Overview on the spatial-temporal characteristics of ozone formation regime in China

Haoxian Lu[1], Xiaopu Lyu[1], Hairong Cheng[2], Zhenhao Ling[3], Hai Guo[1*]

1. Air Quality Studies, Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Hong Kong, China
2. School of Resource and Environmental Sciences, Wuhan University, Wuhan, China
3. School of Atmospheric Sciences, Sun Yat-sen University, Guangzhou, China

* Corresponding author. ceguohai@polyu.edu.hk

Abstract

Ozone (O_3), a main component in photochemical smog, is a secondary pollutant formed through complex photochemical reactions involving nitrogen oxides (NO_x) and volatile organic compounds (VOCs). Since the past decades, with the rapid economic development, industrialization and urbanization, the mixing ratio of O_3 has been increased substantially in China. O_3 non-attainment days have been frequently observed. Despite great efforts made in these years, it is still difficult to alleviate O_3 pollution in China, due to its non-linear relationship with the precursors. In view of the severe situation in China, this study carries out a comprehensive review on the spatial-temporal variations of relationship between O_3 and its precursors (i.e. O_3 formation regime), built upon the previous reviews of the spatial-temporal variations of O_3 and its precursors levels. Valuable findings from previous studies were laid out for better understanding of O_3 pollution, followed by implications for the control of O_3 pollution. Literature review indicates that O_3 formation in most areas of North China Plain (NCP), Yangtze River Delta (YRD) and Pearl River Delta (PRD) regions is in a VOC-limited regime during the high-O_3 seasons due to dramatic emissions from human activities in cities. Out of these metropolitan areas, NO_x-limited regime dominates rural/remote areas. From summer to winter, O_3 formation regime over China shows a tendency to shift to a VOC-limited regime. Furthermore, O_3 formation in China moved toward increasing sensitivity to VOC emissions before the 12th-Five-Year-Plan. However, after the 12th-Five-Year-Plan, successful reduction of NO_x slowed down this trend. Further effective

controls of VOCs are expected to achieve sustained O_3 attainment in the future. To timely solve the current O_3 pollution problem, precise control of O_3 precursors is proposed, together with the joint prevention and control of regional air pollution.

Key words: Ozone; O_3 formation regime; Spatial-temporal; China

1. Introduction

Because of the rapid industrialization and urbanization in China, air pollution, such as haze and photochemical smog characterized by high-levels of fine particulate matters and/or ozone (O_3), has become more and more severe and aroused public attention in recent years. Due to its strong oxidative capacity, surface O_3 poses adverse effects on humans' health (Goodman et al., 2015; Sousa et al., 2013), growth and productivity of crops (Bhatia et al., 2012), visibility (Aneja et al., 2004) and climate change (Ogundele et al., 2011). To study O_3 pollution in China, nationwide O_3 monitoring has been systematically conducted by the China National Environmental Monitoring Center (CNEMC) and the local Environmental Monitoring Centers since 2013 (http://www.mep.gov.cn/), and extensive field measurements were also taken from time to time by scientists over the past 20 years. Particularly, most of the measurements were undertaken in North China Plain (NCP), Yangtze River Delta (YRD) and Pearl River Delta (PRD) regions, where severe O_3 pollution has been often observed (Wu and Xie, 2017; Wang et al., 2017a). The characteristics of tropospheric O_3 pollution in China are high concentrated, long lasting, wide spread, and yearly increasing. On one hand, most cities such as Beijing, Tianjin, Shanghai, Nanjing, Guangzhou and Hong Kong frequently suffered from high-level O_3 exposures, which exceeded either the National Ambient Air Quality Standard (maximum hourly O_3 of 200 $\mu g/m^3 \approx 100$ ppbv) or the World Health Organization Standard (maximum daily 8-h average (MDA8) $O_3 > 50$ ppbv), and sometimes were even as high as 200 ppbv (Guo et al., 2013; Han et al., 2013; He et al., 2012; Cheng et al., 2010; Tu et al., 2007; Wang et al., 2006a). In addition, a recently nationwide study found that four cities including Beijing,

Chengdu, Guangzhou and Shanghai suffered from O_3 exposure with MDA8 > 50 ppbv on more than 30% of the days from 2013 to 2015 (Wang et al., 2017b). Compared to other industrialized regions in the world (i.e. Japan, South Korea, Europe and the United States), the magnitude and frequency of high-ozone events were much greater in China by analyzing the data of surface O_3 in 2013-2017 (Lu et al., 2018). On the other hand, it was revealed that the continuous increases of O_3 levels were found in China, not only in rural/remote areas but also in residential areas ($p < 0.05$). In rural/remote areas, a continuous increase of surface O_3 was firstly observed and reported by Wang et al. (2009) in the background atmosphere of PRD, South China, from 1994 to 2007. After that, increases of surface O_3 were reported likewise at other rural sites in NCP and YRD in the past decade (Ma et al., 2016; Lin et al., 2009; Wang et al., 2006b). In residential areas, the nationwide O_3 monitoring at 617 stations in densely populated regions by CNEMC showed that the yearly average MDA8 O_3 increased from 76.47 ppbv in 2013 to 82.60 ppbv in 2015 (Wang et al., 2017b). Moreover, a recent nationwide study reported that the monthly mean MDA8 O_3 in the four megacity clusters (i.e. Beijing–Tianjin–Hebei (BTH), YRD, PRD, and Sichuan Basin (SCB)) all showed increasing trends in the summers of 2013 to 2017 except for some locations in PRD (Li et al., 2019). Hence, the tropospheric O_3 pollution has become a critical issue in China.

The tropospheric O_3 is generally contributed by two sources, namely, the stratospheric intrusion of O_3 to the troposphere, and the chemical reactions involving nitrogen oxide (NO_x), volatile organic compounds (VOCs) and highly reactive radicals (e.g., hydroxyl radical (OH) and hydroperoxyl radical (HO_2)) in the presence of sunlight in the troposphere (Wang et al., 2017a; Steinfeld, 1998). However, the direct stratospheric O_3 intrusion to the troposphere is very minor and most ground-level O_3 is formed in the troposphere from the photochemical reactions above (Altshuller, 1984; https://www.epa.gov/roe/). Therefore, control focus should be on the chemical formation of O_3 in the troposphere. To achieve the purpose, it is essential to fully

understand the spatial-temporal variations of O_3, its precursors (i.e. VOCs and NO_x) and their relationships so as to implement appropriate control measures for the remediation of O_3 pollution. Though the spatial-temporal variations of O_3 and its precursors over China were overviewed in previous papers, as well as the detailed formation mechanisms of O_3 with its precursors (Diao et al., 2018; Guo et al., 2017; Wang et al., 2017a), the spatial-temporal patterns of the relationship of O_3 with its precursors (i.e. O_3 formation regime) have not been comprehensively reviewed and summarized. In fact, the non-linear relationship of O_3 with its precursors makes the O_3 pollution complicated, leading to continuous increase of O_3 level despite the implementation of intensive control measures in recent years. Therefore, understanding the spatial-temporal patterns of O_3 formation regime would help us determine the most efficient approach for O_3 reduction. All the studies of O_3 formation regime over the past 20 years in China were thoroughly reviewed in this paper. To our best knowledge, this paper is in fact the first comprehensive review on the spatial-temporal characteristics of O_3 formation regime in China.

