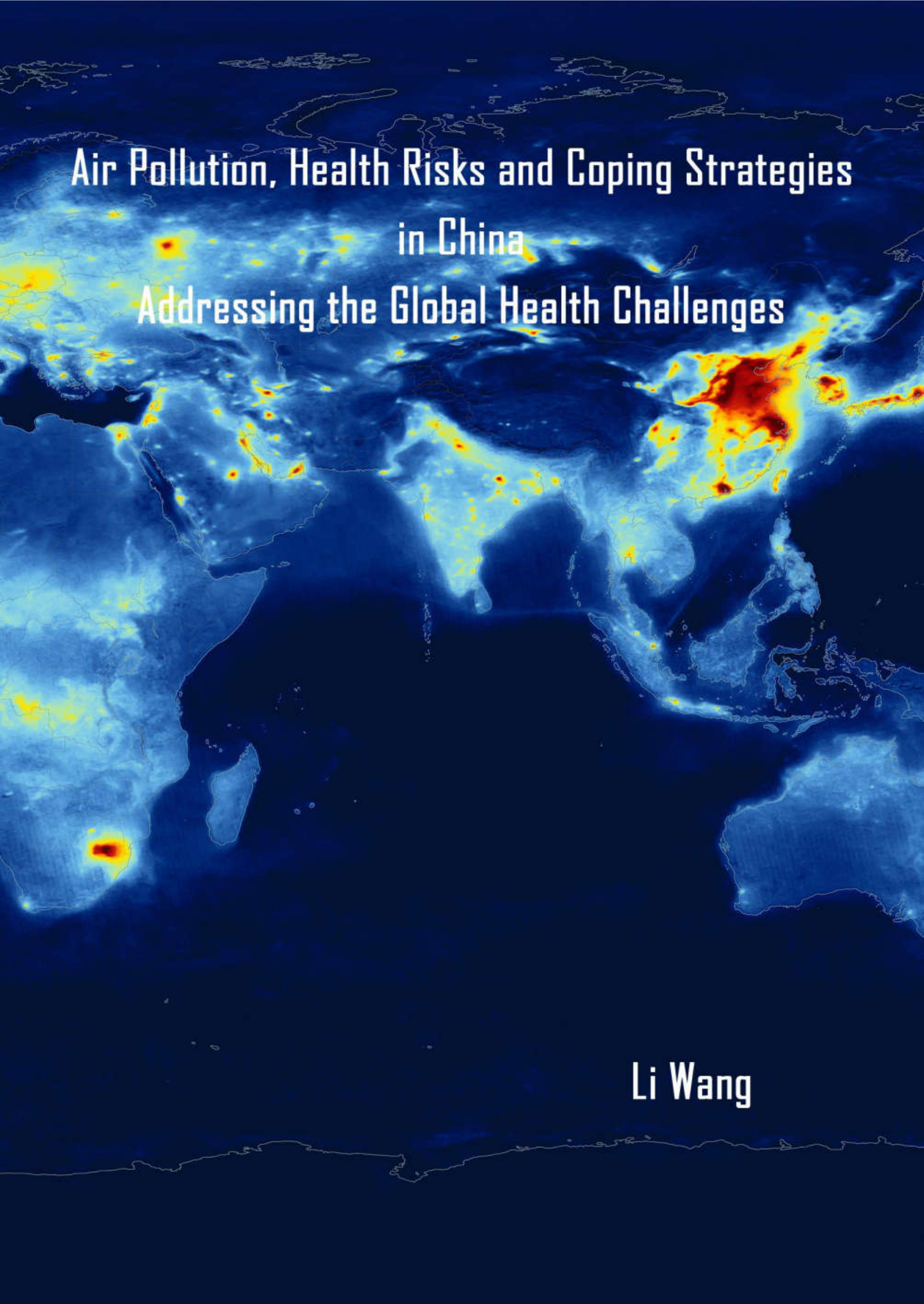
Air pollution, health risks and coping strategies in China



Air Pollution, Health Risks and Coping Strategies in China

Addressing the Global Health Challenges

Li Wang

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DISSERTATION

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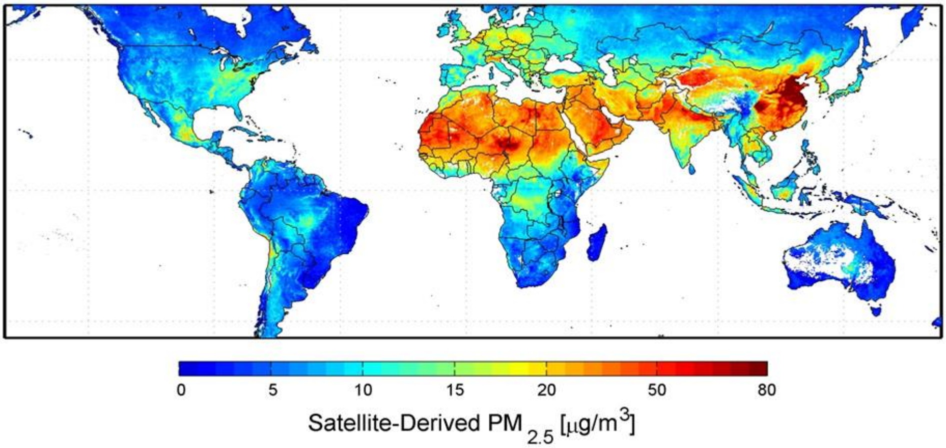
CHAPTER 1

General introduction and objective of this dissertation



Global satellite-derived map of $PM_{2.5}$ averaged over 2001-2006 (van Donkelaar et al., 2010)

Why this thesis?

For most of my university education I have lived in Beijing. I saw the city sprawling at an extreme pace, and I experienced the visible changes in air quality. I know this is not only happening in Beijing, but in many cities across China. In 2004, when I moved to Beijing, air pollution didn't feature on peoples' agenda, but for the frequent heavy sandstorms in spring season. However, with the Olympic Games in 2008, and the thrill and surprise of blue skies during that period, I realized how polluted the air already was, not only during the sandstorms but the high level of everyday pollution. It was then I started to pay attention to air pollution, and one sentence from an online course about the air pollution control history in the United Kingdom (UK) caught my attention, "in many respects, law follows the significant recognition of a threat that is a surprise in a sense" (Wangyi open course). This "surprise" hit China at the end of 2011 and afterwards.

Very often, when writing an academic report or study that aims to change thinking, especially national thinking, there is a mixture of wild optimism and impending disappointment: wild optimism that the evidence that will be presented will be heard for what it is, but impending disappointment because the chance of influencing change is small. I am not sure that this is the case here. I am, of course, optimistic that the evidence can invite change, and I do feel that this is a moment to be heard. Alarmed by the heavy haze episodes happening regularly since 2011, the government took actions in the forms of revising legislations, upgrading emission standards and air quality standards, and implementing strict actions. Many of these standards took European standards as a reference. For example, China adopted stringent European vehicle emission standards with a pace even faster than Europe. This deepened my scientific curiosity on how to contribute to a better understanding regarding air pollution control strategies in China. The initial and overall intent in writing this dissertation is about contributing to a deeper understanding of the health impact of air pollution and control strategies including different stakeholders - the government, the public, industries - and thus arousing a deeper debate among the stakeholders within China and even internationally, which in the end could lead to policy recommendations to decision-making.

Urbanization, environment and health

Urbanization is a result of the population migration from rural areas in addition to the natural urban demographic growth. From 1950 to 2014, the number of the urban population increased from 30% to 54% globally (United Nations, 2014). The developing countries have been and are still experiencing the fastest and the largest growth of urban expansion, both in number and in size. Rapid, unplanned, and unsustainable patterns of urban development are making developing cities focal points for many emerging environmental and health hazards (WHO, 2015). An unsustainable urbanization process could cause environmental, demographic and cultural problems. An economic growth decoupled from other social-environmental aspects (natural environment, economic geographical inequality, varied health investment, life habit change, mentality change, etc.) is the major reason for the emerging public health risks caused by environmental pollution.

Urbanization and air pollution in EU

Accelerated urbanization in Europe took place mainly in the 18th century, with an early start occurring in the UK. There, in the mid-nineteenth century, the population in London first surpassed one million residents (Bairoch, 1988). Pollution related diseases and deaths marked the industrial history of the UK, such as the cholera outbreak episodes in the 18th century because of water contamination (Trueman, 2016). As the pioneer of industrialization, England was early to experience the environmental health burden. For example, air pollution in London was of serious concern and the most prominent environmental health problem during the urbanization process; that was triggered by the coal - driven industrialization since the early 18th century. Although some legislation (The Public Health Act 1875) was issued in the early stage to control air pollution, it had if at all, only slight effect, and the air pollution reached to its peak in the early and middle 19th century. According to research, airborne particulate matter reached 4mg/m^3, sulphur dioxide (SO_2) reached 3.8mg/m^3, and smoke and dust reached 4.5mg/m^3 during the "toxic smog" in 1952 (Zhang and Samet, 2015; Bell and Davis, 2001). The Clean Air Acts in 1956 and 1968 provided local authorities with the responsibility to declare Smoke Control Areas, and the power to legislate against the use of non-compliant fuels and appliances in domestic properties within these areas (Zhang and Samet, 2015; UK, 1956). Around the 1980s, concerns about the pollutant sources shifted from coal combustion (industrial) to vehicle emissions. The first UK air quality regulation (National Air Quality Strategy, requited by the Environment Act 1995) was published in 1997, which established HEALTH-BASED objectives for eight major pollutants (benzene, 1,3-butadiene, carbon monoxide, lead, nitrogen dioxide, ozone, particulates and Sulphur dioxide) (UK, 1997; Elsom and Longhurst, 1997). The regulation worked well and air pollutants decreased dramatically, but air pollution is still (seen as) a serious threat for public health in the UK. Research estimated that, in 2010, around 10,000 people died prematurely in London because of air pollution, mainly nitrogen dioxide (NO_2) and fine particle matter ($PM_{2.5}$, particles with aerodynamic diameter less than 2.5 micrometres) (Heather et al., 2015). Without more stringent strategies to control air pollution, $PM_{2.5}$ will continue to be responsible for a high level of morbidity and mortality across the European Union (EU) by 2020 (EC, 2005), and OECD countries are likely to have one of the highest rates of premature death from ground-level ozone by 2050 (OECD, 2012).

