concentrations of fine particles, has become an increasingly serious issue in China [1–4] due to rapid economic and social developments. The Central Committee and the State Council regard air pollution control as an important component in ecological civilization construction and introduced the "Air Pollution Prevention Action Plan" in 2013. The CMA introduced the "Environmental Meteorology Services Development Guidance" to help nationwide meteorological departments carry out EnMet services in 2014. *Local meteorological departments* in some large- and mid-size cities have actively conducted diverse EnMet services, and these services have attained a large operational scale because of their continuous developments. The Shanghai Municipal EnMet Centre began to release its ozone forecast to the public in 2007 and started air quality forecast at subdaily time scales of morning, afternoon, and night in 2013. The Jing-Jin-Ji (which stands for Beijing-Tianjin-Hebei province) EnMet Centre was established in 2013, which provides forecast and early warning for heavy air pollution, fog, and haze.

At current stage, the EnMet services are generally concerned with atmospheric environment quality issues that are linked to human activities and directly impact human health. They include the following: (1) monitoring, forecasting, and warning for atmospheric environment and atmospheric composition; (2) health related EnMet forecasting services, including UV intensity, pollen concentration, air negative oxygen ions, comfort degree of human body, and meteorological forecasting index related to occurrence and prevalence of diseases; (3) EnMet emergency warnings, including leaks of radioactive material and toxic gases.

The Environmental Meteorological Centre (EMC) of the CMA was established in March 2014. It is responsible for providing national EnMet monitoring and forecasting services and coordinating related efforts. In this paper, we summarize the operation and development of the national EnMet services and the challenges and demands they face.

2. Current State of the EnMet Services *of EMC*

The establishment of EMC aimed to improve the capability and levels of the national EnMet services by integrating national research and development resources. The EMC is affiliated with the National Meteorological Centre and receives supports from the National Satellite Meteorological Centre, the CMA's Meteorological Observation Centre, and the Chinese Academy of Meteorological Sciences (CAMS).

2.1. Main Responsibilities of the National EnMet Services. Consider the following.

(1) The national EnMet services include monitoring, forecasting, and warning of fog, haze, dust, air pollution *event*, meteorological conditions, and city air quality; it also includes forecasting quality assessment. EnMet emergency response service tasks for important or unexpected events have also been established.

(2) Guidance products and technical support including national atmospheric environmental model products, diagnostic analysis, and objective correction products based on model outputs, as well as subjective forecast, for various meteorological departments have been provided. Decision-making services as well as professional and public meteorological services for governments, industries, and society stakeholders are offered.

(3) National EnMet forecasting consultation and regional heavy air pollution warnings have been organized, including consultation with the Ministry of Environmental Protection and internal consultation with the meteorological departments.

(4) Development plans, technology standards, and regulations of the EnMet services are formulated. Since its establishment, the EMC has participated in the revision of the national standards for haze observation and forecast and formulated the standards for atmospheric pollution meteorological condition assessment.

(5) The EMC is responsible for leading EnMet research programmes. The core technical responsibility of the EMC is to provide national atmospheric environmental model products. CMA's Unified Atmospheric Chemistry Environment (CUACE) is a fully online coupled meteorological/chemistry/aerosol system, developed by CAMS, which has been in operation since 2007 [5–7]. The CAMS is currently leading a research project covering atmospheric composition data assimilation, pollution source inversion based on ensemble Kalman filter, and bidirectional feedback mechanism of heavy air pollution and weather. Its purpose is to enhance forecasting skill of their coupled model.

2.2. EnMet Product System at the EMC. Products of the EnMet services can be divided into three categories, namely, monitoring, forecasting, and assessment.