This review paper mainly focuses on the O_3 formation regimes in different regions in China. The 'Introduction' section provides the background and significance of the review; The Section 2 reviews the spatial variations of O_3 formation regimes in China; The Section 3 summarizes the seasonal, diurnal and long-term patterns of O_3 formation regimes in China; and the Section 4 provides some directions for the control of O_3 pollution.

2. Spatial variations of O_3 formation regimes

In general, O_3 formation regimes can be classified into three categories: VOC-limited (VOC-sensitive), NO_x-limited (NO_x-sensitive) and transition regime. The cause of different O_3 formation regimes is mainly attributed to the dual role of NO_x in O_3 formation by regulating the chemistry of HO_x radicals. On one hand, NO_x drives O_3 formation through the photochemical cycle involving NO_x, atomic oxygen (O), O_2 and

sunlight. On the other hand, NO_x retards the rate of O_3 formation through the reactions with HO_x radicals to remove OH from oxidation cycle and produce relatively non-reactive species such as HNO_3. Moreover, the peroxy radicals (i.e. HO_2 and RO_2) generated from the reactions of VOCs with OH efficiently convert NO to NO_2, resulting in the accumulation of O_3 due to lack of NO titration effect ($NO+O_3 \rightarrow NO_2+O_2$) (Jenkin and Clemitshaw, 2000; Sillman, 1999; Barker, 1995; Wang et al., 2017a). Therefore, at low VOC/NO_x conditions, the reaction between OH and NO_2 is the dominant chain terminating reaction, competing with chain propagating reactions of OH and VOCs. Reducing the concentration of VOCs would lead to a decrease in O_3 formation (VOC-limited regime). On the other hand, at high VOC/NO_x ratios, reactions of OH and VOCs are the dominant chain terminating reactions, while the oxidation of NO to NO_2 by HO_2 and RO_2 is the key propagating reaction, which forms O_3 consequently. Hence, any reduction in NO_x would decrease the photochemical O_3 formation (NO_x-limited regime). Lastly, when the levels of VOCs and NO_x are comparative, the reaction of OH with neither VOCs nor NO_x is dominant and thus O_3 formation is limited by both NO_x and VOCs. Namely, O_3 level is reduced by cutting both precursors (transition regime). To determine O_3 formation regimes, there were a number of methods used to investigate the O_3-precursors relationship, including relative ratios of VOCs/NO_x, observed indicators (i.e., O_3/NO_z, H_2O_2/NO_z or H_2O_2/HNO_3), correlation analysis of O_3 with VOCs and NO_x, observation-based model (OBM) and emission-based model (EBM), which were comprehensively concluded and discussed by Wang et al. (2017a) and Guo et al. (2017). The first three approaches simply use the field measurement data of O_3 and its precursors to identify O_3 formation regimes. VOCs/NO_x ratios reflect the abundant O_3 precursors at a specific site and determine the O_3 formation regime based on the experiential criteria in previous studies. Similarly, the values of observed indicators represent the dominant precursor and/or reaction in O_3 formation according to the standards summarized from previous studies and thus indicate O_3 formation regimes. Correlation analysis of O_3 with VOCs and NO_x visually display the

relationship of O_3 with its precursor based on large quantities of averaged data covering multiple days. Although these approaches are simple and straightforward, they are not completely reliable by themselves and do not provide comprehensive analyses on the nonlinear O_3 formation mechanism. In addition to the three approaches, the sensitivity of O_3 production to various O_3 precursors can be quantified by conducting sensitivity modeling analyses with an assumed reduction in the concentration of target precursors via OBM and EBM. OBM simulates O_3 formation by inputting measurements of gaseous pollutants and meteorological conditions, while EBM simulates O_3 formation by importing the emission of VOCs and NO_x from the emission inventory. Compared to EBM, OBM simulates O_3 photochemical production and destruction based on measured ambient concentrations of O_3 and its precursors, which can avoid the uncertainties caused by emission inventories and the simulated boundary layer dynamics (Russell and Dennis, 2000). Nevertheless, EBM is able to study O_3 pollution without the restriction of observation data and break the limitations of time and space to investigate O_3 formation in a large-scale region and expected time period. It is noteworthy that the determination of different O_3 formation regimes is difficult to reach an agreement since it is dependent on the approach used for analysis of the O_3-precursor relationships, and the criteria of different approaches are not the same. Despite the potential differences of results, O_3 formation regime is basically determined by how the O_3 formation responds to the changes of its precursors, no matter which method is adopted.

Previous studies indicated that large amount of O_3 precursors was emitted in the NCP, YRD and PRD regions - the most developed regions in China, and thus led to the elevated O_3 levels in these regions with continuously increasing trends in these years (Diao et al., 2018; Guo et al., 2017; Wang et al., 2017a). Among the three regions, the highest maximum O_3 and VOCs concentrations were found in NCP, followed by PRD and YRD. In addition, all these three regions had comparable and high NO_x emissions. Furthermore, the levels of O_3 and its precursors varied in different land-use function

areas in these regions. In urban/populated areas, the levels of O_3 precursors were usually higher due to the massive anthropogenic emissions. However, higher values of maximum hourly O_3 were mostly observed in rural/remote areas because of the aging of air masses. Similarly, the relationship of O_3 with its precursors was extensively explored in NCP, YRD and PRD regions for seeking enlightenments on O_3 pollution control, especially in summer and autumn, when O_3 levels were usually higher due to the favorable circumstances for O_3 formation (i.e. high temperature, strong solar radiation, low relative humidity and high precursors levels) (Wang et al., 2017a). The detailed review on the spatial variations of O_3 formation regime using the above approaches in the three regions during the high-O_3 seasons is given below.

2.1 The NCP region

Different O_3 formation regimes were frequently found in NCP during the high-O_3 season (i.e. summer). Representative studies are listed in Table 1. Most of these studies in NCP were conducted in Beijing and its surrounding areas. In general, NO_x-limited regimes were found in the rural/remote areas, whereas urban/populous areas were under the VOC-limited regimes. Besides, transition regime was more frequently found in NCP than in PRD and YRD.