Urbanization and pollution in China

China's rapid urban expansion started more than three decades ago, but since the 1990s, the urbanization process in China has further accelerated and the urban area has expanded at an unprecedented speed. By 2012, the urbanization rate (urban population rate) was over 50%, compared to 21% in 1982. It has been predicted that there will be another 200 million people moving from rural to the urban areas in the current decade (Zhu and Jones, 2010). China's urbanization was largely driven by the economic growth, or we can say the urbanization in China was economically-oriented. In the past 30 years, economic growth has pulled more than 500 million people out of poverty, but it has also brought sever environmental and social issues. According to Pan, the cost of urbanization in China is huge. One important cost is the environmental degradation - sever water, soil and air pollution, and ecosystem degradation during the fast urbanization process - that will take a much longer time to recover as compared to the EU (China dialogue, 2013). According to the Ministry of Land and Resources of China, in 2014, 16.1% of the land in China was polluted (MEP, 2014). Around 300 million people from rural areas are using water contaminated by human and industrial waste, and according to the Ministry of Environmental Protection of China over half of the urban groundwater is seriously polluted (MEP, 2014). The heavy smog covering a large part of China from 2011 to 2013 brought the air pollution issue to the public's attention. The Chinese government is ambitious to eliminate the sever pollution (days with Air Quality Index (AQI) over 200) in the next 10 years according to the "Air Pollution Prevention and Control Action Plan" in 2013. Scientists remain sceptical because after a 5-years effort to control the pollution, the air quality, though improved, can barely meet the 5-year target of the Action Plan (Wang et al., 2015; Liu et al., 2013; Ma et al., 2013). Under the "pollution first, treatment after" motto (prioritizing rapid economic growth over environmental concern) air pollution in big cities has already reached "intolerable limits". Even with the recently much more stringent enforcement of air pollution control strategies, only 21.6% of the prefectural-level cities met the national air quality standard in 2015 (73 out of 338; these cities are exclusively from Tibet, Yunnan, Guizhou, Fujian and Guangzhou province), and most of those cities are smaller and less dynamic (MEP, 2015). It is now fair to say that air pollution has become a huge public health issue in China.

Air pollution in China and regional characteristics

Whereas a small proportion of air pollution can be attributed to natural causes (like volcanoes, biogenic source, and natural forest fires), anthropogenic activities are the major causes of outdoor air pollution. According to a recent report, among the top 80 cities/towns with the highest $PM_{2.5}$ concentration globally, 58 are from China. Within these 58 cities, most of the cities with high $PM_{2.5}$ concentration are from central China, and the top five with the highest $PM_{2.5}$ concentration are in the Beijing-Tianjin-Hebei (BTH) region (WHO, 2014).

The origin of this dangerous level of air pollution in China can be traced back to only a few decades ago when industry activity accelerated nationally with increasing pollution sources and various polluting features. Throughout the three decades between 1970 and 2000, coal consumption has been the main source of air pollutants. The major air pollutant was total suspended particulates (TSP) and sulphur dioxide (SO_2). With the increase in industrial activities and the rapid surge of private motor vehicles, oxides of nitrogen (NOx) and particulate matter, mainly particles with aerodynamic diameter less than 10 micrometres (PM_{10}) and $PM_{2.5}$

overtook these as the dominant air pollutants. For urban agglomerations the concentrations of secondary air pollutants like ozone and $PM_{2.5}$ are also becoming increasingly high. Table 1-1 illustrates the track of air pollutants and major actions in different development periods in China.

Table1-1. The major air pollutants and the actions related to air pollution control since 1970*

Period	Main sources	Major pollutants[#]	Major actions during the period
1970-1990	Coal, industrial - point sources	TSPs	• 1973: Industrial "Three wastes**" emission standards • 1987: Adoption of the "Air Pollution Prevention and Control Law", aiming to control emissions from industry and coal consumption • 1988: Introduction of "Maximum Allowable Concentration of Pollutants in Atmosphere for Protection Crops"
1990-2000	Coal, industry	SO_2, TSPs	• 1996: Introduction of "Ambient Air Quality Standard" • 1998: "Two control zones" for acid rain and SO_2 • 2000: Total SO_2 emission control standard in "Two control zones"
2000-2010	Coal, industry, dust, vehicle	SO_2, TSPs, NOx, PM_{10}	• 2000: The 1st amendment of the "Air Pollution Prevention and Control Law" (total SO_2 emission control) • 2000: Firstly introduced vehicle emission standards • The 11th Five-Year Plan (first introduced atmospheric pollution reduction) • Regional prevention and control on air pollution for special event, like Olympic Games and World Expo
2010-now	Coal, industry, vehicle	$PM_{2.5}$, PM_{10}, O_3, NOx	• The 12th Five-Year Plan (air pollution control was embedded in the national plan) • 2012: Upgraded "Ambient Air Quality Standard" • 2013: "Air Pollution Prevention and Control Action Plan" • 2015: The 2nd amendment of the "Air Pollution Prevention and Control Law"

* Source: Hao (2013); ** waste water, gas and solid; #TSPs - total suspended particles, SO_2 - sulphur dioxide; NOx - nitrogen dioxide; PM_{10} - particles with aerodynamic diameter less than 10 micrometres, $PM_{2.5}$ - particles with aerodynamic diameter less than 2.5 micrometres, O_3 - ozone.

In the past four decades, coal burning and industrial emission (coal-driven) have been the major causes for air pollution. TSPs were the major air pollutants in the first 20 years, and from 1990 to 2010, SO_2 was one of the major air pollutants. The heavy smog episodes (mainly particles) in large parts of China between 2011 and 2013 have prompted central government to promulgate legislations and actions to reduce air pollution concentrations, and the air pollution control has reached an "improvement" phase since 2014 (Feng and Liao, 2016). Control strategies have led to a significant decrease in traditional ambient coarse particulate matter and SO_2 from stationary sources. With the increase of the vehicle numbers and the upgraded emission standards for industries, the major sources of air pollutants in urban areas have switched from coal-driven industry to a combination of traffic, industry and coal combustion; and the main perpetrators have switched from coarse particles and primary gaseous pollutants (NO_2 and SO_2) to a combination of primary and secondary pollutants, mainly $PM_{2.5}$, ozone (O_3), and NOx. The research focus on the particulate matter size also evolved from TSPs to PM_{10} and now to $PM_{2.5}$ (Liu et al., 2016).

Types of the emission sources and the main pollutants show variations at regional level in China. For example, $PM_{2.5}$, NOx and volatile organic compounds (VOCs) are the main air pollutants for Beijing-Tianjin-Hebei region, mainly from transportation, industrial and coal combustion. Ozone has replaced $PM_{2.5}$ becoming the dominant pollutant in the Yangtze River Delta, while PM_{10} and NOx are still the dominant air pollutants in the Northwest China. The concentrations of particulate matters (PM_{10} and $PM_{2.5}$) in the cities in the Northeast and Northwest China are generally higher than in the regions of the East, South, and Southwest China (Hu et al., 2010). The sources for the particles are different. The industrial (44%) sector is the dominant contributor to urban $PM_{2.5}$ in Beijing-Tianjin-Hebei (BTH) region (Li et al., 2015). Among the BTH region, traffic emission is the dominant contributor for $PM_{2.5}$ in Beijing, while industry and coal combustion are the dominant contributors in Hebei. For Pearl River Delta, the local emitted fine particles are mainly from mobile vehicles and industries, and cross regional transport also contribute significant amount to the total concentration (Wu et al., 2013). For Yangtze River Delta, industrial, biofuels combustion and traffic are the major contributors, accounting for around 38%, 29% and 17% respectively to the total $PM_{2.5}$ concentration (Li et al., 2015). It is notable that with the stringent enforcement of primary air pollutants control, the concentrations of SO_2 and coarse particle have decreased dramatically in the past decade, while the concentrations of some secondary air pollutants (mainly ozone and its precursors) increased. The current control legislations and the respective implementation strategies are still focusing mainly on fine particles.

The association between air pollution and health

Air pollution can cause multiple diseases and shorten life expectancy. Ambient $PM_{2.5}$ is currently regarded as the fifth-ranking mortality risk factor globally, and it was responsible for around 4.2 million premature deaths in 2015 (Cohen et al., 2017). The well-known air pollution and health event, which brought air pollution to a broad public attention, was the 1952 "London Smog". The incident has caused about 4,000 premature deaths within a few days, with 80%–90% of the deaths caused by cardio-respiratory conditions (UK, 2015). This event was instrumental to trigger modern air pollution related health epidemiology studies. With decades of air pollution control strategies and the subsequent policy responses, air quality improved greatly in many developed countries. But it is still, or has become, a big public health issue in most developed and developing countries. According to the WHO, around 7 million deaths, amounting to one-in-eight of the total global deaths, were attributable to air pollution exposure in 2012. This high toll is the most serious in low- and middle-income countries in the WHO South-East Asia and Western Pacific Regions (such as China and India). Air pollution is associated with cardiovascular diseases, stroke and ischaemic heart disease, as well as respiratory diseases, mainly including COPD, lung cancer and acute lower respiratory infection (WHO, 2014). Air pollution has become one of the major risk factors for developing acute respiratory infections in developing countries (WHO, 2014). The Global Burden of Disease report (2010) estimated that the ambient air pollution ranked fourth in mortality and health burden risk factors in China, and lung cancer has become the leading cause of cancer-induced death in China, with the lung cancer related death rate and age-adjusted death rate increasing by 464% and 261% respectively from 1973-1975 to 2004-2005. Air pollution has serious direct effects on public health in China. The serious air pollution in China has already caused substantial health and non-human-health related economic loss. Chen et al. (2014), estimated a possible loss of up to 2.5 billion life years of life expectancy for 500 million residents of the northern China. The major culprit is coal burning (Chen et al., 2014). The mechanisms of how air pollutants damage or affect health, though not fully clear, varies according to the type of the air pollutants and the exposure-duration time. Table 1-2 summarizes the major mechanisms of different air pollutants influencing health and the main health outcomes.