2.2.1. EnMet Monitoring. EnMet monitoring refers to the products involved in monitoring and analysing the occurrence, development, dissipation, scope, and intensity of fog, haze, dust, and heavy air pollution, based on data from routine meteorological observations, atmospheric composition monitoring, and satellite remote sensing. Satellite remote sensing monitoring can cover a vast area, which makes up for the lack of ground monitoring stations in many areas. Based on FengYun (FY) polar and FY geostationary orbit satellites, real-time monitoring has been conducted for haze (optical image monitoring), haze pollution index, haze optical thickness, fog, and dust (http://rsapp.nsmc.org.cn/uus/index.jsp) [8, 9].

2.2.2. EnMet Forecasting and Warning. Currently, the EMC produces and publishes nationwide meteorological conditions associated with air pollution, city air quality, and forecasting and warning products for visibility, fog, haze, and dust (http://www.nmc.cn/publish/haze.html). Among them, the forecast of meteorological conditions associated with air pollution was officially launched on September 1, 2013, which included dilution, diffusion, accumulation, and scavenging capacities of atmospheric pollutants; it was designed to use six levels from good to bad consistent with the national air quality standards [10].

In 2014, a meteorological index of firework burning forecast service was developed for the Spring Festival holiday season. By considering the meteorological factors affecting the safety of firework burning and the spread of pollutants, the index covers four levels from low to high: suitable, fairly suitable, unsuitable, and very unsuitable [11].

2.2.3. EnMet Assessment. EnMet assessment is essential for proposing proper strategies for the prevention and control of atmospheric pollution. By analysing variations of air pollution, pollution related meteorological conditions, and satellite observation data, the effects of emission control measures during major social events such as the 2008 Beijing Olympic Games, 2010 Guangzhou Asian Games, and 2014 Beijing APEC Conference were evaluated [12–18]. Regional transport contribution to heavy haze in big cities was discussed by simulating the source of air pollutants in an atmospheric environmental model [19, 20]. Based on the atmospheric environmental products of global meteorological satellites, a lot of research was carried out to reveal spatial and temporal distribution and long-term trends of China's regional atmospheric quality and greenhouse gases [21–25].

Based on the technical achievements provided by the above-mentioned research, the EMC has established an operation of EnMet assessment, including monthly, quarterly, and annual reports and EnMet assessment products for serious air pollution processes and major social activities.

2.3. Technological System for EnMet Services of EMC

2.3.1. Integrated EnMet Observations and Analysis. The CMA has developed a sizable atmospheric composition observation network since the 1980s, including one global atmospheric background station, six regional atmospheric

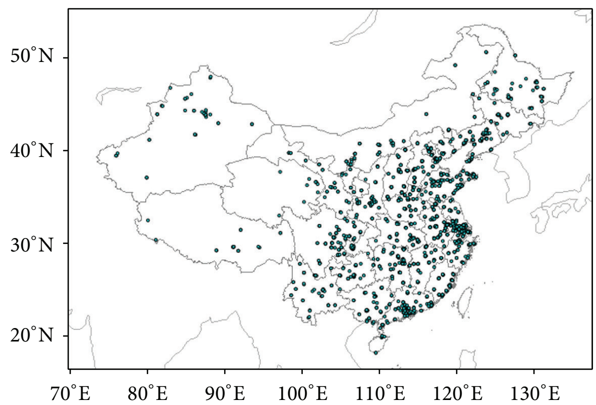

Figure 1: The air quality monitoring network of China.

background stations, 241 fog and haze observation stations with the capability to observe atmospheric composition, and 365 acid rain observation stations [26–28]. For boundary layer meteorological observations, the CMA has 120 L-band upper-air sounding systems, providing second-level sounding data at 00 and 12UTC each day. In addition, the network combined with 43 wind profile radar installations can achieve continuous vertical wind observations under all weather conditions on the timescale of minutes [29].

The CMA has also conducted many research projects in satellite remote sensing monitoring. The AQUA/MODIS aerosol optical depth (AOD), which is a product provided by NASA, is used to analyse aerosol events such as haze, dust storm, or volcano eruption [30–32]. Based on FY polar and FY geostationary orbit satellites, technology is developed to support real-time monitoring, such as haze pollution index, haze optical thickness, fog, and dust storm (optical image monitoring, dust index, and quantitative monitoring of dust optical depth) [33–39].