VOC-limited regimes dominated in the urban areas of Beijing, a densely-populated city with serious pollution problems (Zhang et al., 2014; Tang et al., 2010; Chou et al., 2009; Shao et al., 2009a; Xu et al., 2008). By adopting different emission inventories in different domains in a community multiscale air quality (CMAQ) model, Xu et al. (2008) revealed that in summer 2000, the urban areas of Beijing were generally in a VOC-limited regime, while the urban downwind areas changed gradually to a NO_x-limited condition. Similarly, sensitivity analysis of O_3 formation in central urban Beijing was performed by Tang et al. (2010) in August 2006 using the Nested Air Quality Prediction Model System (NAQPMS). It was found that abatement of the most contributing VOCs could be more efficient on reducing the high levels of surface O_3, while inadequate abatement of NO_x would lead to a reverse outcome. Apart from model

simulation, a few field measurements at PKU (an urban site) in summer proved that O_3 formation was mostly in a VOC-limited regime (Zhang et al., 2014; Chou et al., 2009; Shao et al., 2009a). In addition to Beijing, a VOC-limited regime was also identified at an urban site in Tianjin (i.e. Tieta) using the NCAR-Master Mechanism model (NCAR-MM) to reveal the response of local O_3 to the emissions of its precursors during July-August of 2010 and 2011 (Wei et al., 2015).

Furthermore, NO_x-limited regime in NCP was reported by few studies. A 5-week field campaign was conducted at a suburban site in Tianjin in summer 2009. In the study, a NO_x-limited regime was identified, diagnosed by the VOCs/NO_x ratios and further verified by a photochemical box model (i.e. NCAR-MM) (Ran et al., 2011). Apart from field measurements, the chemical sensitivity of O_3 formation over NCP region was investigated in summer 2015 by a recent study using the regional atmospheric modeling system-community multiscale air quality (RAMS-CMAQ) (Han et al., 2018). Results indicated that NO_x-sensitive regimes dominated in remote/rural areas in the NCP.

Besides, areas in NCP were frequently found under transition regimes. For instance, from a sampling campaign at PKU and Yufa (a rural site) in summer 2006, transition regimes were identified at both sites by two studies (Lu et al., 2010; Shao et al., 2009a). On one hand, Lu et al. (2010) adopted the relative incremental reactivity (RIR) values and the parameter L_N/Q (fraction of radicals removed by reaction with NO_x related to total radical production rates) to determine the O_3 formation regime. It was reported that NO_x-sensitive and VOC-sensitive regimes existed and frequently shifted to each other at both sites. On the other hand, Shao et al. (2009a) analyzed the O_3 formation regime at Yufa through the correlation between the daily maximum O_3 and the initial VOCs and NO_x level (correlation: $[O_3]_{max} = 0.26[VOCs]_{initial} + 2.24[NO_x]_{initial} + 48.9$). The correlation suggested that O_3 formation was sensitive to both emissions of VOCs and NO_x. Moreover, a recent study at a rural site downwind of Jinan in summer 2013 suggested that O_3 production was in a transition regime, analyzed by the OBM model (Zong et al., 2018). In addition to measurement-based analyses, Liu et al. (2012)

simulated the summertime photochemistry near the surface in Beijing in 2007 using a 1-D photochemical model. It was found that O_3 production was neither NO_x-limited nor VOC-limited, but was in a transition regime. Furthermore, a recent model study indicated that the emissions of VOCs and NO_x both vastly influenced O_3 formation in the suburban areas of NCP region in summer 2015 (Han et al., 2018).

Table 1 Summary of the studies of O_3 formation regime in the NCP

City	Site/Area	Year & Season	Land-use function	O_3 formation regime	Method	Reference
Beijing	PKU	2004-2006, Summer	Urban	VOC-limited	Correlation analysis	Shao et al. (2009a)
		2005-2011, Summer	Urban	VOC-limited	Observation-based model & Correlation analysis	Zhang et al. (2014)
		2006, Summer	Urban	VOC-limited	Observation-based model	Chou et al. (2009)
		2007, Summer	Urban	Transition	Emission-based model	Liu et al. (2012)
		2006, Summer	Urban	Transition	Observation-based model	Lu et al. (2010)
	Yu Fa		Rural			
		2004-2006, Summer	Rural		Correlation analysis	Shao et al. (2009a)
	Central urban Beijing	2006, Summer	Urban	VOC-limited	Emission-based model	Tang et al. (2010)
The whole Beijing	N/A	2000, Summer	Urban	VOC-limited	Emission-based model	Xu et al. (2008)
			Urban downwind area	NO_x-limited		
Tianjin	Wu Qing	2009, Summer	Suburban	NO_x-limited	Observation-based model	Ran et al. (2011)
	Tieta	2010-2011, Summer	Urban	VOC-limited	Observation-based model	Wei et al. (2015)
Jinan	Yu Cheng	2013, Summer	Rural	Transition	Observation-based model	Zong et al. (2018)
The whole NCP	N/A	2015, Summer	Rural	NO_x-limited	Emission-based model	Han et al. (2018)
			Sub-urban	Transition		

2.2 The YRD region

Compared to PRD and NCP, fewer studies were carried out in YRD. Nevertheless, cities/areas under different O_3 formation regimes (i.e. VOC-limited and NO_x-limited regime) were still reported by a few studies, which are summarized in Table 2. Briefly, O_3 formation in most of the areas in YRD was under VOC-limited regimes. Shanghai and Nanjing were the two popular cities for investigating the O_3 formation regime.

Previous studies indicated that Shanghai and its surrounding cities were basically in VOC-limited regimes (Xu et al., 2017; An et al., 2015; Xue et al., 2014; Tang et al., 2008; Geng et al., 2008). For instance, it was reported that O_3 production at two urban sites in Shanghai was situated in a non-methane organic compounds (NMOC)-limited regime based on the ratios of VOCs/NO_x (Ran et al., 2009; Tang et al., 2008). Consistent result was found by Li et al. (2012a) in urban Shanghai with the help of a CMAQ modeling system with Carbon Bond 05 (CB05) chemical mechanism. Aside from urban areas, a VOC-limited regime was also identified at a suburban site near Shanghai in summer 2005 using a photochemical box model with master chemical mechanism (PBM-MCM) (Xue et al., 2014). In addition to Shanghai, VOC-sensitive regimes existed likewise in Nanjing. For instance, by analyzing the VOCs/NO_x ratios and RIR values, An et al. (2015) proved that the O_3 formation in Pancheng town (a rural site) was VOC-limited in the summer of 2013. Moreover, the same O_3 formation regime was found at the station for Observation Regional Processes of the Earth System (SORPES) in Nanjing (a suburban site) by two studies. One was analyzed through the OBM method based on the data collected on National Day holiday in 2014 (Xu et al., 2017) and the other was indicated by the correlations of CO-NO_y-O_3 using the data collected in 2011 for one year (Ding et al., 2013).