Table 1-2. The mechanisms of major air pollutants influencing health*

Pollutants	Main mechanisms	Main health outcomes
PM	• Irritation and corrosion • Metabolic activation • Oxidative stress • Mutagenicity/genotoxicity • Damage red blood cell • Inflammatory injury • Metabolic activation • Others...	• Pulmonary disease • Cardiovascular disease • Diabetes mellitus • Adverse birth outcome • COPD exacerbation • Central nervous system problems • Asthma exacerbation • Possible venous thrombotic disorders • Damage immune system • Adverse pregnancy outcomes • DNA damage • Cancer • Others...
Ozone	• Strong oxidation, reaction with cells, disturbing intracellular redox and impairing tissues • Irritation • Others…	• Respiratory diseases, like impaired lung function, bronchial reactivity. • Increased airway hyper-reactivity • Exacerbate asthma, bronchitis and other cardiopulmonary problems • Coronary vascular function perturbed • Adverse cardiac autonomic • Possible reproductive system(animal experiment)

		• Symptoms like fatigue, lethargy, headaches • Others…
NO_2	• Irritation (lung tissue) • Corroding the tissue when the concentration is too high • Impair lung function • Others…	• Acute respiratory infection • Airway inflammation • Exacerbating the respiratory symptoms like cough, runny nose, sore throat, etc. • Acute subclinical syndromes and chronic clinical respiratory diseases • Bronchial asthma exacerbation • COPD exacerbation • Allergic rhinitis, particularly for gestational and early life • Cardiovascular diseases • Possible children overweight and obesity • Others…
SO_2	• Irritation (eyes and respiratory system) • Genotoxic • Others...	• COPD exacerbation • Asthma severity • Decreased pulmonary function • Together with particulate matter, it can go deep into the lung system and damage the lung tissue • Cardiovascular diseases • Genetic damage • Others…

*Source: the author made this table based on the references in this section.

For particulate matter, the mechanisms are more complex than for the other air pollutants, very much depending on the components and size of the particle. Particles first reach the respiratory tract, irritate and corrode the alveolar wall, and thus damage the defence function of the respiratory tract and the pulmonary function (Brauer et al., 2001; Riva et al., 2011). Symptoms like cough, phlegm, wheezing can occur and respiratory diseases like chronic bronchitis, emphysema, chronic obstructive pulmonary disease, and asthma can be induced (Tsai et al., 2013; Habre et al., 2014; Bloemsma et al., 2016). Particles under 10 micrometres in diameter (PM_{10}) can pass through the nose and throat, and then enter the lungs, with the smaller ones, $PM_{2.5}$ and even smaller size-fractions, penetrating most deeply, even entering the bloodstream (Watterson et al., 2007; Krishnan et al., 2012). After being absorbed into the cells, $PM_{2.5}$ can impair the cellular physiological/biochemical processes and thus damage the tissues and organs, through inducing oxidative stress, genotoxicity, inflammation, and changing the normal physiological functions and/or fates of target cells. In the end, it can trigger or induce cardiopulmonary diseases, diabetes, adverse birth outcomes reproductive development system, etc. (Watterson et al., 2007; Gualtieri et al., 2011; Shah et al., 2011; Bell et al., 2012; Brook et al., 2013; Longhin et al., 2013; Barrett, 2014; Feng et al., 2016; Li et al., 2016). Long-term exposure to particulate matter can also damage the immune system and thus impair the immune system function (Williams et al., 2011). It can also prompt carcinogenesis through damaging DNA and replicating the damaged DNA (Mehta et al., 2008). Fine particles are also associated with problems of the reproductive system. Through maternal and infant exchange, it can damage genetic material and influence endocrine function. Adverse pregnancy outcomes like premature birth, miscarriage, low birth weight, abnormal embryo development, and infertility can occur (EPA, 2009; Shah et al., 2011; Bell et al., 2012; Barrett, 2014; Nancy et al., 2014; Feng et al., 2016). In 2013, the International Agency for Research on Cancer defined particulate matter as a cause of cancer, especially lung cancer (WHO, 2013; Watterson et al., 2007).

Ozone is a highly reactive gas that can react with cells lining the airways, and it involves in the formation of reactive oxygen species (ROS) and inflammation (González-Guevara et al., 2014). The main mechanisms of ozone affecting health are oxidation and irritation. Researchers have found that ozone is related to respiratory diseases by damaging the respiratory protection system or triggering pre-existing respiratory conditions like COPD and asthma (Gleason et al., 2014; Thaller et al., 2008; Khaniabadi et al., 2016). Ozone can also cause cardiovascular related diseases (Khaniabadi et al., 2016). Through strong oxidation with biomolecules, ozone can help to form free radicals, and these can pass through the circulatory system further leading to cardiovascular diseases and heart attack (Sun et al., 2013). Ozone can influence health largely through oxidation, but the exposure-effect relationship is ambiguous so far and the threshold for the health risk is not entirely defined (Wang et al., 2016).

NO_2 can first irritate the respiratory organs and reach to the deep bronchioles and alveoli through the respiratory tract, and then cause or exacerbate allergic airway inflammation (Ji et al., 2015). Dissolved into the water of the alveolar surface, it can form nitrous acid and nitric acid, strongly irritate and corrode the system, and thus cause or aggravate pulmonary oedema (Ware et al., 2015). Further, nitrous acid can enter the blood system, react with haemoglobin and form methaemoglobin, which can cause tissue hypoxia and affect the heart (Cesaroni et al., 2013). The respiratory diseases related to NO_2 exposure mainly include chronic bronchitis, emphysema, asthma, allergic rhinitis, COPD and impaired pulmonary function (Hochscheid et al., 2005; Liu et al., 2016; Chen et al., 2012; DeVries et al., 2016). NO_2 related cardiovascular diseases mainly include hypertension, acute heart failure, arrhythmia, and congestive cardiac failure. NO_2 is possibly associated with diabetes, overweight children and childhood obesity (Savitz et al., 2013).

SO_2 could lead to respiratory diseases, mainly through irritating the respiratory system or by corroding the tissue. Long-term exposure to SO_2 can impair the respiratory immune system and its defence function, and cause respiratory tract infection and inflammation (Tam et al., 2014). It can also cause tracheal contraction and increase ventilation resistance through irrigation, and thus impair the lung function. Like NO_2, SO_2 can irritate the alveolar and cause emphysema. SO_2 can also trigger asthma even with low concentration (Zhang et al., 2016). Respiratory diseases related to SO_2 exposure are mainly COPD and asthma (DeVries et al., 2016; Li et al., 2016; Zhang et al., 2016). SO_2 has been found to be related to cardiovascular diseases like high blood pressure and arrhythmia (Dong et al., 2016). Further, SO_2 is a genotoxic agent, which might damage the chromosome and lead to cell mutation (Prasad et al., 2013).

Thus air pollutants can lead to serious health damage, with the risks being much higher for vulnerable populations. Individual factors such as age, gender, previous health conditions are influencing susceptibility to air pollution exposure (Uphoff et al., 2014; Pinault et al., 2016). Infants, adolescents and elderly have been found to be especially sensitive to air pollutants (Bruce et al., 2000; WHO, 2014). Pre-existing diseases, long-term toxic accumulation, and impaired immune systems, make the elderly more susceptible to air pollutants. Compared to adults, children's respiratory system is not fully developed, respiratory-specific and non-specific immunity are low, and alveolar phagocytic cell-function is not perfect. This makes children more sensitive to air pollutants (UCLA, 2015). Finally, people with pre-existing diseases like asthma, cardiopulmonary diseases and diabetes, appear more susceptible to the deleterious effects of ambient air pollution (Mudway and Kelly 2000; Hazucha, et al., 1989).

External factors, like weather conditions, occupation, socioeconomic position (SEP), and behaviour, can also influence the health effect of air pollutants (Tonne, et al., 2008; Clougherty, 2009; Brook et al., 2013; Wong et al., 2010). Outdoor sport was found to increase absorption of ozone, and a lack of vitamin E and vitamin C can also increase the sensitivity to pollution exposure (Thiele et al., 1997; Moreno-Macías et al., 2013; Bell et al., 2014). The majority of epidemiologic studies on air pollution and health focus still on single pollutants. As synergistic effect (synergisms effect) of multiple pollutants is likely to aggravate the health outcomes (Mauderly and Samet, 2009), further research on multiple effects of pollutants is needed. And for China up to now, most studies focus on the short term health impacts, but the long term (harvest effect) health cost will be enormous.

The air quality control strategies in China

Since the turn of the millennium, it has become more evidenced that air pollution in China influences economic growth, is associated with serious health risks, and undermines the international commitment on climate protection. Air pollution control legislations in China can be traced back for half a century with four discernible phases up to now: preceding (1956-1978), beginning (1979-1999), development (2000-2013), and improvement (since 2014) (Shi et al., 2016). With the acceleration of China's economic growth, a coordinated government's response to the increasingly serious air pollution, culminating in the so called "heavy haze" at the end of 2011, became indispensable. A range of broad strategies of laws, policies, actions, programs, guidelines, monitoring systems and other interventions has been formulated and issued in favour of improving the air quality. This was also pushed forward as a response to the increasing health and economic cost, and the increasing climate change mitigation responsibility at the international level. The strategies cover the items of energy control, energy transition (from fossil fuels to renewables), upgrade gasoline and diesel quality standards, enhanced vehicle emission control and vehicle number (car registration) control, and industrial re-structuring with technological innovation and upgraded emission standards.

