The Pearl River Delta Regional Air Quality Monitoring Network – Regional Collaborative Efforts on Joint Air Quality Management

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ABSTRACT

In November 2005 the Guangdong and Hong Kong governments established the Pearl River Delta regional air quality monitoring network (“PRD RAQMN”), which represented the first joint regional air pollution and reporting effort in this rapidly developing and heavy-polluted area in southern China. This project has recorded the air quality trends during the 11th Five-Year Plan (FYP), implemented between 2006 and 2010, and will continue to do so throughout the period of economic development and stringent emission control of coal-fired power plants and vehicles that are part of the 12th FYP, to be implemented between 2011 and 2015. The PRD RAQMN serves as a role model for cooperation among local administrative authorities, as well as for the joint prevention and management of air pollution. The PRD RAQMN demonstrates that regional collaboration is critical to address the air pollution problems that China faces in a more effective manner.

Keywords: Pearl River Delta Region; Regional Air Quality Management; Joint prevention and control.

INTRODUCTION

The Pearl River Delta (PRD) region is located in the south coast of China, one of the most economic vibrant areas in the nation. The land area of the PRD region covers about one-third of the Guangdong Province at an area of 179,800 km² with population density at 13,461 persons per sq. km in 2009 excluding the two special administrative regions, Hong Kong and Macao (GDSB, 2011). Associated with rapid economy growth, China is one of the areas in the world with heavy air pollution in terms of trace gases and particulates, evident by satellite observations (Lin et al., 2010; van Donkelaar et al., 2010). While it is well-known that eastern part is the most polluted area among China, the PRD region in southern China is also suffering seriously from the problem where megacities are located (Chan and Yao, 2008; Zheng et al., 2010). The yearly increasing trend of surface extinction coefficient over the PRD was observed by satellites (Fig. 1). The seasonal average Aerosol Optical Depth (AOD) up to 1.2 (at 550 nm) was measured by MODIS over PRD (Wu et al., 2007).

The air pollution problems in the PRD have aroused attention to the scientific communities with over 100 publications (Chan and Yao, 2008) since 1990. Intensive sampling and data analysis campaigns – the Program of Regional Integrated Experiments on Air Quality over Pearl River Delta of China (PRIDE–PRD) have been held biannually since 2004 to investigate the complex air pollution in the PRD region (Hofzumahaus et al., 2008; Zhang et al., 2008;). While special field studies on certain air pollution characteristics were usually conducted in a few sites in the past, long term quality-assured ambient air monitoring data are generally lacking not until the late 2005 when the PRD Regional Air Quality Monitoring Network (“PRD RAQMN”) was jointly established by the governments of the Guangdong Province and the Hong Kong Special Administrative Region (HKSAR).

There are a number of critical reasons to set up a comprehensive monitoring network in the PRD. First, the PRD region is associated with intense emissions of primary pollutants. In 2006, the estimated anthropogenic sulfur dioxide (SO₂), nitrogen oxides (NOx), volatile organic compound (VOC) and respirable particulate matter (RSP or PM₁₀) emissions (1175, 1493, 1780 and 942 Gg/year,
respectively) in Guangdong Province (where the PRD is located) are among the top ten in China (Zheng et al., 2009). In particular, the emissions of ozone precursors NOx and VOC are the second and third highest among all the provinces in China. Meanwhile, the sources of these pollutants are concentrated in the PRD region, namely Foshan, Zhongshan, Dongguan, Guangzhou and Shenzhen cities (Zheng et al., 2009), which is also evident by aerial measurements of AOD in the PRD (Zheng et al., 2011). Therefore, knowledge of real-time influences of these massive pollution loadings is essential in air quality management point of view. Second, recent studies within China indicated that air pollution in the PRD is largely regional and complex in nature which involves the interactions of primary and secondary pollutants (e.g., Zhang et al., 2008; Zheng et al., 2009). Therefore, setting up a regional monitoring network is imperative to understand air pollution characteristics and detect the effectiveness of the pollution control strategies holistically (Hao, 2008). For example, the National 11th Five-Year Plan (FYP, 2005–2010) required SO2 emissions to be capped at 1100 kt/year in 2010 in Guangdong Province, about 15% reduction based on the 2005 figure. It was about 5% more reduction on the national level and the target was dynamic as it did not take into account of the accompanying economic growth. The target could be higher than 10% in reality. The levels of these targeted pollutants should be therefore monitored continuously and extensively to evaluate the effectiveness of the imposed control measures. Finally, the availability of pollutant concentrations from the network also helps to evaluate the pollution impacts, in term of the
criteria pollutants including PM$_{10}$, O$_3$ and SO$_2$, on health and crop loss within the PRD region (Xie et al., 2011; Huang et al., 2012).

This paper accounts for the nation’s first regional air quality monitoring network development such as measurement technology, and data management and dissemination and Quality Assurance/Quality Control (QA/QC) system, reviews the monitoring results and looks ahead the upcoming challenges and priorities in tackling regional air pollution in the south coast of China.