Moreover, NO_x-sensitive regime and transition regime were barely found in YRD based on observation-based studies. Nevertheless, with the help of a CMAQ modeling system with Carbon Bond 05 (CB05) chemical mechanism, Li et al. (2012a) pointed out that NO_x-sensitive regime existed in rural areas of YRD in summer 2010, such as Jinshan district in Shanghai.

Table 2 Summary of the studies of O_3 formation regime in the YRD

City	Site/Area	Year & Season	Land-use function	O_3 formation regime	Method	Reference
Shanghai	Tai Cang	2005, Summer	Suburban	VOC-limited	Observation-based model	Xue et al. (2014)
	Song Jiang	2006-2007, All seasons	Urban	VOC-limited	VOCs/ NO_x ratios	Ran et al. (2009)
	Xu Jia Hui	2006, Summer to Winter	Urban	VOC-limited	VOCs/ NO_x ratios	Tang et al. (2008)

Nanjing	Pan Cheng	2013, Summer	Suburban	VOC-limited	Observation-based model	An et al. (2015)
	The Station for Observing Regional Processes of the Earth system	2011, Summer	Rural	VOC-limited	Correlation analysis	Ding et al. (2013)
	Xian Lin	2014, Summer (National Day holidays)	Suburban	VOC-limited	Observation-based model	Xu et al. (2017)
Urban Shanghai	N/A	2010, Summer	Urban	VOC-limited	Emission-based model	Li et al. (2012a)
Suburban Shanghai (Jinshan)			Suburban	NO_x-limited		
Nanjing			Urban	N/A		
Hangzhou			Urban	N/A		

2.3 The PRD region

Numerous studies have investigated the O_3 formation regime in PRD during the high-O_3 seasons (i.e. summer and autumn) over the past 20 years, especially in Hong Kong and the inland PRD region. Summary of these studies is shown in Table 3. Basically, O_3 formation was controlled by the emission of VOCs in most of the areas of PRD, which was consistent with the result of previous studies (Wang et al., 2017a; Guo et al., 2017), whereas the other O_3 formation regimes (i.e. NO_x-limited and transition regime) were only found out of the densely populated areas/cities.

Different approaches used in previous studies have proved that most of the areas in PRD were under VOC-limited regimes. In 2000, gaseous pollutants and VOCs samplers were measured in the central of Guangzhou from summer to autumn. It was reported that O_3 formation was generally limited by the concentrations of VOCs according to the RIR values extracted from the OBM model (Shao et al., 2009b). In addition to urban areas, several studies pointed out that VOC-limited regimes also existed in rural areas of Guangzhou (Xue et al., 2014; Cheng et al., 2010; Zhang et al., 2008). Apart from Guangzhou, areas under VOC-sensitive regimes were found in Hong Kong as well. From 23 October to 01 December 2007, ambient O_3 and its precursors were measured at Tung Chung (TC), a suburban site in Hong Kong. Using the database, two studies reported that O_3 production at TC was generally VOC-limited, which meant reducing VOCs decreased the O_3 formation and reducing NO_x could increase O_3 level (Cheng et al., 2010; Guo et al., 2009). Moreover, from 6 September to 29 November 2010, a field

286 measurement of O_3 and its precursors was conducted at Tai Mo Shan (TMS) and Tsuen
287 Wan (TW) (a rural site and an urban site, respectively). The O_3 formation regimes at
288 two sites were revealed. At TMS, photochemical O_3 formation was mostly influenced
289 by VOCs with a measurable effect of NO_x according to the RIR analysis (Guo et al.,
290 2013), while O_3 concentration was negatively correlated with NO_x at TW, implying that
291 O_3 formation was primarily VOC-sensitive, further validated by the VOCs/NO_x ratios
292 and RIR values (Ling and Guo, 2014; Lam et al., 2013). Aside from measurement-based
293 analyses, consistent results were obtained using the emission-based models. By using
294 a WRF/SMOKE-PRD/CMAQ modeling system to explore the photochemistry over the
295 entire PRD region in August and October 2010, Ou et al. (2016) suggested that intensive
296 controls of anthropogenic VOC were more efficient for short-term despiking of peak
297 O_3 levels in urban and port areas of PRD. The results were in line with another modeling
298 study, which reported that O_3 formation was VOC-limited in the central inland PRD,
299 PRE, and surrounding coastal areas in autumn 2004 (Wang et al., 2010). In addition, a
300 modeling study investigated the peculiarity of O_3 episode days in Hong Kong in
301 summer 2005 by a high-resolution air quality model (Pollutants in the Atmosphere and
302 Their Transport in Hong Kong (PATH)). It was pointed out that the chemical regime for
303 O_3 formation in Hong Kong seemed to be mainly limited by VOCs (Huang et al., 2005).
304 Furthermore, NO_x-limited regime was only found in rural areas of PRD by few
305 modeling studies. Based on the anthropogenic emissions inventory and the biogenic
306 emissions inventory provided by HKEPD and inland PRD authority, Wang et al. (2010)
307 simulated O_3 pollution over the PRD region in October 2004. Results showed that O_3
308 formation was generally NO_x-limited in rural southwestern PRD, where the air masses
309 were photochemically aged. Moreover, Ou et al. (2016) indicated that O_3 formation was
310 always NO_x-limited at a rural site in PRD (Jiangmen) on the O_3 episode days in August,
311 based on the O_3 isopleth profiles obtained from a WRF/SMOKE-PRD/CMAQ
312 modeling system.
313 Noteworthily, shift among different O_3 formation regimes was reported by few field

studies in PRD, which indicated that O_3 formation was limited by both VOCs and NO_x. For instance, the chemical sensitivity of O_3 formation was investigated at a remote island site (Wan Shan Island) in 2013. Results found that O_3 production at the oceanic site changed from transition regimes on non-O_3 episode days to VOC-limited regimes on O_3 episode days (Wang et al., 2018). Moreover, at a suburban site in Guangzhou (i.e. Panyu), O_3 formation in summer and autumn was usually NO_x-limited at noon but shifted to VOC-limited when O_3 concentrations became low in the morning and at night according to the VOC/NO_x ratios (Zou et al., 2015). In addition to field studies, transition regimes were also identified at a suburban site and a rural site in Guangdong in the summer and autumn of 2010, respectively, with the help of the WRF/SMOKE-PRD/CMAQ modeling system (Ou et al., 2016).