The "Air Pollution Prevention and Control Action Plan" is regarded as the so far strictest and the most promising action plan for air pollution control (Lin and Elder, 2014; Chen et al., 2013). Its measures and goals are much more specific compared to the former air pollution control strategies, such as the Blue Sky Plan for Beijing of 1998. The Action Plan includes evaluation indexes linked to the local government performance, which can hopefully raise the political visibility and priority of air pollution issues at local level. In 2016, the central government revised the "Environmental Protection Law", adding four crucial and novel sections to the law: 1) **"two control zones"** (the acid rain control and sulphur dioxide control): the territory of the two control zones expands to the entire national territory from the earlier mere 11.4% of the territory, and combines enhanced assessment and supervision obligations; 2) **vehicle and coal emission**: the law strengthens the gasoline and diesel quality standards at national level, puts further restrictions on the coal market and coal consumption, and promotes clean energy to replace coal; 3) **financial punishment:** the law abandons the former financial punishment ceiling (500,000 RMB under the former law). Punishment now is based on the actual extent of the pollution, and financial punishment ranges from one- to five-times the direct economic loss caused by the pollution; 4) **information disclosure and reporting system**: the law standardizes the reporting mediums, enhances the protection of informants, and provides financial support for non-anonymous informants. And further, the law clarifies and protects the public's rights of the access to and the use of environmental information and pollution information.

In general, the strategies and legislations represent a remarkable progress for air pollution control resulting in first improvements in air quality. Research-based projection made by the Chinese Academy for Environmental Planning, suggests that 200,000 premature deaths could be avoided yearly if the annual level of PM_{10} in Chinese cities reached the first-level standard of 40 μg/m^3, as set in the newly revised China National Ambient Air Quality Standards (GB3095-2012). However, the multiple pollution sources, the diverse characteristics of the pollution in different regions, and the long-term coal-dependent economy continue to be major hurdles hindering an immediate and comprehensive implementation of the strategies. After a few years of combating air pollution, improvements have been achieved but they are far from meeting the public's and government's expectations. At the recent National People's Congress (2017), air pollution was therefore one of the top policy priorities and concerns discussed emphasizing the importance that the Chinese government is now giving to this issue. For the densely populated Beijing-Tianjin-Hebei region, where the air pollution is very serious, the provincial governments have set up explicit air pollution reduction targets for 2017 (for Beijing and Hebei, $PM_{2.5}$ concentration with 18% and 6% reductions respectively, and for Tianjin, to shut down heavy polluted industries and coal-fired boilers).

Parallels of air pollution and related health risks between the EU and China

For years developing countries have been arguing that in order to close or at least to narrow the development gap to the leading economies compromising environmental concerns would be unavoidable. China's earlier reservation against fully committing to the Kyoto protocol was certainly influenced by these considerations. The recent change in attitude is probably both, a result of the new economic strength and the increased global political importance of China, and the growing understanding of the need to provide environmental health protection for its citizens. To identify suitable pathways and possible strategies for environmental health protection it seems appropriate to analyse earlier experiences with such a necessary transition. Earlier experiences particularly in Europe and North America show that the environment deteriorated significantly in the beginning of the urbanization/industrialization era (Environmental Kuznets Curve, Grossman and Krueger, 1994). Legislations to protect natural environment and natural resources (clean air, safe water and soil, abundant forest) followed much later when the consequences of the environmental deterioration had become apparent and could not be ignored anymore. It was the high toll of some 12,000 deaths from acute and persisting effects during and in the aftermath of the London Smog from December 1952 to February 1953 (Bell and Davis, 2001; Bell et al., 2004) that changed the approach from scattered and often ineffectual regulations to a comprehensive legislation. Led by Sir Gerald Nabarro, laws and regulations from national level to local level were put forward, resulting in the Clean Air Act 1956, which was among the first comprehensive laws on air pollution control (The New York Times, 2015). Along with the launching and implementation of the policies and laws, the air quality improved soon after the smog in UK. There are some parallels to the recent development in China. The heavy haze in the winters of 2011, 2012 and 2013 caused a sharp increase in morbidity and especially an increase of patients consulting the respiratory, paediatrics and allergies sections in hospitals (seven- to eight-times more than normal) in Beijing. In September 2013, the central government promulgated the "Air Pollution Prevention and Control Action Plan" with specific emphasis on the Beijing-Tianjin-Hebei region.

The health consequences attributed to air pollution and the benefit of air pollution control strategies show some similarities. The major cause of air pollution in UK was coal combustion in the 1950s and being replaced by vehicle exhaust since the 1980s. SO_2 was the major air pollutant caused by coal combustion in the early development stage, followed by NO_2 (nitrogen dioxide) and now particulate matter (particularly $PM_{2.5}$) is the major cause of air pollution related health damage. In China, the sources of urban air pollutants are mainly from industrial, vehicle exhaust and coal combustion. Still, after a sixty-year fight against smog, Europe cannot declare a complete success. The current debate on manipulation software for European manufactured diesel engines and the open conflict between the influential lobby of the car manufacturers and environmental protection agencies is but one example of the still unfinished agenda of European air pollution control (Dyrhauge, 2015). There are even signs for a deterioration of the situation: severe smog episodes hit Paris in March 2014 and 2015 and the air quality in London has been far from satisfying for quite some time again. France, Germany, Italy, Spain and the UK are facing fines from the European Commission for breaching the air quality standards. The European Commission is challenged with enforcing the stricter air pollution standards while at the same time being confronted with opposition from member states that fear negative consequences for the competitiveness of their industrial base. Although there are obvious differences in scale and the extent of the problem, China and the EU are facing the similar issues regarding air pollution and health consequences but also in regards to the conflicting interests. Linking the EU and China together in a study on air pollution and health is therefore appropriate as a mutual learning approach but also to better understand the future options for China. Many of the Chinese emission standards (for example, vehicle emission standards and some industry emission standards) refer to European standards, and the EU has much more experience in formulating and implementing policies and legislations. In May 2012, the People's Republic of China and the EU released a joint declaration, the China-EU partnership on sustainable urbanization, which set up a framework of mutual learning and mutual development on environment, health and global change for European countries and China at both local and national levels (China-Europa Forum, 2013). Within the strategies and policies relevant to urbanization and urban ecological protection, environmental protection is regarded as one of the important subjects and challenges that both partners intend to address jointly.

According to some experiences in the EU, the public and civil society represented by inter alia NGOs are powerful forces to push forward the formulation and enforcement of legislations and actions. Indeed, a clean and healthy environment is an essential component of fundamental human rights. Excessive pollutant emissions from either industries or traffic ultimately lead to the violation of human rights, and therefore human rights have been used in formulating different approaches for fighting the environmental degradation. These forces have participated in combating air pollution in many western countries but rarely in China (Cory, 2015; Manashi and Arabinda, 2016).

Shared solutions?

The similarities that Chinese and the EU governments are facing or have faced regarding air pollution, health and urbanization highlight the potential for mutual learning from their respective urbanization and globalization contexts and histories. While extent and scale of environmental health risks and the respective the socioeconomic contexts may differ, there can be little doubt that both the EU and China share hopes to find a path towards cleaner and more sustainable urban development, even if sustainability implies adaptation of different solutions for different climates, territories and societies (China-Europa Forum, 2013). What the EU has experienced a few decades ago influences the solution to China's environment challenge now. What China is tackling now is increasingly becoming a reference for the EU to address environmental health issues on a global scale.

Research aims and sections

The main aims of this thesis are to help to understand the health risks caused by air pollution in China, to explore the challenges of air pollution control strategies in China (Beijing-Tianjin-Hebei as a point in case), and eventually to provide a contribution to the discussion on (health) evidence based decision making. More specifically, through this work,

- we learn how and to what extent air pollution is challenging public health;
- we review the strategies used to control air pollution and their health benefits, and to extract the experience of how to contribute to a healthier environment through decision-making;
- we assess the progress and the challenges of air pollution control strategies in China.

Currently, China is facing tremendous pressure from inside and outside of its border regarding the severe air pollution. The characteristics of the pollution, the health risks, and the coping strategies are of major concerns for the public, the government and the international community. The work underpinning this dissertation therefore explores the air pollution and related health risks, and the challenges that might hinder the air pollution control. The dissertation is designed to provide extra understandings on health risks from spatial perspective and from ozone pollution, which have been neglected in mainstream research. Based on a clear understanding of the air quality control strategies in China and in the EU, this thesis also intends to exhume the success and hampers of air quality control strategies in China.

Content of this dissertation

The **1st chapter** (introduction) summarizes the urbanization and environment (air pollution) development in China and the EU; reviews the air pollution related health studies and the mechanisms of how air pollution influences health; and in the end, illustrates the air quality control strategies in China and the EU. A brief introduction on the research aims and the structures of this thesis is also provided in this chapter.

The **2nd and 3rd chapters** analyse the relationship between air pollution and health from spatial and temporal perspectives. The **2nd chapter** analyses the spatial differences of the health risks caused by air pollution at Prefecture-city level in China using geographic weighted regression (GWR). In this chapter, the socioeconomic factor is included as a confounder to explore how this factor can influence the air pollution - related health issues. The **3rd chapter** analyses the health damages (respiratory and cardiovascular diseases related mortality) associated with ozone pollution in Shenzhen using time-series study. The meteorological factors and other air pollutants are used as confounders. Age and gender of the affected population are adjusted in the regression. The aims of the **2nd chapter** and **3rd chapter** are to identify the regional and the individual differences of air pollution related health risks.

The **4th chapter** systematically reviews the public health and health equity benefits of recent air pollution control strategies in the EU; summarizes the effectiveness of the interventions from different fields, including general regulations on air quality control, energy efficiency or energy saving, transport related emission reductions, and greenhouse gas emission reductions; and in the end, analyses the related health indicators and the methodologies for health impact assessment of air pollution control strategies. This chapter provides insights and further understanding of the potential health benefit derived from the air pollution control strategies in EU, which might be relevant as a reference for China.

The **5th chapter** summarizes the progress and challenges of the air quality control strategies with specific focus on Beijing-Tianjin-Hebei region in China based on quantitative method and semi-structured interviews; discusses the opportunities and the challenges of the currently air quality control strategies mainly on industrial restructuring and traffic emission control; and provides extra suggestions for further air quality control strategies.