PRD REGIONAL AIR QUALITY MONITORING NETWORK

A Brief Chronicle - Evolution of the Nation’s First Regional Air Quality Monitoring Network

Historically, the PRD region has built city-based air quality monitoring networks which are operated individually by nine prefectural-level cities within the region, and published API (Air Pollution Index) daily by cities, since 2000. However, along with the economic development, the city-based networks can well characterize urban air quality but may not capture the air quality which wreaked havoc in the PRD region. Realizing the possible regional air quality deteriorations caused by rapid economic development, in 1998, Guangdong Provincial Government and the HKSAR Government had agreed to jointly draw up a project named as the “Study of Air Quality in the Pearl River Delta Region” (CH2M HILL, 2002), to study the regional trans-boundary air pollution problem with a view to develop effective regional control measures under “one atmosphere” concept. Subsequently, the Air Quality Management Plan (AQMP) was also drawn up and endorsed by two governments which proposed to reduce anthropogenic emissions of SO$_2$, NO$_x$, PM$_{10}$ and VOC, by 40%, 20%, 55% and 55% respectively in the PRD region by 2010, using 1997 as the base year (JWGSDEP, 2007). The PRD RAQMN was then conceptualized in order to probe the regional air quality, assess the effectiveness of emission reduction measures and enhance the roles of monitoring networks in characterizing regional air quality and supporting air quality management.

With this motivation, the first regional RAQMN in China was set up between Environmental Monitoring Center of Guangdong (GDEMC) and the Environmental Protection Department of the Hong Kong Special Administrative Region (HKEPD) under the AQMP. The PRD RAQMN was found between 2003 and 2005 with the joint efforts of the GDEMC and HKEPD which allows for local air pollution problems to be reflected in an appropriate regional context. The PRD RAQMN came into full operation in November 2005. It consists of 16 automatic air quality monitoring stations across the PRD region as shown in Fig. 2. Thirteen of these stations are operated by the Environmental Monitoring Centers in the Guangdong Province while the other three located in Hong Kong are managed by the HKEPD. The sites at Tianhu in Guangzhou and Tap Mun in Hong Kong are served as the background stations while the remaining 14 stations are primarily located in urban or sub-urban areas. Ambient concentrations of PM$_{10}$, SO$_2$, nitrogen dioxide (NO$_2$), CO and O$_3$ are measured at all of these stations. Came into full operation on November 30, 2005, the

Fig. 2. Spatial distribution of the PRD Regional Air Quality Monitoring Stations.
network has been providing quality data for reporting of Regional Air Quality Index (RAQI) (Table 1) since then to inform the public of the regional air quality.

The purposes of PRD RAQMN are multi-faceted but worked toward one common goal - compliance of the ambient air quality standards in China and Hong Kong (Table 2). The PRD RAQMN aims at providing long-term and real-time monitoring measurements of pollutant concentrations that can help the Guangdong and Hong Kong governments to appraise the air quality and pollution problems in the PRD region for formulating appropriate control measures. It also plays a significant role in evaluating the effectiveness of the regional air pollution control measures through long-term monitoring, as well as informing public about the air quality in the form of simplified information as RAQI of various places in the region.

In order to ensure a high degree of accuracy and reliability of the air quality monitoring results, a set of “Standard Operating Procedures on Quality Assurance and Quality Control of the PRD Air Quality Monitoring System for Hong Kong and Guangdong” (QA/QC Operating Procedures) has been developed by the two governments for both Guangdong and Hong Kong. The design and operation of the PRD RAQMN has been to comply with the requirements set out in the QA/QC Operating Procedures. Meanwhile, it also provides pollutants monitoring concentrations semi-annually and annually.

**Operation of the PRD RAQMN**

Monitoring instruments deployed in the PRD RAQMN are fully equipped with technology-proven, EU or USEPA designated methods. Specific information on the monitoring equipment can be referred to the annual data report (e.g., GDEMC and HKEPD, 2010). In Guangdong, monitoring is

### Table 1. Descriptions of the PRD Regional Air Quality Index.

<table>
<thead>
<tr>
<th>Grade</th>
<th>Value</th>
<th>Regional Air Quality Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>0–1</td>
<td>Pollutant concentrations are well within the air quality standards [#]</td>
</tr>
<tr>
<td>II</td>
<td>1–2</td>
<td>Pollutant concentrations are generally within the air quality standards</td>
</tr>
<tr>
<td>III</td>
<td>2–3</td>
<td>Concentrations of individual pollutants may approach or exceed the air quality standards</td>
</tr>
<tr>
<td>IV</td>
<td>3–4</td>
<td>Air quality standards are generally exceeded</td>
</tr>
<tr>
<td>V</td>
<td>&gt; 4</td>
<td>Air quality standards are significantly exceeded</td>
</tr>
</tbody>
</table>

Remark: [#] Grade 2 National Air Quality Standards.