Table 3 Summary of the studies of O_3 formation regime in the PRD

City	Site/Area	Year & Season	Land-use function	O_3 formation regime	Method	Reference
Guangzhou	Guangzhou Research Institute of Environmental Protection	2000, Summer -Autumn	Urban	VOC-limited	Observation-based model	Shao et al. (2009b)
	Wan Qin Sha	2007, Autumn to Winter	Rural	VOC-limited	Observation-based model	Cheng et al. (2010)
		2004, Summer		VOC-limited	Observation-based model	Xue et al. (2014)
	Xin Ken	2004, Autumn	Rural	VOC-limited	Observation-based model	Zhang et al. (2008)
	Pan Yu	2011-2012, Summer & Autumn	Suburban	Transition	VOC/NO_x ratios	Zou et al. (2015)
Hong Kong	Tsuen Wan	2010, Summer to Autumn	Urban	VOC-limited	Observation-based model	Ling and Guo (2014), Lam et al. (2013)
	Tai Mo Shan		Rural	VOC-limited	Observation-based model	Guo et al. (2013)
	Wan Shan Island	2013, Summer to Autumn	Rural	Transition	Observation-based model	Wang et al. (2018)
	Tung Chung	2007, Autumn to Winter	Suburban	VOC-limited	Observation-based model	Cheng et al. (2010), Guo et al. (2009)
The whole Hong Kong	N/A	2004, Summer	N/A	VOC-limited	Emission-based model	Huang et al. (2005)
Guangzhou	N/A	2010, Summer	Urban	VOC-limited	Emission-based model	Ou et al. (2016)
		Autumn				
Dongguan		2010, Summer	Suburban	Transition		
		Autumn		VOC-limited		

Nansha		2010, Summer	Suburban	VOC-limited		
		Autumn				
Jiangmen		2010, Summer	Rural	NO_x-limited		
		Autumn		Transition		
The whole PRD	The central inland PRD and costal area	2004, Autumn	Urban/Suburban	VOC-limited	Emission-based model	Wang et al. (2010)
	The rural southwestern PRD		Rural	NO_x-limited		

2.4 Other regions

Apart from the three most developed regions above, the O_3 formation regimes were also investigated in cities of other regions, as shown in Table 4. In Lanzhou, O_3 was formed under a NO_x-sensitive regime at a suburban site while VOC-sensitive regime was found in downtown area in summer 2013 according to the O_3-isopleth plots (Jia et al., 2016). The result was consistent with the previous study of Xue et al. (2014), which conducted a field measurement at other rural site in Lanzhou in 2006. Moreover, in Wuhan, the central China, O_3 formation was mostly controlled by the emission of VOCs (except July 2013) because of the great contribution of vehicle emission and coal burning (Lyu et al., 2016). In southwestern China, Tan et al. (2018) investigated the O_3 formation regime at four sites in Chengdu using an OBM model and found that reduction of anthropogenic VOCs was the most efficient way to mitigate O_3 pollution since most of the sampling sites were under the VOC-limited regimes. At this stage, summary of O_3 formation regime in other regions besides NCP, YRD and PRD is difficult to achieve due to the limited references. More intensive studies are expected to fill the knowledge gap in the future.

Table 4 Summary of the studies of O_3 formation regime in other regions

City	Site/Area	Year & Season	Land-use function	O_3 formation regime	Method	Reference
Lanzhou	Lanzhou Environmental Monitoring Station	2013, Summer	Urban	VOC-limited	Correlation analysis	Jia et al. (2016)
	West suburban site		Suburban	NO_x-limited		
	Renshoushan Park	2006, Summer	Suburban	NO_x-limited	Observation-based model	Xue et al. (2014)

Wuhan	Hubei Provincial Environmental Monitoring Center	2013-2014, All seasons	Urban	VOC-limited	Observation-based model	Lyu et al. (2016)
Chengdu	Peng Zhou	2016, Autumn	Suburban	Transition	Observation-based model	Tan et al. (2018)
	Pi Xian			VOC-limited		
	Shuang Liu					
	Cheng Zhong		Urban			

Overall, O_3 formation in the most areas of NCP, YRD, and PRD regions is likely in a VOC-limited regime due to the vastly anthropogenic emissions of air pollutants. Out of these metropolitan areas, O_3 formation in rural/remote areas is mainly limited by NO_x levels. Such discrepancy of O_3 formation regime is mainly attributed to the disparity of different O_3 precursors' levels in different land-use function areas. In general, NO_x levels are high in metropolitan areas due to the vast emission of NO_x from human activities (i.e. combustion and vehicle emission), and thus NO_x is saturated for O_3 formation. However, NO_x-limited regime dominates rural areas as VOCs are usually sufficient for O_3 formation because of the abundance of biological VOCs emission from plants and rare NO_x emission from human activities. Furthermore, more intensive studies in other regions besides NCP, YRD and PRD are expected in the future.

3. Diurnal, seasonal and long-term patterns of O_3 formation regimes

Apart from the spatial distribution, it is pointed out that O_3 formation regimes in China have several temporal characteristics, including diurnal, seasonal and long-term variations (Wu et al., 2018; Jin and Holloway, 2015; Brown and Stutz, 2012; Liu et al., 2010).

3.1 Diurnal variation of O_3 formation regimes

O_3 pollution basically occurs in the daytime since sunlight is the major driving force for the photochemical chemistry. Therefore, majority of researches conducted O_3 pollution investigation during daytime. It was not until 10 years ago, night-time chemistry in the troposphere began to be explored and thus the relationships between

O_3 and its precursors at night were revealed (Brown and Stutz, 2012). Generally, O_3 level rises in the morning, peaks in the afternoon and then gradually declines at night (Reddy et al., 2011; Xu et al., 2008). The increase of O_3 in daytime is caused by the O_3 production sequence in the presence of sunlight, while O_3 concentration declines at nighttime through the process of NO_x titration. In the night-time process of NO_x titration, O_3 is firstly removed by its reaction with NO, which generates NO_2 and O_2. This reaction also exists in the daytime. However, in the absence of the photolysis of NO_2 to prompt O_3 formation at night, the result is net conversion of O_3 to NO_2. After that, the nitrate radical, NO_3, is generated through the reaction of NO_2 with O_3, which further consumes O_3 and thus reduces O_3 level. Detailed mechanism of night-time chemistry was summarized by a recent paper (Brown and Stutz, 2012). Overall, the O_3 concentration at night is mainly controlled by the NO_x level.