The **6th chapter** gives a general discussion on the findings of the previous chapters; summarizes the added value of the thesis in terms of research, knowledge transferring, and decision making; provides implications for research and practice; and illustrates the limitations.

CHAPTER 2

A study of air pollutants influencing life expectancy and longevity from spatial perspective in China

Li Wang, Binggan Wei, Yonghua Li, Hairong Li, Fengying Zhang, Mark Rosenberg, LinshengYang, Jixia Huang, Thomas Krafft, Wuyi Wang (2014). A study of air pollutants influencing life expectancy and longevity from spatial perspective in China. Sciences of the Total Environment. doi: 10.1016/j.scitotenv.2014.03.142

Abstract

Life expectancy and longevity are influenced by air pollutants and socio-economic status, but the extend and significance are still unclear. Understanding how the spatial differences of life expectancy and longevity affected by air pollutants was needed for generating public health and environmental strategies since the whole China is now threatened by deteriorated air quality. 85 major city regions were chosen as research areas. Geographically Weighted Regression (GWR) and Stepwise Regression (SR) were used to find the spatial correlations between health indicators and air pollutants, adjusted by per capita GDP. The results were, regions with higher life expectancy were mainly located in the east area and areas with good air quality, a regional difference of 10 μg/m^3 in ambient air SO_2 could cause adjusted 0.28 year's difference in life expectancy, a regional difference of 10 μg/m^3 in ambient air PM_{10} could lead to a longevity ratio difference of 2.23, and per capita GDP was positively associating with life expectancy but not longevity ratio, with a regional difference of 10,000RMB (renminbi) associating with adjusted 0.49 year's difference in life expectancy. This research also showed the evidences that there exist spatially differences for ambient air PM_{10} and SO_2 influencing life expectancy and longevity in China, and this influences were clearer in south China.

Introduction

Life expectancy is considered as one of the three major parameters for calculating the Human Development Index (HDI), which is used by the United Nations Development Program to rank human development levels of countries (UNDP, 2011). It has also been used to assess the health impact of air pollution (Chen et al., 2013; Pope et al., 2009b; Pope et al., 2013; Wang et al., 2013). Life expectancy is affected by multiple factors, and the social environment is considered as one of the most important factors (Blum, 1974). Ambient air SO_2, PM, and NO_x have been proved to lead to multiple diseases and diminished life expectancy (Chen et al 2013; Cao et al., 2011; Guang et al., 2013; Pope et al., 2002, 2003, 2009a, 2009b, 2013). The elderly population is found to be more vulnerable to air pollutants except ozone and more sensitive to air pollutants because of their depressed immune systems, existing diseases, and the accumulation of toxic agents in their bodies (Fischer et al., 2003; Sun and Gu, 2008). Most of the studies on air pollution affecting the elderly focused on the population of 65 or 75 years old and over (Fischer et al., 2003; Wen and Gu, 2012). Due to the toxic accumulation effect, the 100 years old and over population is more sensitive to air pollutants. A clear understanding of the effects of air pollutants to the longevity group (people living to be 100 and over) is critically needed for the county with the increasing elderly population. The negative associations between air pollutants and health outcomes have been largely proved through time-series or cohort based studies (Zhang et al., 2011; Cao et al., 2011; Gouveia and Fletcher, 2000). But there was no study considering the regional differences of population's sensitivity to air pollutants. A research regarding spatial differences of health outcomes associating with air pollutants is urgently needed for formulating regional healthy coping strategies against air pollutants.

In this paper, we used life expectancy and longevity as public health outcomes. Socioeconomic represented by per capita GDP (gross domestic product), and air pollutants, including PM_{10} and SO_2, which are regarded as the major ambient air pollutants challenging China's public health, were analyzed to find out how they influence life expectancy and longevity. We hypothesized that spatial differences of PM_{10} and SO_2 were associated with changes in life expectancy and longevity. Regional differences in life expectancy and longevity could also be partly attributed to socioeconomic status. This research was conducted at the prefecture-city level.

The major objectives of this paper were: (1) to demonstrate the spatial distribution of life expectancy and longevity at the prefecture-city level; (2) to analyze the spatial relationship between air pollutants and the two health indicators; (3) and to analyze the socioeconomic effect on life expectancy and longevity. The research findings lead to policy recommendations for decision-makers to use in developing health strategies to help the elderly population cope with the deteriorated air quality and to find a balance between environmental protection and socioeconomic development from a public health perspective.

Method and data

Method and explanatory variables for models

Using ArcGIS software, we constructed a geographic and attribute database of the longevity group using an administrative map and the sixth national population census of China. Geographic distribution maps of the longevity group, life expectancy, PM_{10}, SO_2, per capita GDP were generated on prefecture-city level. In order to find out the possible effect of pollutants and socioeconomic factors on life expectancy and longevity, we collected data on PM_{10}, SO_2, and per capita GDP for our analysis. Life expectancy and longevity ratio were analyzed against air pollutants and socioeconomic indicator using the Stepwise Regression (SR) by SPSS 18.0 and Geographically Weighted Regression (GWR) by ArcGIS 10.1.

In SR, PM_{10}, SO_2 and per capita GDP were used as independent variables, while life expectancy and longevity ratio were dependent variables, respectively. After we conducted SR, we used the variables included by SR for GWR. GWR generates a separate regression equation for every feature analyzed in a sample dataset as a means to address spatial variation. A general version of the model can be expressed as:

$$y_i = \beta_0(u_i, v_i) + \sum_{z=1}^{n} \beta_z(u_i, v_i)\, x_{iz} + \varepsilon_i$$

Where y_i denotes the dependent variable, in this case the life expectancy or longevity i at location i, $\beta_0(u_i, v_i)$ denotes the intercept coefficient at location i, x_{iz}

is the value of the zth explanatory variable at location i and $\beta_z(u_i, v_i)$ is the location regression coefficient for the zth explanatory variable. Furthermore, (u_i, v_i) denotes Cartesian x and y point coordinates and ε_i is the random location specific error term. When GWR was used, the parameters can be estimated by solving:

$$\beta_f(u_i, v_i) = (X^T W(u_i, v_i) X)^{-1} X^T W(u_i, v_i) y$$

where $\beta_f(u_i, v_i)$ is the estimate of the location-specific parameter, $W(u_i, v_i)$ is an n by n spatial weight matric whose off-diagonal elements are zero and the diagonal elements denote the geographical weights of observed data a location i. The geographic weight structure (u_i, v_i) is based on a Gaussian Kernel function such that the influence of data points in the proximity of i is given larger weights in the estimation.

This paper used an adaptive bi-square function to generate the geographic weights. An adaptive function fitted the demographic data analyzed in this paper since the research points clustered in some regions. The spatial context (the Gaussian kernel) is a function of a specified number of neighbors. Where feature distribution is dense, the spatial context is smaller; where feature distribution is sparse, the spatial context is larger (Charlton et al., 2009).

The bandwidth may be either defined by a given distance, or a fixed number of nearest neighbors from the analysis location. In this case we used AICs, that the optimal number of nearest neighbors was determined through selecting the model with the lowest Akaike Information Criterion (AIC) score (Hurvich et al., 1998), given as:

$$\mathrm{AICc} = 2\mathrm{n}\ln(\sigma) + \mathrm{n}\ln(2\pi) + \mathrm{n}\left\{\frac{n + tr(s)}{n - 2 - tr(s)}\right\}$$

Here tr(s) is the trace of the hat matrix. The AIC method can be used to select between a numbers of competing models by taking into account differences in model complexity (Fotheringham et al., 2002).

Data

Life expectancy data was calculated from demographic data, which were obtained from the demographic database of the six national population census of China

(Tabulation on the 2010 population census, 2010). The formula for calculating life expectancy was illustrated in Table 2-1.

Table 2-1. Abbreviated decennial life table for one city region in China

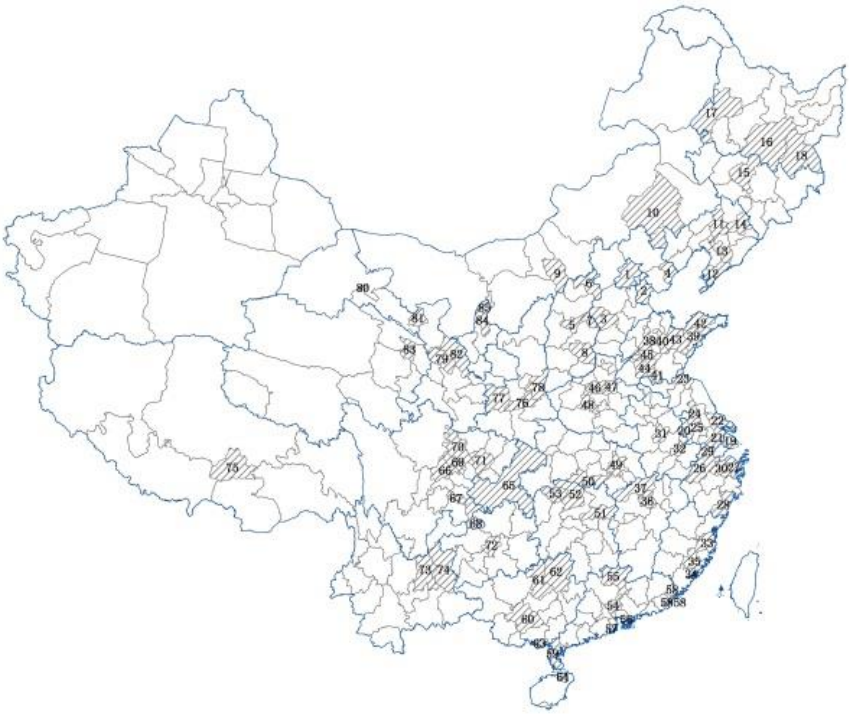
Age(yr)	I(x)	d(x)	q(x)	m(x)	L(x)	T(x)	e(x)	P(x)	D(x)
0	100000	550	0.00550	0.00550	99533	7987240	79.87	47647	262
1-4	99450	185	0.00187	0.00047	397429	7887707	79.31	188449	88
5-9	99264	137	0.00138	0.00028	495980	7490278	75.46	217311	60
10-14	99127	138	0.00139	0.00028	495292	6994298	70.56	283046	79
14-19	98989	217	0.00220	0.00044	494402	6499005	65.65	326943	144
……	……	……	……	……	……	……	……	……	……
80-84	58180	16974	0.29175	0.06831	248468	568788	9.78	34019	2324
85+	41206	41206	1	0.12864	320320	320320	7.77	16542	2128