### Table 2. Ambient Air Quality Standards in China and Air Quality Objectives in Hong Kong.

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Averaging Time</th>
<th>Grade II Level of China Ambient Air Quality Standard[^](GB 3095-1996 &amp; amendment in 2000)</th>
<th>Grade II Level of China Ambient Air Quality Standard[^](GB 3095-2012)</th>
<th>Hong Kong AQO (μg/m^3)</th>
<th>No. of Exceedance allowed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sulfur dioxide (SO2)</td>
<td>1-hour</td>
<td>500</td>
<td>500</td>
<td>800</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>24-hour</td>
<td>150</td>
<td>150</td>
<td>350</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Annual</td>
<td>60</td>
<td>60</td>
<td>80</td>
<td>N/A</td>
</tr>
<tr>
<td>Total suspended particulates (TSP)</td>
<td>24-hour</td>
<td>300</td>
<td>300[^](GB 3095-2012)</td>
<td>260</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Annual</td>
<td>200</td>
<td>200[^](GB 3095-2012)</td>
<td>80</td>
<td>N/A</td>
</tr>
<tr>
<td>Respirable suspended particulates (RSP or PM10)</td>
<td>24-hour</td>
<td>150</td>
<td>150</td>
<td>180</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Annual</td>
<td>100</td>
<td>70</td>
<td>55</td>
<td>N/A</td>
</tr>
<tr>
<td>Fine suspended particulates (FSP or PM2.5)</td>
<td>24-hour</td>
<td>--</td>
<td>75</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>Annual</td>
<td>--</td>
<td>35</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Nitrogen dioxide (NO2)</td>
<td>1-hour</td>
<td>240</td>
<td>200</td>
<td>300</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>24-hour</td>
<td>120</td>
<td>80</td>
<td>150</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Annual</td>
<td>80</td>
<td>40</td>
<td>80</td>
<td>N/A</td>
</tr>
<tr>
<td>Ozone (O3)</td>
<td>1-hour</td>
<td>200</td>
<td>200</td>
<td>240</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>8-hour</td>
<td>--</td>
<td>160</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Carbon monoxide (CO)</td>
<td>1-hour</td>
<td>10000</td>
<td>10000</td>
<td>30000</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>8-hour</td>
<td>--</td>
<td>--</td>
<td>10000</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>24-hour</td>
<td>4000</td>
<td>4000</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Lead (Pb)</td>
<td>3-month</td>
<td>1.5</td>
<td>1[^]</td>
<td>1.5</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>Annual</td>
<td>1</td>
<td>0.5[^]</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

[^](GB 3095-1996 & amendment in 2000)
[^](GB 3095-2012)
[^](The standard to be implemented nationwide in 2016.)
[^](Implementation of this standard is under the discretion of the Environmental Protection Department under the State Council or provincial government.)
framed by various guiding principles, e.g., Station operation - Automated methods for ambient air quality monitoring (HJ/T 193-2005), Manual methods for ambient air quality monitoring (HJ/T 194-2005), Technical guideline on environmental monitoring quality management (HJ 630-2011); sampling sites requirements (MEP Notice No. 4 in 2007); Measurement methods such as gravimetric method for PM_{10} and PM_{2.5} (HJ 618-2011), CO by non-dispersive infrared absorption (GB 9801), etc. which are promulgated by the Ministry of Environmental Protection (MEP), the central authority to direct the overall environmental issues in China (MEP, 2012).

The GDEMC, responsible for the network in Guangdong, is certified for the Competence of Testing and Calibration Laboratories in accordance with ISO/IEC 17025:2005 by China National Accreditation Service for Conformity Assessment, and automatic monitoring of air quality has become part of it since 2005. Whereas Hong Kong has established its monitoring protocols since the inception of the monitoring network in the early 1990s, the Hong Kong network itself is certified under the Hong Kong Laboratory Accreditation Scheme (HOKLAS). HOKLAS Accreditation Criteria are deployed in accordance with ISO/IEC 17025:2005, "General Requirements for the competence of testing and calibration laboratories" which contains both elements of technical and management aspects. By and large, the monitoring standard operating procedures are comparable and attain international standards.

Quality Systems

The PRD RAQMN has dedicated team to provide on-site management, quality control and assurance. To ensure that the air quality monitoring results attain a high degree of accuracy and reliability, the network is equipped with technology-proven air monitoring equipment and in compliance with the requirements set out in the stringent quality control and assurance operating procedures. The set-up of the PRD RAQMN was based on primarily from the experiences of Hong Kong’s network operation, particularly the quality assurance and quality control (QA/QC) is achieved under a set of standard protocol. Now the two governments have fully carried out the agreed QA/QC activities, which include zero/span checks, precision checks and dynamic calibration in accordance with the QA/QC Operating Procedures.