Because of the typical O_3-precursor relationship at night, hourly O_3 levels show different diurnal patterns in areas of different land-use function (e.g. urban and rural areas). Generally, O_3 concentrations peak at around 14:00 and decrease significantly at night in urban areas, while the peak values of O_3 usually appear several hours later and do not drop instantaneously after sunset in rural/remote areas due to the lower emissions of NO_x from human activities. For instance, according to a field measurement of O_3 at an urban site and a downwind rural site around Beijing from June 2005 to September 2006, 90% of the O_3-episode events (hourly O_3 level exceeded the China's norm) took place before 16:00 at the urban site, while more than 82% of those happened at night at the rural site (Ma et al., 2011). Moreover, from another four-year measurements of O_3 and its precursors from 2005 to 2008 at an urban and a rural site in Beijing, peak O_3 value appearing time in the rural area was delayed by 2-3 hours from the time in the urban area (i.e. 14:00) (Xu et al., 2011). In addition to field measurements, Li et al. (2012a) adopted the CMAQ model to simulate the O_3 levels over the YRD region during the O_3 episode days in summer 2010. The O_3 concentration decreased rapidly after sunset in urban areas due to the strong effect of NO titration, whereas O_3 could

still spread to rural areas and maintain high levels. Thus, O_3 pollution could be a notable problem in rural areas at night.

3.2 Seasonal variation of O_3 formation regimes

Previous review has revealed the seasonality of O_3 levels in the three regions (Wang et al., 2017a). In NCP and YRD, higher O_3 level was generally observed in the summertime. In PRD, O_3 levels were high in summer and autumn but it generally reached maximum value in autumn. Though the seasonality of O_3 level had been clearly discussed and summarized previously, the seasonal variation of O_3 formation regime was still unknown. A few field measurements were conducted in different seasons to solve the puzzle previously. Based on the observation-based studies, it seemed that in urban and rural/remote areas, O_3 formation regime was consistent throughout the entire year, whereas it became variable in suburban area in different seasons. For example, based on the diurnal variations of O_3 and NO_x measured in central and rural areas of Guangzhou from 2006 to 2007, the O_3 production in central Guangzhou was mostly VOC-limited throughout the entire year, while O_3 production was limited by NO_x in the rural area all the time (Zheng et al., 2010). Furthermore, in downtown Shanghai (i.e. Xujiahui), Geng et al. (2008) reported that O_3 formation was mainly limited by VOCs concentrations in both summer and winter, according to the ratios of CH_2O/NO_y and the results of NCAR-MM model. In addition, after measuring O_3 and its precursors in the center of Tianjin for one year, Liu et al. (2016) pointed out that the central Tianjin belonged to the VOC-limited region during most seasons in view of the ratios of VOC/NO_x. In contrast, at a suburban site in Guangzhou (i.e. Panyu), O_3 formation was more likely to be VOC-limited in spring and winter while in summer and autumn, NO_x-limited regimes and VOC-limited regimes frequently shifted to each other in a day (Zou et al., 2015).

However, due to the limits of resource and technique, site measurements are often limited in time period and spatial extent (Jin and Holloway, 2015; Zhang et al., 2008). To clearly explore the season pattern of O_3 formation regime over China, a few recent

studies have employed different kinds of indicators (i.e. $P_{HNO_3}/P_{H_2O_2}$, $H_2O_2/(O_3+NO_2)$, O_3/NO_x, O_3/NO_y, $HCHO/NO_y$ and $HCHO/NO_2$) to identify and analyze the sensitivity of O_3 formation to VOCs and NO_x in different seasons over China (Jin and Holloway, 2015; Liu et al., 2010). These photochemical indicators were proposed and developed by Sillman (1995), and were applied in previous studies (Zhang et al., 2009; Tonnesen and Dennis, 2000). By comparing and validating the values of diverse indicators in different months over China, Liu et al. (2010) proved that several megacities such as Beijing, Shanghai, Tianjin, and some big cities in the YRD and PRD regions were always under the VOC-limited conditions throughout the entire year due to large amounts of traffic and industrial emissions of NO_x. Except these metropolitan areas, O_3 formation over almost the entire China during summer was in a NO_x-limited regime. However, in winter, the O_3 formation regime basically shifted to VOC-limited chemistry over the eastern China, as well as some major cities in most of the provinces. Furthermore, by analyzing the ratios of $HCHO/NO_2$ (FNR ratio) over the three most developed regions (NCP, YRD, and PRD) and their surrounding areas, Jin and Holloway (2015) indicated that in high-temperature seasons (defined as near-surface air temperatures >20 °C in the early afternoon), VOC-limited regimes basically dominated in the megacities (i.e. Beijing, Guangzhou and Shanghai) and cities with high density of power plants (i.e. Tangshan, Shijiazhuang and Zibo), while a widespread transitional regime was found in NCP, YRD and PRD, and NO_x-limited regime was dominant out of these regions. Similarly, O_3 formation regimes in the three regions were all intended to shift to VOC-limited in winter according to the lower FNR ratios. In addition to the usage of photochemical indicators, such a shift was also discovered by Ou et al. (2016), using a WRF/SMOKE-PRD/CMAQ modeling system to investigate the seasonal differences of O_3 formation regimes in the urban and port areas of PRD.

3.3 Long-term variation of O_3 formation regimes

The elevated O_3 levels in China are mainly attributed to the great emission of anthropogenic pollutants in the process of industrialization and urbanization over the

last 20 years. After the awareness of severe O_3 pollution in China, dramatic controls of the emissions of VOCs and NO_x were implemented by the central government, especially in the past decade. Previous studies have revealed the long-term variations of the VOCs and NO_x levels before and after the implementation of control measures (Diao et al., 2018; Wang et al., 2017a). Dramatic control of industrial NO_x was implemented during the China's 12th-Five-Year-Plan in 2011. Since then, the total emissions of NO_x reached its peak since it had increased in 1980s and began to decline. However, compared with the successful control of NO_x, the reduction of VOCs emission was delayed. No turning point of the emission of VOCs was observed up to 2014 since it had also increased in 1980s. Due to the variations of O_3 precursors' levels, the sensitivity of O_3 formation to VOCs and NO_x in China varied over the past decades as well.

Although the sensitivity of O_3 formation to VOCs and NO_x was investigated through numerous emission-based and/or observation-based studies over the last 20 years, it is still difficult to comprehensively reveal the long-term variation of O_3 formation regime over China. Emission-based studies basically depend on emission inventories, meteorological inputs, chemical processes, and boundary layer dynamics, all of which have associated uncertainties, while long-term and large-scale field measurements are very rare in China. Therefore, the photochemical indicators are very suited to analyze the long-term variation of O_3 formation regime over China. A mass of continuous and long-term data can be obtained from the satellite in given area and time period. For example, using the satellite data of HCHO and NO_2 measured by NASA from 2005 to 2013, Jin and Holloway (2015) revealed the variations of HCHO and NO_2 levels over China, and investigated the spatial-temporal variation of O_3 formation regime by calculating the FNR ratios. A significant increasing trend in NO_2 and an insignificant tendency in HCHO were observed in the three most developed regions (i.e. NCP, YRD and PRD), resulting in a widespread decrease in FNR ratios. As such, the O_3 photochemistry in China became more sensitive to VOCs, embodied in the spatial