In addition to the comprehensive EnMet observation system built by the CMA, the Ministry of Environmental Protection has set up a nationwide environmental air quality monitoring network, which has grown from initial 661 stations in 1992 to 1436 in 2015 (Figure 1). The environmental air quality monitoring systems set up by the two ministries complement each other and allow for optimal resource utilization for atmospheric environmental monitoring.

Observational data from the CMA's integrated observing system and air quality data from the Ministry of Environmental Protection's environmental air monitoring stations include hourly PM_{10}, $PM_{2.5}$, PM_1, SO_2, NO_2, CO, and O_3 concentrations as well as the Air Quality Index (AQI). Using these data in combination with conventional meteorological observations, the EMC can achieve real-time monitoring of fog, haze, and atmospheric composition at a national level, as well as real-time monitoring of highly polluted days, key regions, and key urban air quality metrics. Conventional meteorological observation data are used for atmospheric environmental monitoring, while the application of unconventional data needs to be improved. For example, the structural features of the atmospheric boundary layer can be analysed by using L-band upper-air sounding data; the entire boundary layer inversion strength can help to judge visibility change and then improve fog and haze forecasting; the observation tower and wind profiler observations can be used to analyse the evolution of urban boundary layer characteristics at high temporal and vertical resolutions [40–45].

2.3.2. Atmospheric Chemistry Models. Currently, CUACE/fog and haze and CUACE/dust and pollutant dispersion models are operated by the national service department to provide technical support for air pollution, dust, nuclear proliferation, and other EnMet forecasting services. In addition, Community Multiscale Air Quality (*CMAQ*), *WRF-Chem*, and other regional atmospheric chemistry models have been introduced in some provinces to build atmospheric environmental numerical forecasting systems [46–48]. Numerical forecast system of air quality and photochemical smog of the Pearl River Delta region was established by coupling Mesoscale Model Version 5 (MM5), Sparse Matrix Operator Kernel Emissions (SMOKE), and CMAQ models, which use local sources of emission inventories [49–52]. Based on the WRF-Chem model, the Shanghai Meteorological Bureau has established and operationally implemented a coupled regional chemical transport model [53]. These models provide important technical support for forecasting and warning of regional and urban air quality, visibility, haze, and so forth.

There is still room to improve the forecasting capabilities of atmospheric chemistry models given the uncertainties associated with emission sources, as well as atmospheric chemistry and boundary layer meteorological processes. Thus, further verification based on model products is important. The forecasting performance of CUACE model has been quantitatively evaluated at the scale of individual stations and small areas by the EMC. The average deviation and mean error as well as the correlations between forecast and observed visibility, $PM_{2.5}$ concentration, temperature, relative humidity, and other meteorological elements were analysed to provide recommendations for model developers and forecasters. Various methods such as adaptive nudging scheme, self-adaptive partial least regression, and dynamic statistical forecasting scheme have been applied to modify the prediction of these models [54–57].

2.3.3. Analysis of Meteorological Conditions Associated with Air Pollution. Although the emission of pollutants is the main cause for air pollution, meteorological conditions ultimately determine the level of pollution. Thus, analysing relevant meteorological conditions is important for understanding trends in atmospheric pollution [58–60].

Observations and numerical forecast products have been used to diagnose and analyse the meteorological factors associated with pollutant diffusion, transportation, settling, and elimination. These diagnostic products such as atmospheric mixing height, vertical exchange coefficient, ventilation coefficient, Richardson number, low-wind area, and air-trapping area can help forecasters better understand the environment conditions during forecasting of haze, fog, and air quality [61, 62].