To ensure the operation of the Network complies continuously with the QA/QC requirements, the GDEMC and HKEPD have jointly set up the Guangdong-Hong Kong Quality Management Committee (QMC) for the PRD RAQMN to review, on a quarterly basis, the set-up of the network, its performance in QA/QC and the operation status of its data transmission system. The QMC also conducts system audit once a year to evaluate the effectiveness of the quality management system. The findings of the system audit would be reported. The deficiency found and corrective measures suggested would be listed and followed up by the QMC. With the QA/QC system, the operation of the PRD RAQMN attains a high accuracy and reliability. The process of networked management under the QA/QC systems is shown in Fig. 3.

In 2007, the “Regional Air Quality Monitoring Network QA/QC Manual of the Pearl River Delta” was published (GDEMC, 2007) which summarizes and standardizes the overall quality procedures of an air quality monitoring network stations. The Manual was prepared specifically based on the PRD RAQMN experiences and it was available to the public. It also provided a valuable tool for any other network operators in China to harmonize the QA/QC procedures.

Data Management and Dissemination

Systematic data management and data transparency are vital and valued for any well-established air quality monitoring network and they are the integral elements in the PRD RAQMN. The local authorities (different Environmental Monitoring Centers) make air quality data available on their websites. To better envisage the air quality data, the information is also disseminated on a daily basis via an interactive internet interface (http://www-app.gdep.b.gov.cn/raqi3/RAQI_en.htm) as RAQI regularly. The RAQI is a composite indicator of the aggregate level of four regional air pollutants, PM_{10}, SO_{2}, NO_{2} and O_{3} and the design of the RAQI is for addressing the large scale regional air pollution. Hong Kong’s air pollution index (API) which is primarily dealing with more localized and critical air pollutants which included carbon monoxide (CO) on top of the four pollutants while the air quality index in Guangdong Province reflects the level of conventional three pollutants SO_{2}, NO_{2} and PM_{10}. The RAQI, which integrates the air quality indexing systems between Guangdong and Hong Kong, reflects the three primary pollutants and secondary air pollutant (O_{3}) pollution levels. Similar to some other air quality indexes, the higher the RAQI value, the poorer of the air quality. In February 2012, the MEP has released the latest ambient air quality standard and technical regulation on ambient air quality index (AQI) (on trial) which will be enacted by 1st January 2016 nationwide with the consideration of seven pollutants with the addition of CO, PM_{2.5}, O_{3} (1-hour and 8-hour) values. Since March 8, 2012, the PRD region starts to report the 24-hour AQI by hour based upon the regional network data, which is the first region in China to issue AQI information publicly. The non-attainment is demarcated at a level over 100 among the six levels (Table 1). In general, the API focuses on the primary pollutants especially at urban scale whereas the RAQI focuses on the regional air quality. The new national AQI consists of daily AQI, as well as hourly AQI, which better informs the public about the air quality at different perspectives. In the near future, some kind of integration is foreseen to assimilate the national AQI and RAQI.

The PRD monitoring data are also presented through a range of media including the RAQI as well as summary reports with information such as brief QA/QC, concise statistical analysis, information on site locations and characteristics. The monitoring data, among other items such as site locations and characteristics, are compiled and
published as annual reports which are freely accessible by the public. It is a breakthrough in information disclosure in China as environmental data are still under close scrutiny in the mainland.

**Latest Development - The PRD Regional 3-dimensional Air Quality Monitoring Network**

The air pollution in the PRD region appeared to be regional and complex in nature, characterized by high concentrations of both primary pollutants and secondary pollutants from atmospheric chemistry processes and the complex non-linear interactions among pollutants are supported by local studies (Zhang et al., 2008; Zheng et al., 2010). However, the spatial coverage may not be adequately addressed the air pollution characteristics in more remote areas such as the north and the southwest of the PRD region and the compliance-based monitoring which cannot be well characterized and reflected the complex air pollution. Hence, a new monitoring strategy that augments the concept of taking measurements beyond the basic compliance monitoring is needed in the region. In 2006, with the supports from the National Ministry of Science and Technology and People's Government of Guangdong Province, the PRD region was chosen as the core demonstration area to conduct a major Chinese National Key High-Tech Scientific Program “Synthesized Prevention Techniques for Air Pollution Complex and Integrated Demonstration in Key City-Cluster Region” (also known as “National 863 Program”), and one of its core tasks is to develop advance techniques for enhancing the regional network to fully characterize regional complex air pollution. Under the support of the National 863 Program, the air quality monitoring stations in the Guangdong Province was completely upgraded in 2007. By 2011, the Guangdong air quality monitoring stations under the PRD RAQMN were fully equipped with advanced technology to accomplish 3-dimensional air quality monitoring and effective management for diagnosing the intricate regional air pollution characteristics.