expansion of VOC-limited and transitional regimes and the longer duration of transition and VOC-limited regimes in a year. Moreover, the study pointed out that a VOC-limited regime is likely to occur throughout eastern China as early as 2025, if no significant change in the emissions of VOCs and NO_x occurs and stable trends in FNR ratios remain in the future. However, it should be noticed that the result of linear extrapolation is not reliable to be regarded as prediction since the industry and environment policies change rapidly in China. As mentioned, successful reduction of NO_x has been achieved since the implementation of a series of policies in the 12th Five-Year-Plan. The ambient concentration of NO_x decreased by 10.1% from 2013 to 2016 monitored from 74 mega-cities in China (Zhu et al., 2017). However, the actions on reduction of VOCs were delayed. Therefore, the shift to VOC-limited regimes will be slowed down or even some regions will change to NO_x-limited regimes (Wang et al., 2017a). The assumption was supported by Wu et al. (2018), using the Ozone Monitoring Instrument (OMI) satellite remote sensing data from NASA to analyze the O_3 formation regime in Beijing-Tianjin-Hebei (BTH) region from 2005 to 2016. Wu et al. (2018) demonstrated that the domain of NO_x-limited regime in BTH region showed a trend of increase, mainly due to the effective control of NO_x emission during 12th Five-Year-Plan.

To sum up, literature review revealed that O_3 level at night was mainly controlled by the amount of NO_x at a specific site. Since NO_x levels are usually low in rural areas due to lack of human activities, O_3 pollution could be a notable problem in rural areas at night. Except the metropolitan areas, which were dominated by VOC-limited regimes throughout the entire year due to large amounts of traffic and industrial emissions of NO_x, most of the areas of China intended to shift from other O_3 formation regimes (transition or NO_x-limited regimes) in summer to a VOC-limited regime in winter. In addition, because of the dramatic increase of NO_x since the 1980s, O_3 formation in China moved toward increasing sensitivity to VOC emissions. However, it is likely that the shift will be slowed down or even some regions will change to NO_x-limited regimes owing to the delayed actions on VOCs controls and the successful reduction on NO_x

emission during the 12th-Five-Year-Plan. Hence, effective control measures of VOCs emissions are supposed to be implemented in time.

In addition to variations of O_3 precursors' levels, changes in meteorological conditions also influence the nonlinear O_3 formation chemistry. Pusede et al. (2015) comprehensively investigated the relationship between temperature and the recent trends of the surface O_3 in America and proved that the chemical terms driving produces O_3 (PO_3) vary nonlinearly with temperature. Temperature affected the PO_3 through influencing the reaction rates in photochemical reactions and levels of key components in O_3 formation (i.e. VOCs, NO_x and highly reactive radicals). In a day, the reactivity of HO_x radicals increases when the solar radiation and temperature go up at noon, which leads to the rapid consumption of NO_x and thus the O_3 formation regime becomes more NO_x-limited. In a year, depressed temperature and solar radiation in winter slow down the consumption of NO_x through the subdued reactions with HO_x radicals and thus NO_x level increases and the O_3 formation regime shifts to a more VOC-limited regime. In decades, under the circumstance that global temperatures are projected to rise, the lifetime of NO_x and peroxy nitrates (RO_2NO_2) decreases. NO_x levels in remote areas may become lower as a result of less transportation of NO_x from urban areas, while the abundance of NO_x may increase in populated cities due to the stronger decomposition of RO_2NO_2 to NO_x. As such, O_3 formation regimes may become more VOC-limited in urban areas and more NO_x-limited in remote areas driven by climate change. Overall, changes in meteorological conditions along with future changes in O_3 precursor emissions will alter PO_3 in ways that are predictable but complex.

4. Implications for the control of O_3 pollution

Since O_3 is a secondary pollutant, it cannot be controlled directly. Controls of O_3 pollution should focus on reductions of its precursors. A number of policies were implemented to control O_3 precursors in recent years. For NO_x, the emission of NO_x from industrial companies and coal-fired power plants had been controlled by the

central government since the 12th Five-Year-Plan. As for VOCs, Guo et al. (2017) summarized 23 programs/plans for the control of VOCs in recent years in megacities (or megacity clusters) in China such as Beijing, Shanghai, Guangdong, Zhejiang and Jiangsu. The control measures mainly focused on cutting the emissions from vehicles, vessels and industrial sectors. Although governments have put great efforts on controlling O_3 pollution (i.e. controls of O_3 precursors), O_3 pollution is still a serious problem in China and the development of an effective strategy for reducing O_3 pollution is still problematic due to various characteristics of O_3 pollution (e.g. regionality, seasonality and severity) and the nonlinear dependency of O_3 formation on NO_x and VOCs (Zhu et al., 2017; Lu et al., 2018). After reviewing and summarizing the spatial-temporal variations of O_3 formation regimes over China, implications for the control of O_3 pollution are proposed.

4.1 Precise control of O_3 precursors

In view of the discussions in Sections 2 and 3, precise controls of O_3 precursors are proposed. On one hand, control measures should vary in different regions/areas according to the spatial variations of O_3 formation regime. To effectively reduce the O_3 levels in the three most developed regions (i.e. NCP, YRD and PRD) during the high-O_3 seasons (summer and autumn), intensive controls of VOCs or both precursors are effective since most of the areas in these regions are likely VOC-sensitive or mixed-sensitive due to the vastly anthropogenic emission from populated cities. According to our previous review on tropospheric VOCs in China (Guo et al., 2017), the dominant sources of VOCs emissions in the populated cities of the three regions were summarized. In brief, vehicular emissions and industrial emissions were the common VOC sources. In addition, solvent usage made significant contribution to VOCs in PRD. Therefore, by controlling these sources, VOCs emissions could be effectively reduced in the cities of the three regions. However, in areas out of these metropolitan cities and/or in the rural/remote areas in the three regions, O_3 production is mainly limited by NO_x and thus reduction of NO_x emission is more helpful for alleviating O_3 pollution.

On the other hand, the priority of control measures should alter with respect to the temporal variations of O_3 formation regime. First, although the tremendous emission of anthropogenic pollutants leads to the elevated O_3 levels over China, the strong effect of NO_x titration significantly reduces the O_3 levels in populated/urban areas at night. However, in rural/remote areas, O_3 may reach the maximum value at dusk and maintain a high level at night (Figure 1). Therefore, O_3 pollution at night in rural areas should be taken into consideration in term of policy making. Second, enhanced controls of VOCs should be adopted in winter since the satellite data showed that O_3 formation regimes over China were intended to shift to VOC-limited in winter (Figure 1). Third, due to the dramatic emission of NO_x from traffic and industrial emissions since the 1980s, O_3 formation in China moved toward increasing sensitivity to VOC levels. Until the time launching the 12th Five-Year-Plan, significant controls of NO_x emission from industry successfully reduced the NO_x levels in China and thus delayed the trend (Figure 1). Due to dramatic NO_x decline in the 12th Five-Year-Plan, the effect of NO titration will be reduced at night and the minimum level of O_3 may become higher, especially in urban areas. Therefore, further intensive control of VOCs is expected in the future to realize synchronous reduction of O_3 precursors and eventually achieve O_3 abatement.