Typical weather for air pollution often depends on the stability of synoptic weather [1, 63]. The stable weather index was developed by considering physical elements such as humidity, wind speed, inversion intensity, and the height of the mixing layer, which can be used to quantitatively evaluate the degree of atmospheric static stability and characterize horizontal and vertical diffusion capacity of atmospheric pollutants. The stable weather index is a quantitative factor that contains meteorological information for forecasters, and it plays a positive role in major meteorological services and assessment of processes. In addition to stable synoptic conditions, regional transport of pollutants is also an important factor in pollutant concentrations; and advection plays an important role in pollutant movement [64–70]. The EMC is studying a composite index of pollutant transport strength, which combines the intensity of $PM_{2.5}$ emissions and the capability of pollutant transport.

2.3.4. EnMet Objective Prediction Technology. Compared with routine weather forecast such as precipitation, the ability of numerical models to forecast fog and haze is limited. Objective forecast technologies play important roles in helping forecasters to improve fog and haze forecast skill. At present, objective forecast technologies mainly include the methods based on artificial neural networks, overlapping sets of multi-index, and multiple regression [71–76].

2.3.5. System Platform for EnMet Services. As an interdisciplinary field, environmental meteorology involves large amount of data with extensive sources, so there is a large difference between the analysis methods of environmental meteorology and conventional weather forecasting. Current database and platform construction has become a key limiting factor for the development of EnMet operations. The EMC began the construction of an EnMet database and a platform for EnMet operation in 2015. The goal was to increase functionality, including EnMet monitoring, diagnostic analysis, and forecasting.

3. Problems and Future Development of the EnMet Services *of EMC*

3.1. New Requirements of the National Environmental Meteorology. The demands for the national environmental meteorology can be divided into three areas.

(1) Decision-Making Requirements. The requirements for decision-making support derive from the need to control air pollution and guarantee major social activities. These requirements are mainly concentrated on long-term forecast and emphasize forecasts of major processes, quantitative evaluation, and comparative analysis.

(2) Public Service Requirements. The public health consciousness is growing, and people want more detailed EnMet forecast products to guide their daily lives. Thus, the public demands mainly focus on the increase in EnMet forecast products with fine temporal and spatial resolution.

(3) Operational Guidance Requirements. Most local stations that provide EnMet products have less technology than regional centres such as those in Beijing, Shanghai, and Guangzhou. Operational guidance requirements can be embodied in forecasting technology, diagnosis analysis methods, and operational standards.

3.2. Goals and Priorities of the Development of the National EnMet Operation. Consider the following.

(1) To improve the EnMet monitoring abilities, we need to gradually build nationwide observation network of atmospheric composition and strengthen the construction of boundary layer meteorological observation. It is important to improve satellite remote sensing monitoring recognition methods and quantitative monitoring and evaluation technologies for haze and air pollution. At the same time, it is necessary to strengthen comprehensive analysis of the boundary layer using both conventional and unconventional meteorological observations.

(2) Atmospheric chemistry models and numerical weather models should be further integrated, incorporating relevant physical and chemical processes and mechanisms. In addition, data assimilation technology should be developed to assimilate EnMet observations, which should help to improve the initial values of these models.

(3) Developing medium- and long-term forecasts is important for improving the ability to guide decision-making. Due to the current forecasting ability of the models, objective forecast technologies based on statistical method should be established to support the medium- and long-term forecasts.

(4) Air pollution assessment and preassessment should be strengthened for government departments to deal with air pollution scientifically and effectively. Using model simulations is an important way to evaluate contributions of meteorological conditions in air pollution.

(5) Researching how haze and heavy pollution combined with other meteorological conditions can impact human health represents an important avenue for expansion of the EnMet operation.

(6) Cooperation should be strengthened, relying on the CMA's fog and haze monitoring and prediction innovation team, to promote the development of EnMet research operation personnel.

4. Concluding Remarks

A review and analysis of the national EnMet services shows that the EnMet operation has been developed rapidly in China. It has provided various operational products and a technical support system, which play important roles in meteorological services. However, in the face of rapid growth of demand for services, it is urgent to improve the capability of EnMet forecasts. There are still obvious deficiencies in comprehensive monitoring analysis, forecasting, medium-to long-range prediction, and assessment and preassessment technology. These issues are crucial in the development of EnMet operations in the future.