The ground monitoring of the 3-dimensional monitoring network has 69 stations consisting of a background station, a Supersite, 8 regional stations, 54 urban stations, a rural station, 4 roadside stations. For example, the background station located in the Guangdong Province Nanling National Nature Reserve (112°53'56" and 24°41'56") at 1689 m above sea level which is about 200km from Guangzhou City; while the Supersite is located at Heshan in Jiangmen (112°9290E and 22°7279N) at altitude 60m above ground, a downwind site from two major cities, Guangzhou and Foshan. The Supersite is primarily for diagnosing the evolution and formation mechanism of the photochemical air pollution and regional haze problem. The Supersite is furnished with advanced ground-monitoring instruments, such as single-particle time-of-flight mass spectrometry and an online VOC measurement system.

Fig. 3. The process of network management under the QA/QC system.
The 3-dimensional monitoring network also integrates the Light Detection And Ranging (LIDAR), wind profiler radar and satellite remote sensing to investigate the aerosol extinction coefficient and wind speed, wind direction, the vertical distribution of pollutants and to identify the spatial relationship between the column density and optical thickness in the PRD region. In support of the National 863 Program, the 3-dimensional monitoring network system is an ensemble of satellite remote sensing monitoring systems such as sensors deployed on the China satellites (HJ-1A and B), Atmospheric Infrared Sounder (AIRS) and Ozone Monitoring Instrument (OMI) deployed on the Aqua satellite as the main sources of ambient air quality information retrieved from remote sensing. The system monitors the column concentration of gaseous air pollutants such as O₃, NO₂ and SO₂, greenhouse gases such as CH₄ and CO, near-ground atmospheric particulates concentrations and visibility. The system is also capable of assessing regional or super-regional air pollution phenomenon such as biomass burning and haze. Details of the PRD 3-dimensional monitoring network set-up, functions and observables of various monitoring sites are provided in supplementary information.

The PRD 3-D RAQMN implements an extensive and influential quality system which is made use of automated and real-time technology with interactive intelligent system. It builds upon a comprehensive quality control system to ensure the system integrates with QA/QC in every aspect to produce data with high quality (Fig. 4). Since 5th June 2012, the Guangdong network is the first region to adopt the new air quality standards which will be formally adopted on 1st January 2016 in the nation. It also releases the hourly air quality information from 62 stations (including the urban stations which released the API previously) in the “Guangdong Environmental Information Issuing Platform” (http://www.gdep.gov.cn/). The PRD 3-dimensional monitoring network leads the nation in interactive release of the regional air quality information in real-time, enhancing data transparency, and promoting the joint pollution prevention and control in the PRD region.

SUPPORTING REGIONAL AIR QUALITY MANAGEMENT

Characteristics of the PRD Regional Air Quality

Figs. 5(a)–5(d) show the monthly variations of the major pollutants (SO₂, NO₂, O₃, and PM₁₀) measured by the PRD RAQMN from 2006 to 2010. The stations are grouped based on geographical features – urban, sub-urban, coastal and background. Detailed analysis of the network measurements is out of the scope of the paper. Nevertheless, the characteristics of the 5-year dataset of all measured pollutants are discussed here, followed by the findings of other research works using the network measurements.

The overall concentrations of SO₂, NO₂ and PM₁₀ were generally higher during the winter season (first and fourth quarters of year) and relatively lower in the summer months. The lower pollutants levels in summer were mainly due to the relatively clean maritime air stream prevailed in the PRD region under the influence of southern monsoon together with the higher mixing layer height that favored the dispersion of pollutants.

For SO₂, no clear seasonality is found for stations with lower measured concentrations (< 0.04 mg/m³). It is noted that not all non-background stations measured high SO₂ levels. Low SO₂ levels at coastal stations - Tsuen Wan and Tung Chung are attributed to the less industrial activities and stringent source control such as sulfur reduction in diesel and liquid fuel and flue gas desulfurization equipment installed in power plants in Hong Kong. Interestingly, lower concentrations were also measured at Jinguowan and Xiapu, which could be due to the less SO₂ sources in Huizhou County. Seasonality for NO₂ was evident for most of the non-background stations, with similar ranges of NO₂ levels measured at these stations. Lower NO₂ levels (< 0.03 mg/m³) were measured at station Jinguowan since the station is located in a residential area which is away from major roads or other major pollution sources mentioned in the Introduction. Seasonality for PM₁₀ was also apparent. The maximum monthly PM₁₀ levels could be reached to about 0.2 mg/m³ at three urban or sub-urban stations. On the other hand, the PM₁₀ levels at all the coastal stations were as low as the background levels (5-year arithmetic mean of 0.05 mg/m³).

For O₃, the highest monthly averages occurred in October and November because of more days in the period with meteorological conditions that favored photochemical reactions (such as strong solar radiation, less amount of clouds, weak wind speed etc.), hence causing more ozone formation (GDEMC and HKEPD, 2010). The maximum 5-year mean levels (≥ 75 mg/m³) were measured at the background stations - Tap Mun and Tian Hu. This is explained by the lack of NO titration as in other stations which are located closer to the pollution sources (Gilge et al., 2010; Zheng et al., 2010). As such, lower O₃ levels were measured at urban stations and those near significant NO sources (e.g., major roads) such as the in the station Tsuen Wan.