From left to right, where, x represents age. l(x) is "the survivorship function": the number of persons alive at age x. For example of the original 100 000 people in the hypothetical cohort, l(14-19) = 98989 (or 98.989%) live to age 14-19. These values are computed recursively from the d(x) values using the formula l(x+i) = l(x)-d(x), with l(0), the "radix" of the table, arbitrarily set to 100,000. For example, l(1-4) = l(0)-d(0) = 100000- 550= 99450. d(x) is number of deaths in the interval (x,x+i) for persons alive at age x, computed as d(x) = q(x)*I(x). For example, the I(10-14)= 99,127 persons alive at age 10-14, d(10-14)= 0.00139*99127=138 died prior to age 10-14. q(x) is probability of dying at age x. Also known as the (age-specific) risk of death. Generally these are derived using the formula q(x) = 1 – exp[-m(x)], under the assumption that the instantaneous mortality rate, or force of mortality, remains constant throughout the age interval from x to x+i(here i=5). m(x): the mortality rate at age x. Generally these quantities are obtained from P(x) and D(x). By construction, m(x) = D(x)/P(x). D(x) and P(x) are death and live number of population at x year, which are the inputs in the life table. The data are obtained from national census. L(x) is total number of person-years alive by the cohort from age x to x+I (here i=5). This is the sum of the years lived by the l(x) and I(x+i) persons who survive the interval. L(x)=i/2 [I(x)+I(x+i)]. For I(0), this is the sum of the years lived by the L(1) persons who survive, and the d(x) persons who die during the interval, L(0) = I(1) + 0.5*d(0).T(x) is total number of person-years lived by the cohort from age x until all members of the cohort have died. This is the sum of numbers in the L(x) column from age x to the last row in the table. e(x): the (remaining) life expectancy of persons alive at age x, computed as e(x) = T(x)/l(x).

The longevity ratio was defined as the number of centenarians per 10 000 inhabitants. This indicator reflects the feature of longevity. The data were also obtained from demographic database of the six national population census of China (Tabulation on the 2010 population census, 2010). Per capita GDP data were from the provincial statistical year book (China Statistic yearbook, 2010). PM_{10} and SO_2 data were obtained from the data center of Ministry of Environmental Protection of the People's Republic of China (Chinese National Environmental Monitoring Center, 2010). PM_{10} concentration was monitored daily according to Gravimetric method (GB 6921-86), and SO_2 concentration was monitored daily according to formaldehyde absorbing-pararosaniline spectrophotometry (GB/T 15262) or tetrachloromercurate (TCM)-pararosaniline method (GB 8970). All the monitoring equipments were calibrated regularly, and all these methods meet the National Ambient Air Quality Standard (GB 3095-1996). Month concentrations of the two pollutants were obtained by averaging day concentrations, and the year concentrations were obtained by averaging month concentrations. The air pollutants data in this research were the year average concentrations from 2004 to 2010.

Study area

85 major city regions were chosen as our research areas, including 25 provincial capital city regions, 4 municipalities, and 56 other sub-major city regions. We excluded Xinjiang autonomous region because the demographic data in Xinjiang autonomous region were deemed to be unreliable by most demographers in China. City regions included the urban area and rural area under the city's administrative jurisdiction. The 85 research regions were showed in Figure 2-1.



The blue line is province boundary and the gray line is city region boundary. The locations of the city regions included in this study are shown in gray. Those regions are coded by number as follows: 1—Beijing, 2—Tianjing, 3—Shijiazhuang, 4—Qinghuangdao, 5—Taiyuan, 6—Datong, 7—Yangquan, 8—Changzhi, 9—Huhehaote, 10—Chifeng, 11—Shenyang, 12—Dalian, 13—Anshan, 14—Fushun, 15—Changchun, 16—Haerbing, 17—Qiqihaer, 18—Mudanjiang, 19—Shanghai, 20—Nanjing, 21—Suzhou, 22—Nantong, 23—Lianyungang, 24—Yangzhou, 25—Zhenjiang, 26—Hangzhou, 27—Ningbo, 28—Wenzhou, 29—Huzhou, 30—Shaoxing, 31—Hefei, 32—Wuhu, 33—Fuzhou, 34—Xiamen, 35—Quanzhou, 36—Nanchang, 37—Jiujiang, 38—Jinan, 39—Qingdao, 40—Zibo, 41—Zaozhuang, 42—Yantai, 43—Weifang, 44—Jining, 45—Taian, 46—Zhenzhou, 47—Kaifeng, 48—Pingdingshan, 49—Wuhan, 50—Jingzhou, 51—Changsha, 52—Changde, 53—Zhangjiajie, 54—Guangzhou, 55—Shaoguan, 56—Shenzhen, 57—Zhuhai, 58—Shantou, 59—Zhanjiang, 60—Nanning, 61—Liuzhou, 62—Guilin, 63—Beihai, 64—Haikou, 65—Chongqing, 66—Chengdu, 67—Zigong, 68—Luzhou, 69—Deyang, 70—Mianyang, 71—Nanchong, 72—Guiyang, 73—Kunming, 74—Qujing, 75—Lhasa, 76—Xi'an, 77—Baoji, 78—Weinan, 79—Lanzhou, 80—Jiayuguan, 81—Jinchang, 82—Baiyin, 83—Xining, 84—Yinchuan, 85—Shizhuishan.

Figure 2-1. Distribution of research regions.

Results

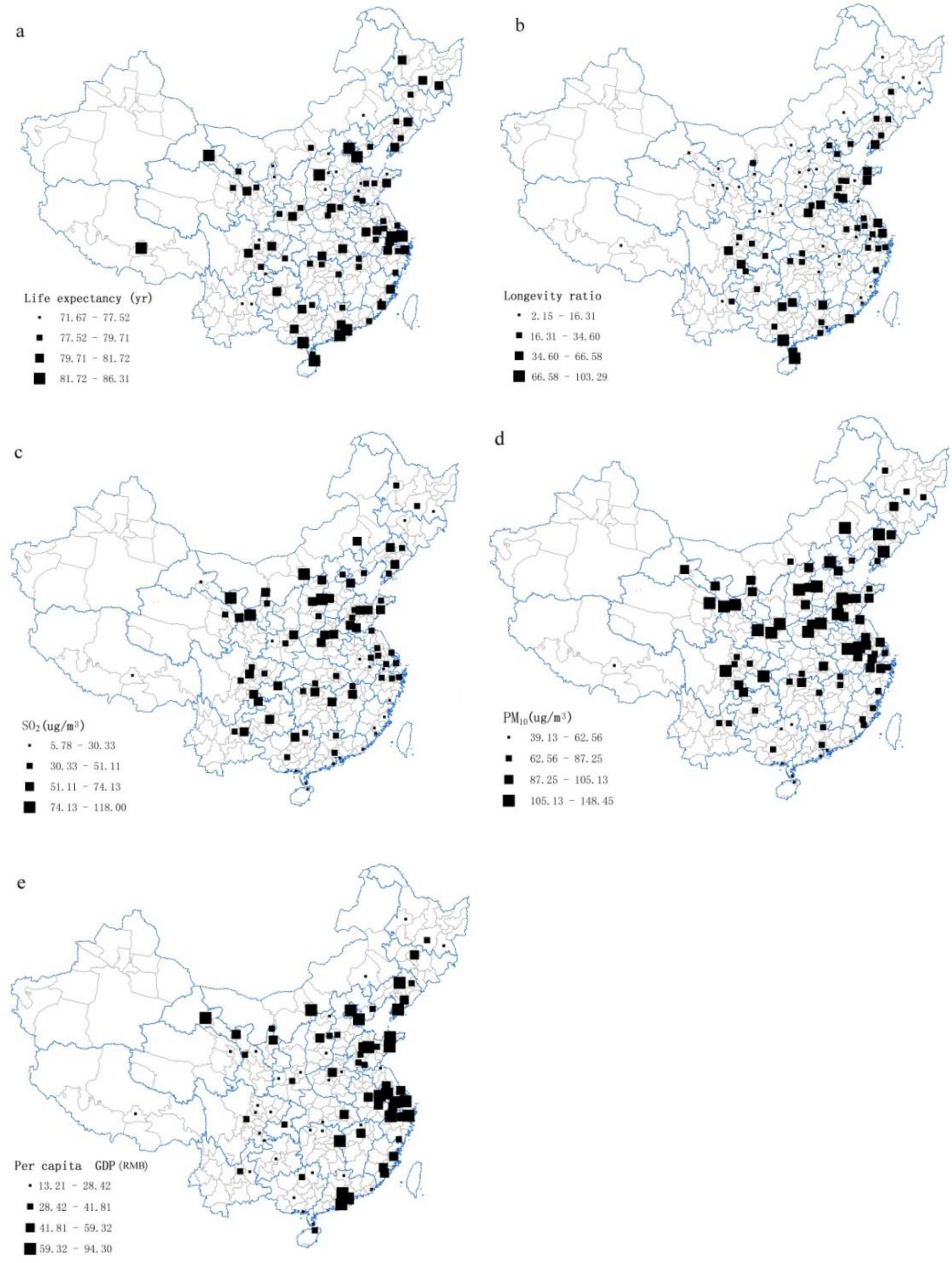
Spatial distribution characteristics

Summary statistics for key variables (e.g. life expectancy, longevity, PM_{10}, SO_2, and per capita GDP) in the research regions were listed in Table 2-2 and the spatial characteristics of the variables were illustrated in Figure 2-2.