Competing Interests

The authors declare that there are no competing interests regarding the publication of this paper.

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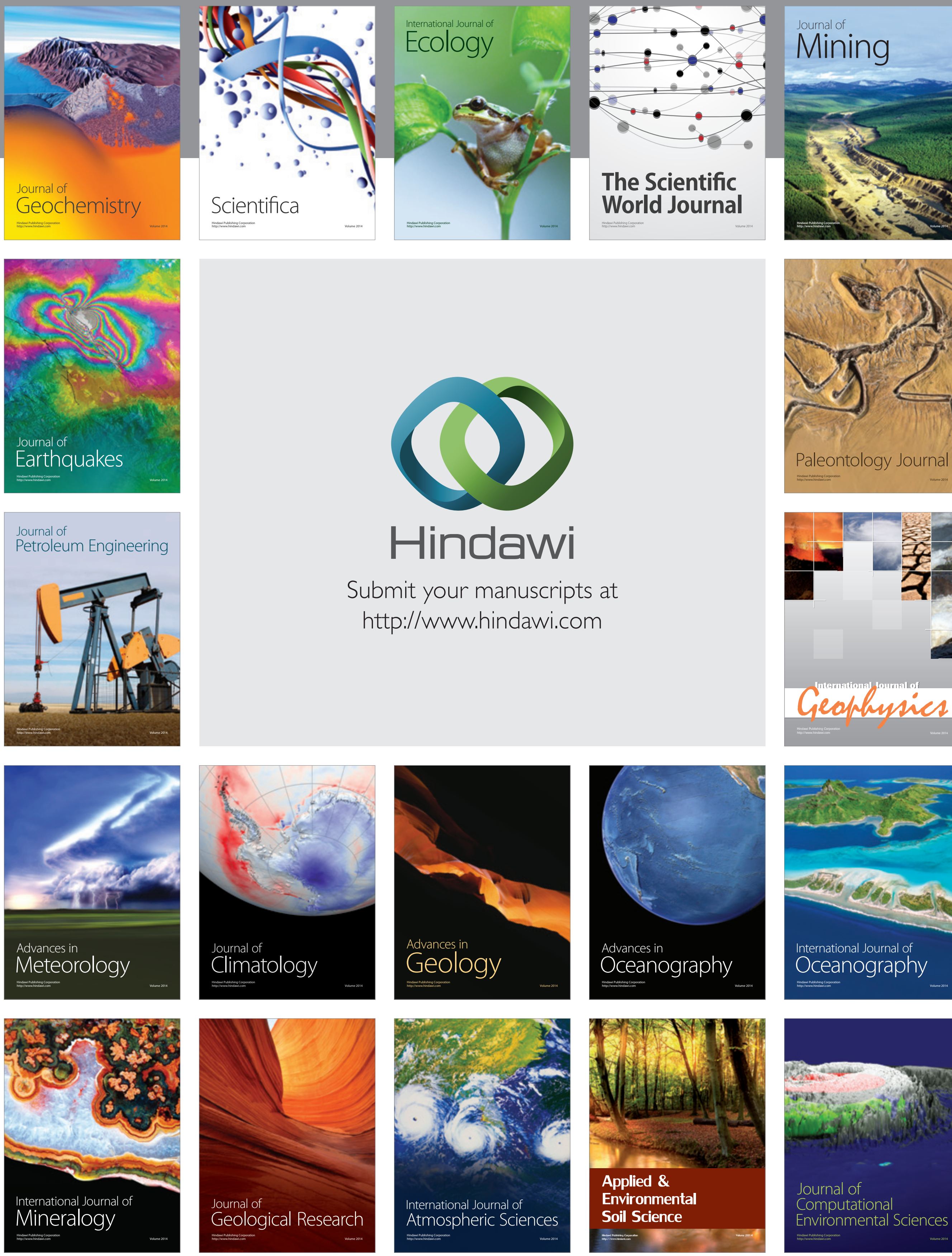
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