Annual variations of the major pollutants (SO₂, NO₂, O₃, and PM₁₀) measured by the PRD RAQMN from 2006 to 2010 are illustrated in Fig. 6. The annual arithmetic mean recorded by the PRD RAQMN for SO₂, NO₂, and PM₁₀ are trending downward by 47%, 7% and 14% respectively. The significant SO₂ emission reduction is primarily linked to the national pollution control policy by the National 11th FYP with discernible impact and reflected in the monitoring results. The reductions also reflected other sulfur control measures implemented in recent years by Guangdong and Hong Kong, including the retrofitting of power plants with flue-gas desulfurization facilities, tightening the vehicle emission standards and fuel specifications, phasing out the more polluting industrial facilities in the PRD, etc., had brought improvements in the overall air quality in the PRD region. On the contrary, the annual ozone increased by 10% in the same period which reflected the photochemical smog pollution in the region has not yet improved (GDEMC and HKEPD, 2010). After all, the PRD RAQMN plays an important role to detect the effectiveness of the pollution control policy.
Since 2005, pilot measurements of PM$_{2.5}$ were also monitored in three sites such as Tianhu and Wanqingsha in Guangzhou, and Jinguowan in Huizhou with the purpose of technology transfer to the whole network in order to support the comprehensive PM$_{2.5}$ monitoring in later years. Compared with the concentrations of PM$_{2.5}$ in the PRD in the year of 2006, those measured in 2010 are about 6%–28% lower. With a view of complying with the new national ambient air quality standard and served as the demonstration area, the PRD RAQMN were fully equipped with PM$_{2.5}$ monitors in all network stations to report online at the website administered by the Guangdong EPD since 8th March 2012, (MEP, 2012a), ahead of the official promulgation on 1st January 2016.

In Hong Kong, PM$_{2.5}$ measurements have commenced in the last decade. Clear seasonal variation of PM$_{2.5}$ concentrations in a recent year (e.g., 2011) was found at the three Hong Kong stations, Tap Mun (background site)
and the two urban sites, Tung Chung and Tsuen Wan. Higher concentrations in winter-spring months and lower concentrations in summer months were observed. Detailed analysis of the PM$_{2.5}$ data can be found in Louie et al., (2005, 2005a), Hagler et al. (2007) and So et al. (2007).

**Other Findings and Applications of the Network Measurements**

The PRD RAQMN data has been supported for a number of studies (e.g., Zheng et al., 2010; Zhang et al., 2011; Zheng et al., 2011a) of which photochemical smog caught...
most researchers’ interests including a two-year study (2006–2007) of the ground-level O₃ in the PRD (Zheng et al., 2010). Similar findings as above such as the O₃ peaks found in autumn and lower O₃ concentrations in urban areas were obtained. Further, the O₃ concentrations showed no statistically significant difference between weekend and weekdays in contrast to the findings in other urban areas, e.g., Tokyo and Osaka (Sadanaga et al., 2008), Southern California (Qin et al., 2004) and Phoenix, Arizona (Atkinson-Palombo et al., 2006), etc. The PM₁₀ measurements at 5
stations of the network were also used to correlate with the MODIS AOD datasets, an attempt was made to estimate the surface PM$_{10}$ levels using satellite product (Zheng et al., 2011).

Since the establishment of the PRD RAQMN, the monitoring data had been making support to policy formulation on regional air quality and some mega-events held in the PRD region such as the 16th Asian Games at Guangzhou in November 2010 and the Universiade Games at Shenzhen in August 2011. The data also supported
scientific projects including two national core scientific studies - the National 863 Program and “973 Program” (state key basic scientific research aiming to better understand the formation, precursors transport and control of acid rain), as well as regional air quality improvement plan such as the PRD Regional Joint Air Pollution Control Program in the 12th FYP. The PRD RAQMN has provided reliable monitoring data before, during and after these mega-events to support evidence-based policy formulation for these mega-events. The experiences of holding mega-

Fig. 5(d). Monthly variations of O₃ (mg/m³) at the PRD RAQMN.
Fig. 6. Box-whisker plots of annual variations of (a) SO$_2$, (b) NO$_2$, (c) PM$_{10}$, and (d) O$_3$ (mg/m$^3$) measured at the PRD RAQMN between 2006 and 2010.

Events in China are often associated with various mandated or voluntary air quality management measures that could bring in the opportunities of improving the air quality swiftly, though entailed with lots of infrastructural support and related intense pollution temporarily.