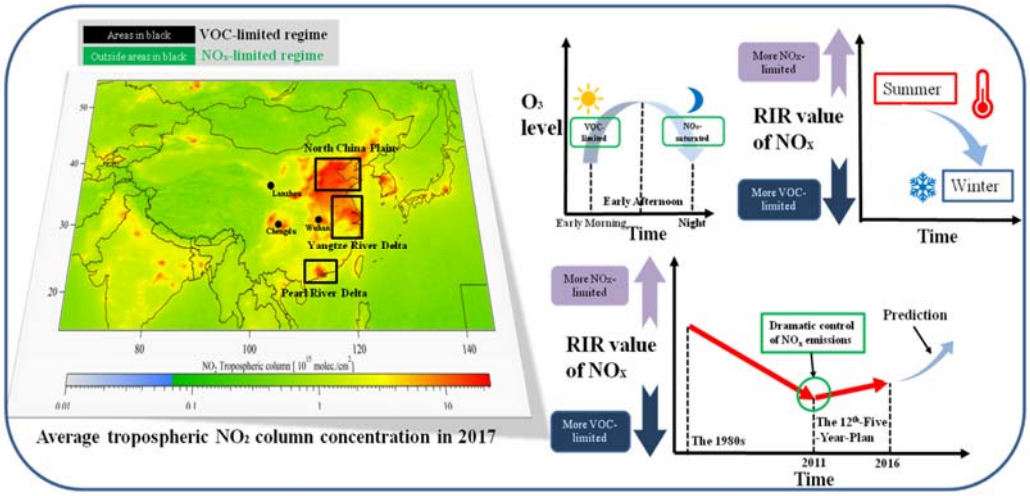

Figure 1 Spatial-temporal characteristics of O_3 formation regimes and the implications for O_3 pollution control in China

4.2 Joint prevention and control of regional air pollution

O_3, as a secondary pollutant with relatively long lifetime, caused not only an autochthonous problem but also a regional transboundary problem. O_3 attainment cannot be simply achieved by the control of pollutant emissions only by local governments as O_3 and its precursors can transport to the downwind areas with the help of wind. Also, joint prevention and control of regional air pollution are indispensable to achieve precise control of O_3 precursors mentioned above. Previous studies pointed out that regional collaborations were important for developing effective strategies on air quality improvement and/or sustained O_3 attainment (Jin et al., 2016; Wu et al., 2015; Wang et al., 2014; Li et al., 2012b). By using the CMAQ model to simulate emission reduction in BTH and YRD regions, Wang et al. (2014) found that reduction in a specific province may not only benefit the improvement of local air quality inside the province, but also has a considerable contribution to the improvement of the air quality in nearby cities. For example, the 10% emission reduction of SO_2 and NO_x in Hebei enhanced the reductions of different pollutants (i.e. NO_2, SO_4^{2-} and NO_3^-) with 1%~4% in Beijing and Tianjin. In addition, Xing et al. (2011) examined multiple emission reduction options using the CMAQ model. It was found that reduction of local NO_x or VOC emissions in Beijing was not sufficient to achieve O_3 attainment while synchronous regional reductions in VOC and NO_x by 60% to 80% were recommended across the entire NCP region. Moreover, Wu et al. (2015) proved that joint regional air pollution control in the BTH region will save the expense on air pollution control compared to a locally-based pollution control strategy. Taking reduction of SO_2 as an example, it was estimated that 3.6 billion CNY could be saved if joint regional air pollution control was implemented in Beijing and its surrounding cities for reducing 6 ppbv of SO_2. Such strategy is applicable to reductions of other pollutants to save cost (i.e. NO_x and VOCs).

To effectively proceed regional joint controls, the central government of China has promulgated a few policies since 2010. For example, nine regions, including the BTH

region, the PRD region, the YRD region, central Liaoning region, Shandong Peninsula, Western Taiwan Straits Metropolitan region, Cheng-Yu Metropolitan region, Wuhan Metropolitan region, and Cheng-Zhu-Tan region have been designated as the pilot and key regions by the State Council for the joint prevention and control of regional air pollutants (i.e. SO_2, NO_x, PM and VOCs) in 2010 (Zhou and Elder, 2013). In addition, the General Office of the State Council published a guideline on strengthening joint prevention and control of atmospheric pollution to improve air quality on 11 May 2010 (http://www.gov.cn/gongbao/content/2010/ content_1612364.htm). In the Guideline, "joint planning," "joint monitoring," "joint supervision," "joint assessment," and "joint coordination" were proposed for regional air pollution management. In particular, a number of measures were proposed, including 1) implementation of the discharge permit system; 2) build-up of stronger environmental protection verification systems for key industries; 3) development of a franchising system for the construction and operation of pollution control facilities; 4) establishment of stronger environmental information disclosure system, and 5) development of a system of compliance management of urban air quality standards.

As a matter of fact, several regions/cities followed the guideline and implemented joint control measures for regional pollution in recent years. For instance, in November 2017, three cities, including Harbin, Daqing and Suihua, jointly signed a protocol on joint prevention and control of regional air pollution, in which it required to build environmental information sharing system, promote prohibition of straw burning and utilization of straw, and establish coordination mechanism for heavy polluted events (http://www.hlj.gov.cn/zwfb/system/2017/11/04/ 010853072.shtml). Moreover, to efficiently improve the regional air quality in Beijing and its surrounding areas, the Beijing Municipal Environmental Protection Bureau solicited public opinions in March 2014 in regard to the implementation of joint prevention and control of regional air pollution in six cities, including Beijing, Tianjin, Hebei, Shanxi, Shandong and inner Mongolia (http://www.bjepb.gov.cn/ bjhrb/hdjl/jyxc/lflkgzjzhzdcszqgzyj/index.html).

In addition to the above nine regions, a new and enhanced network was proposed and established in September 2014, named Guangdong-Hong Kong-Macao PRD Regional Air Quality Monitoring Network, aiming to 1) provide accurate data to help three Governments appraise the air quality in the PRD and formulate appropriate control measures; 2) evaluate the effectiveness of executed control measures through long-term monitoring; and 3) provide the detailed information of air quality to the public.

Although air pollution seems to be a persistent problem due to the on-going urbanization and industrialization, it is expected that the air quality would be gradually improved if there are monitoring stations monitoring air quality and appropriate control measures are implemented.

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