Table 2-2. Summary characteristics of the 85 city regions

Variable	Arithmetic mean	Standard deviation	Max	Min
Life expectancy (yr)	79.44	2.25	86.31	71.67
Longevity (ratio 100+)	23.98	18.50	103.30	2.15
PM_{10} ($\mu g/m^3$) (2004-2010)	90.16	20.79	148.44	39.13
SO_2 ($\mu g/m^3$) (2004-2010)	46.31	19.87	118.00	5.78
Per capita GDP (1000 RMB)	42.23	20.51	94.30	13.22

Life expectancy is an index widely used in evaluating the national public health situation. The average life expectancy at birth of Chinese people was 76 years for both sexes (74 years for male and 77 years for female) in China in 2010, which was 5 years longer than that in 2000 and 7 years longer than that in 1990 (Mundi index, 2010). As it can be seen in Table 2-2, the average life expectancy and average longevity ratio of 85 city regions were 79.44 years and 23.98, respectively, whilst the average concentrations of PM_{10} and SO_2 were 90.16 $\mu g/m^3$ and 46.31 $\mu g/m^3$, and the average per capita GDP was 42 230 RMB



The classification method for Figure 2-2 was Natural Breaks (Jenks). The class is based on natural groupings inherent in the data. ArcMap identifies break points by picking the class breaks that best group similar values and maximize the differences between classes. The features are divided into classes whose boundaries are set where there are relatively big jumps in the data values.

Figure 2-2. Spatial characteristics of the life expectancy (Figure 2-2a), longevity ratio (Figure 2-2b), SO_2 (Figure 2-2c), PM_{10} (Figure 2-2d), Per capita GDP (Figure 2-2e).

Figure 2-2a illustrated life expectancy in the 85 regions. Life expectancy in the regions from the east China was obviously higher than that in the central regions. The region with the longest life expectancy was Shenzhen of 86.31 years, followed by Beihai (84.84 yrs), Zhuhai (84.31 yrs), Jiayuguan (83.75 yrs), Taiyuan (82.87 yrs), Shanghai (82.69 yrs), Beijing (82.36 yrs), Haikou (82.23 yrs), Tianjing (82.17 yrs), and Lhasa (82.17 yrs). The regions with higher life expectancy (81.72 yrs-86.31 yrs) mainly clustered in three areas, which were Beijing-Tianjing, Yangtze River Delta (Shanghai) and Pearl River Delta (Zhuhai and Shenzhen). Those regions were also China's three major economic centers with well-developed economies. Taiyuan also had higher life expectancy with 46 144 RMB for per capita GDP. Meanwhile, Lhasa and Jiayuguan having higher life expectancy were partially untapped regions with low PM_{10} and SO_2 concentrations. The other regions with higher life expectancy were Haikou and Beihai, which were tourism regions with relatively clean air. Among the ten regions with higher life expectancy, five regions had lower PM_{10} concentration, six regions had lower SO_2 concentration, and six regions had higher per capita GDP. Qujing had the lowest life expectancy of 71.67 years, followed by Shizuishan (74.94 yrs), Kunming (75.09 yrs), Changzhi (75.48 yrs), Luzhou (75.48 yrs), Yangquan (76.70 yrs), Yantai (76.86 yrs), Chifeng (76.95 yrs), Yinchuan (77.06 yrs), and Shijiazhuang (77.20 yrs). Among these regions, there were no regions with lower PM_{10} or SO_2, one region with higher per capita GDP.

Figure 2-2b demonstrated the longevity ratio in 85 regions. Beihai had the highest longevity ratio of 10.33, followed by Haikou (9.48), Nantong (6.65), Shaoguan (5.73), Zhanjiang (5.56), Liuzhou (5.00), Guilin (4.76), Zaozhuang (4.72), Zigong (4.63), Yantai (4.5). Among these10 regions with higher longevity ratios, there were five regions with lower PM_{10} concentrations, two with lower SO_2 concentrations, and one with higher per capita GDP. Jinchang had the lowest longevity ratio of 0.22, followed by Changzhi (0.42), Jiayuguan (0.43), Yangquan (0.51), Chifeng (0.55), Baoji (0.57), Huhehaote (0.59), Huzhou (0.63), Nanchang (0.69), Yinchuan (0.70), Shenzhen (0.70). Among those regions, there was no region with lower PM_{10}

concentration, two regions with lower SO_2 concentration, two regions with higher per capita GDP, and four regions with lower life expectancy.

Figure 2-2c showed the PM_{10} concentration distribution. PM_{10} is higher in the central China, while lower in the southeast part. Haikou had the lowest PM_{10} concentration of 39.13 μg/m^3, followed by Zhanjiang (46.11 μg/m^3), Zhuhai (47.13 μg/m^3), Guilin (48.11 μg/m^3), Beihai (48.44 μg/m^3), and Lhasa (51.29 μg/m^3). Lanzhou had the highest PM_{10} concentration of 148.44 μg/m^3, followed by Xi'an (126.44 μg/m^3), Weinan (125.78 μg/m^3), Jinan (121.44 μg/m^3), Beijing (121.00 μg/m^3), Pingdingshan (118.33 μg/m^3), and Shijiazhuang (115.89 μg/m^3). Figure 2-2d showed the SO_2 distribution. Most of the regions with lower SO_2 concentration were located in the southeastern China and the western China, while central China had higher SO_2 concentration. Lhasa had the lowest SO_2 concentration of 5.78 μg/m^3, followed by Haikou (7.88 μg/m^3), Zhanjiang (12.78 μg/m^3), Beihai (13.00 μg/m^3), Fuzhou (14.75 μg/m^3), and Zhuhai (17.13 μg/m^3). Huhehaote has the highest SO_2 concentration of 118.00 μg/m^3, followed by Yanquan (93.38 μg/m^3), Shizuishan (74.13 μg/m^3), Liuzhou (73.89 μg/m^3), Taiyuan (72.44 μg/m^3), and Zibo (65.00 μg/m^3).

Figure 2-2e illustrated spatial distribution of per capita GDP respectively. Shenzhen ranked first while Jingzhou ranked last. Regions with highest per capita GDP were mainly located in the east coastal area.

Correlation analysis between health outcomes and air pollutants

First we did SR. Life expectancy and longevity ratio were set as dependent variables separately. SO_2, PM_{10} and per capita GDP were set as independent variables. For the life expectancy related regression, SO_2 and per capita GDP were included, and PM_{10} was excluded. For the longevity ratio related regression, only PM_{10} was included. Using the independent variables in included SR, we did GWR in ArcGIS. All the data were normally distributed. Summary parameters for GWR and SR were shown in table 2-3.

Table 2-3. Parameters for GWR and SR

Regressions	Parameters	PM_{10} to longevity	SO_2 to life expectancy	Per capita GDP to life expectancy	SO_2 and Per capita GDP to life expectancy
GWR	R^2	0.495	0.255	0.476	0.458
	Adjust R^2	0.379	0.195	0.355	0.389
	intercept	40.529	80.810	77.100	78.507
	B	-0.223	-0.035	0.053	-0.028, 0.049
SR	R^2	0.149	0.188	0.242	0.383
	Adjust R^2	0.140	0.178	0.233	0.367
	intercept	55.321	81.784	77.290	79.498
	B	-0.343	-0.050	0.052	-0.047, 0.043
	Sig.	0.000	0.000	0.000	0.000
	r	-0.387**	-0.399**	0.496**	--

** $p<0.05$, * $p<0.1$(2-tailed); we also found there exist significant correlations between life expectancy and PM_{10} (r=-0.237*, CI=95%), between longevity ratio and SO_2 (r=-0.285**, CI=95%), and between PM_{10} and SO_2 (r=0.479**, CI=95%). The reasons that SR excluded PM_{10} for life expectancy regression, and excluded SO_2 for longevity ratio regression could attribute to the multicollinearity between PM_{10} and SO_2.

Table 2-3 showed the GWR and SR results. R-square adjust values for life expectancy associated with SO_2 and per capita GDP were 0.389 and 0.367 for GWR and SR, respectively, which indicated the correlations between two factors and life expectancy. Estimates of the associations between SO_2 and life expectancy with the use of both regressions were sensitive to the inclusion of per capita GDP. The association between SO_2 and life expectancy was stronger without the adjustment for per capita GDP. On the basis of regression models without per capita GDP, every 10 $\mu g/m^3$ increase in ambient SO_2 concentrations could shorten life expectancy by 0.35 year for GWR and by 0.50 year for SR, while life expectancy could be shorten by 0.28 year for GWR and by 0.47 year for SR if included per capita GDP for both regressions. Per capita GDP was positively, significantly associated with life expectancy, which had been documented by other researches (Matthews et al., 2006; Bossuyt et al., 2004). In this research, we found every 10 000 RMB increase in per capita GDP could prolong life expectancy by 0.53 year for GWR and by 0.52 year for SR. $PM_{10}$was associated with diminished likelihood of longevity ratio by 2.23 for GWR and by 3.43 for SR with every 10 $\mu g/m^3$ increase of pollutant concentration. We did not find association between per capita GDP and longevity. This result was in accordance with Lv et al. who reported that people aged 100 and over can be more affected by environmental factors than socioeconomic factors in China (Lv et al., 2011). Although SR excluded PM_{10} for life expectancy regression, and excluded SO_2 for longevity ratio regression, the strong correlations between each set indicated that both air pollutants can influence life expectancy and longevity ratio. SO_2 had a stronger influence on life expectancy than PM_{10} ($p < 0.1$), and PM_{10} had a stronger influence on longevity SO_2 ($p < 0.05$). The robust association between air pollutants and life expectancy indicated that the distribution of life expectancy is related to both air pollutants, which was in good agreement with the literature (Wen and Gu, 2012). Compared with SR, GWR increased R-square adjust values in all the four sets, which indicated that there exist spatial correlation between health indicators and factors.