ROLES AND SIGNIFICANCE OF THE PRD RAQMN

The PRD RAQMN forms the first of its kind in China. Administratively, it signifies the co-operative efforts between the two governments and among various local authorities in Guangdong. The PRD RAQMN measures and its data represents a spatial continuum and change of the air quality data in the city clusters of the rapidly industrialized region in China. The PRD RAQMN not only monitors the air quality per se, it also keeps track in the evolution of industrial growth and emissions control. For example, the effect of reducing SO$_2$ emissions in the 11$^{th}$ FYP was well reflected in the monitoring data. On the other hand, in China, study and report on O$_3$ pollution before 2000
was scarce and there were only some studies taken in 2000 and 2004 (Zhang et al., 2011). Since the inception of the PRD RAQMN, O3 data have become available and provided valuable data for the study of regional photochemical pollution. Today, the ozone monitoring data from the PRD RAQMN form the most systematic and quality-assured datasets in the nation which provide holistic information of this complex secondary air pollutant.

More importantly, the quality assured data provides a continual database for tracking air quality in the rapidly industrialized PRD region. It also gives full support for the philosophy of “joint prevention and control” on air pollution as advocated by the MEP (MEP, 2010). The PRD RAQMN catalyzed the regional cooperative efforts in air quality monitoring and serves as a nurturing ground for developing technical and managerial skills and creates capacity-building in the nation. The data from these regional networks and the related analyses will be critical for drafting the regional air quality control plans, developing more effective emission control measures, and the evaluation of the emerging air quality issues as required in the Guiding Opinions.

The PRD RAQMN is one of the important environmental initiatives under a co-operation programme between Guangdong and Hong Kong and it has obtained the 2008 Environmental Protection Science and Technology Class 2 Award presented by the MEP of China. The award recognized both parties’ efforts and contributions to the advancement of environmental protection, science and technology. This award highlighted the excellent joint efforts between Guangdong and Hong Kong governments on improving the regional air quality.

WAY FORWARD: CHALLENGES AND OPPORTUNITIES

Setting-up long-term and persistent emission reduction goals are crucial for improving air quality in China. This is the key strength in Chinese socialism which promotes stability for long-term, national-level planning and maintains political continuity (Hu and Liang, 2011). It has been gaining the momentum on cutting SO2 emission since the 11th FYP. Significant efforts were made including tightening motor vehicle emission standards, installation of flue gas desulfurization facilities in large-scale thermal power plants and closing down the small and inefficient power plants of 50GW in China (Cao et al., 2009). Both the 11th and 12th FYPs accorded a high priority on improving the citizens’ overall well-being through, for example, education opportunities, healthcare and living environment improvement.

The impacts of regional air pollution on human health, quality of life and the environment are likely to remain of great concern in the coming decade in China (Wang and Hao, 2012). In view of the emissions of multiple pollutants and their complex atmospheric interactions, the identification of emission sources and estimation of pollutant loadings in the PRD region becomes challenging. It is certain that the PRD RAQMN requires upgrade to meet the challenges ahead such as toting up stations to characterize air quality at remote sites, measuring pollutant concentrations such as PM2.5, O3, CO which will be required in 2016 nationwide under the latest air quality standard review (MEP, 2011), and measuring air toxics for health related studies. Given the current situation, the setting up of an air quality monitoring system for addressing photochemical air pollution is much in need in this region. The PRD RAQMN was moved ahead of the nation with O3 and CO, as well as the recent inclusion of PM2.5, measurements since the network establishment. We also make reference to the overseas experience in setting up Supersites to study the multiple impacts from multi-pollutants to further our understanding of the cause and evolution of their complicated interactions, and more importantly, to formulate more effective control measures (Solomon et al., 2008). In order to better understand the complex air pollution problems in the PRD region, the PRD RAQMN will need to equip with fine particles chemical composition and volatile organic compound (VOC) to address the photochemical air pollution problems such as regional haze and visibility impairment in the region.

In the 12th FYP (2011–2015), it focuses on economic restructuring, low-carbon economy, environment and energy efficiency. While the industrial and economic growth will still grow in fast pace with great pressures on environmental resources, the central government determines to control air pollution further in order to improve the quality of life. In Guangdong Province, the SO2 and NO2 emissions are mandated to reduce synchronously by 14.8% and 16.9% respectively in 2015 as compared with 2010 level. These emission reduction rates are topped in China among other major areas such as Shanghai, Chonqing, Jiangsu while only 8% of SO2 and 10% of NO2 will be further slash for other cities (GDEPD, 2011; MEP, 2012b). The goal setting heralded for further emission control on power plants, manufacturing industries, and on-road vehicles in the PRD region. With the combination of tightening the air quality standards in China and Hong Kong in the near future, more drastic emission control measures could be anticipated and a more sophisticated air quality monitoring network should put in place to survey the changes.

As air quality is one of the key indicators for the living environment, the authorities of the PRD are determined to improve its regional air quality. Regional collaborative efforts such as the Guangdong-Hong Kong consortium are evident in improving air quality. The PRD RAQMN is crucial for monitoring the progress of overall changes of atmospheric environment invariably in quantitative targets now and in the years ahead. It catalyzed the regional cooperative efforts to improve nation’s air quality.

SUPPLEMENTARY MATERIALS

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

DISCLAIMER

The opinions expressed in this paper are those of the author and do not necessarily reflect the views or policies of
the Government of the Hong Kong Special Administrative Region, nor does mention of trade names or commercial products constitute an endorsement or recommendation of their use.

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Supplementary Materials

Functions, spatial-scale representation and monitoring items of different type of monitoring stations in the PRD regional 3-D network

<table>
<thead>
<tr>
<th>Type</th>
<th>Spatial Representation (km)</th>
<th>Functions</th>
<th>Observables</th>
</tr>
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</table>
| Background     | 1000                        | ➢ Indicate the background air quality in a less affected anthropogenic activities  
➤ Reflect the air quality characteristics at spatial scale of 1000 km  
➤ Evaluate the effectiveness of control measures implemented at regional or national level | Currently comprising of SO₂, NO-NO₂-NO₃, O₃, CO, PM₁₀, PM₂.₅ and meteorological parameters⁴, will progressively introduce visibility, light absorption and scattering of particulate matters, acid deposition, VOCs, GHGs, inorganic and organic components of particulate matters |
| Supersites     | 100                         | ➢ Investigate regional complex air pollution phenomenon, formation processes and mechanism  
➤ Investigate the synergistic effects between ecosystem and health  
➤ Reflect and characterize the air quality at spatial scale of 100km  
➤ Serve as a nurturing ground and capacity building on monitoring experience of advance instrumentation technique development, QA/QC, etc.  
➤ Evaluate the effectiveness of control measures at regional scale | SO₂, NO/NOₓ/NO₃, NO/NOₓ, CO, O₃, H₂O₂, CH₄, NMHC, VOC, PAN, ATOF/MS, PM₁₋PM₂.₅, PM₁₀, physical properties (e.g., size, distribution) and chemical (inorganic and organic species) components of PM₂.₅ and PM₁₀, EC/OC, light scattering and absorption of particulate matters, LIDAR, wind profiles, J(NO₂)-J(O₃), visibility, MOUDI and meteorological parameters⁴ |
| Rural          | 10–100                      | ➢ Assess the compliance of air quality at rural scale  
➤ Reflect and characterize the air quality at spatial scale from several km to 100 km  
➤ Evaluate the effectiveness of control measures at regional scale | SO₂, NO/NOₓ/NO₃, O₃, PM₁₀, meteorological parameters⁴ |
| Regional       | 10–100                      | ➢ Assess the compliance of regional air quality  
➤ Reflect the air pollution characteristics at regional scale  
➤ Evaluate the effectiveness of control measures in regional scale | SO₂, NO/NOₓ/NO₃, CO, O₃, PM₁₀, PM₂.₅, PM₁₁, NMHC, black carbon, visibility, meteorological parameters⁴ |
| Urban          | 1–10                        | ➢ Assess the air quality at a densely populated area  
➤ Reflect the air pollution characteristics at a more local scale between 1 km and 10 km  
➤ Evaluate the effectiveness of control measures in urban cities | SO₂, NO/NOₓ/NO₃, O₃, PM₁₀, PM₂.₅, visibility, meteorological parameters⁴ |
| Roadside       | 0.01–0.1                    | ➢ Assess air quality at high traffic flow volume  
➤ Reflect and characterize the air quality at micro-scale from 10 m to 100 m  
➤ Evaluate the effectiveness of control measures in urban cities | SO₂, NO/NOₓ/NO₃, O₃, PM₁₀, PM₂.₅, visibility, meteorological parameters⁴ |
| Special purpose| On a need basis              | ➢ Based on air quality management needs, special purpose monitoring shall include complex air quality monitoring such as acid deposition, sandstorm, photochemical air pollution, regional haze, GHGs, toxic substances such as heavy metals | On a need basis |

⁴ Meteorological parameters include temperature, relative humidity, wind direction and speed, solar radiation, rainfall, etc.
Abbreviations

ATOF/MS - Aerosol Time of Flight/Mass Spectrometer
CH₄ - methane
CO - carbon monoxide
EC/OC - elemental carbon/organic carbon
GHGs - greenhouse gases
H₂O₂ - hydrogen peroxide
J(NO₂) - photolysis frequency of nitrogen dioxide
J(O₃) - photolysis frequency of ozone
LIDAR - Light Detection and Ranging
MOUDI - Micro-Orifice Uniform Deposition Impactors
NMHC - non-methane hydrocarbon
NO/NO₂/NOₓ/NO₃ - nitrogen monoxide/nitrogen dioxide/nitrogen oxides/total reactive nitrogen
O₃ - ozone
PAN - peroxyacyl nitrates
PM₁ - particulate matter with aerodynamic diameter of up to 1 micrometer
PM₁₅ - particulate matter with aerodynamic diameter of up to 2.5 micrometer
PM₁₀ - particulate matter with aerodynamic diameter of up to 10 micrometer
SO₂ - sulfur dioxide
VOC - volatile organic compound

The PRD 3-dimensional monitoring network set-up