Spatial correlations between life expectancy and SO2

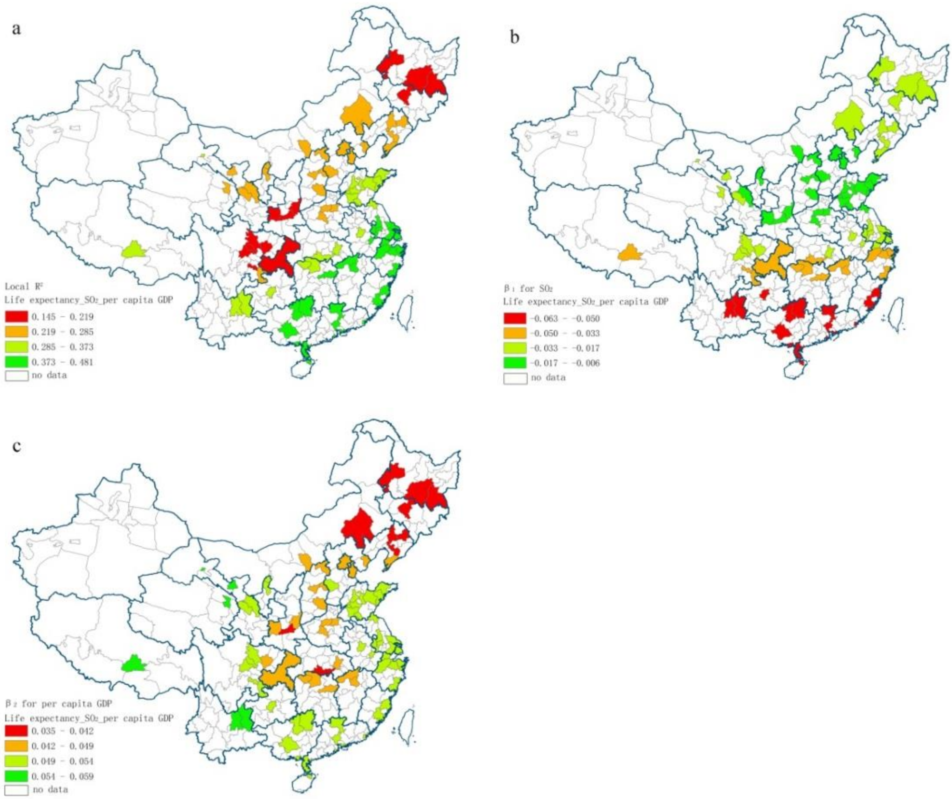


Figure 2-3. Spatial distribution for β-values of SO_2 (β1, Figure 2-3b), per capita GDP (β2, Figure 2-3c) and local R-square values (Figure 2-3a) on the basis of GWR model with per capita GDP.

As Figure 2-3a showed, local R-square values distributed zonally from noutheast to southwest with the values varied from 0.145 to 0.481. The spatial correlated relationship between the two factors and life expectancy were much better proved in southeast areas than in other areas. As Figure 2-3b showed, a regional difference of 10 μg/m³ in SO_2 was found to be negatively associated with adjusted diminish in life expectancy from 0.06 to 0.63 year. A difference of 10 000 RMB in per capita GDP was found to be positively associated with adjusted increase in life expectancy from 0.35 to 0.59 year (Figure 2-3c). According to the β-values in adjust-

SO_2 regression (Figure 2-3b), life expectancy in the regions with higher SO_2 concentration (Figure 2-2c) was less senstive comapered with the life expectancy in regions with lower SO_2 concentration.

Spatial correlations between longevity and PM_{10}

Similar with life expectancy, the longevity ratio was more sensitive to PM_{10} in the south China according to local R-square values (Figure 2-4a). The spatial correlations of longevity ratio and PM_{10} only exist in the south China. A regional difference of 10 μg/m^3 in PM_{10} was found to be negatively associated with 6.74 to 13.49 points' difference on longevity ratio in the south China (Figure 2-4b).

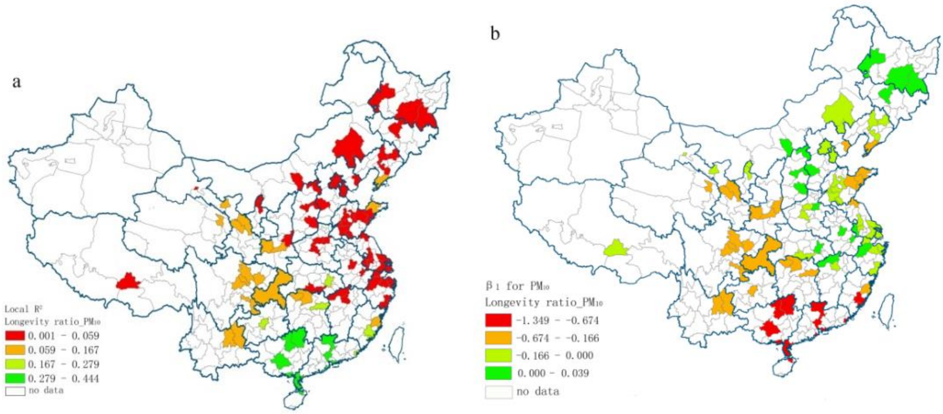


Figure 2-4. Spatial distribution of local R-square values (Figure 2-4a) andβ-values (Figure 2-4b) for the association of PM_{10} to longevity ratio on the basis of GWR.

Through GWR analysis, we found the spatial correlations between health indicators and factors were more significant in south China, where the SO_2 and PM_{10} concentrations were lower. This could be explained by Pope's research (2009) that the exposure dose-effect for ambient air particle matter to health was not linearly associated. With the same particle mater concentration increase, the health hazards were higher in the regions with lower particle matter concentrations (Pope et al., 2009a). There could exist the same pattern for air pollutants influencing health indicators in this research.

Discussions

Life expectancy is an important and representative parameter to indicate a region's public health status. Previous studies indicated that regional life expectancy can be influenced multiple factors, such as economic status (Song et al., 2010), environment (Blum, 1974), education (Bossuyt et al., 2004), infant mortality rate, and even political conditions (Song et al., 2010). Recent research had observed significant associations between air pollutants and life expectancy (Pope et al., 2009b; Wang et al., 2013; Pope et al., 2013). Our research found similar results, particularly for SO_2. A regional gap of 10 μg/m^3 in ambient air SO_2 concentration could associate with 0.28 year's difference in life expectancy. Income had a large effect on perceived health through intermediate factors such as better access to health facilities, affordability for health care, social support, balanced nutrition and healthy lifestyle. The primary strength of this study was that we use spatial variation additionally with socioeconomic indicator. The spatial distribution of life expectancy was strongly associated with per capita GDP and SO_2, and slightly associated with PM_{10}. The impact of SO_2 on life expectancy appeared to be higher in less wealthy regions.

The formation mechanism of longevity is very complex and controversial, but some factors, such as genetic factor (Schachter, 1994), environment (including natural geographical environment and socioeconomic environment) (Liu et al., 2013; Costa, 2005; Magnolfi et al., 2009), and individual behavior (Martin et al., 1996) have been proven to influence lifespan. As one of the most important environmental factors, in this research, both ambient air PM_{10} and SO_2 were found to have significantly negative correlations with the longevity ratio ($p < 0.05$), while SO_2 had a slight spatial association with it. The association between ambient PM_{10} and the longevity ratio was plausible. For one thing, PM_{10} had already been proven to be a major cause of respiratory (Pan et al., 2010; Radim et al., 2013), cardiovascular and cerebrovascular diseases (Pope et al., 2002, 2003). Among those people who aged 100 and over, cardiovascular diseases, hypertension, asthma, allergies, and pulmonary were frequently found in this group. All these diseases can be easily triggered by PM_{10}. In addition, the group aged 100 and over, whose life expectancy was already quite short, had been long cumulatively exposed to air pollutants. Like a "harvesting effect", when the pollutants accumulated to some extent, health effects emerged over time. Previous research already proved that compared to the group under 65, groups at least 85 years old and over were more than twice as likely to die from acute disease from the increases in PM_{10}, and over 50% more likely to die from disease from the increases in SO_2 (Cakmak et al., 2011). A regional gap of 10 μg/m^3 in ambient air PM_{10} concentration could negatively lead to the longevity ratio difference of 2.23. This negative influence was stronger in south China. Regional development and income improvement boosted the life years in Europe (Costa, 2005), but as Table 2-3 showed, no correlation between per capita GDP and the longevity ratio has been found in this research. This could be attributed to the different stage of social development. China's economy essentially changed in the late 1980s, but for those aged 100 and over, they mainly shared the same economic conditions before they were 70 years old. Personal income played fewer roles in longevity in China than in well developed countries. Although we did not find any direct connection between economic status and the longevity ratio, researchers have proven that the mortality effect of pollutants is stronger for those deprived population (e.g., populations with low economic status were more apt to be affected by air pollutants) (Peled, 2011), which indicated that socioeconomic status could mitigate the health risks of air pollutants potentially. With the aging trends sweeping across China, apart from all kinds of air quality control acts, a specialized health care strategy for coping with air pollution for the elderly population is in urgent need.

Conclusions

The present study summarized the spatial distribution characteristics of life expectancy and longevity, and demonstrated the spatial correlations between health indicators and air pollutants adjusted by economic status. Four conclusions can be drawn in this research. First, regions with longer life expectancy were mainly located in China's three major economic centres and other regions with good environments, but no specific distribution pattern for the longevity ratio was found. Second, there existed significant spatial associations between life expectancy and SO_2, between life expectancy and per capita GDP, and between longevity and PM_{10}. Third, a regional difference of 10 μg/m^3 in SO_2 could cause 0.28 year's difference in life expectancy, a regional difference of 10 μg/m^3 in PM_{10} could lead to 2.23 point difference in longevity ratio, and a regional difference of 10

000 RMB could associate with 0.49 year's difference in life expectancy. Fourth, compared with SR, GWR greatly improved the regression accuracy and displayed the spatial fit characteristics.

The causes for life expectancy and longevity ratio's differences were difficult to determine due to numerous factors, such as life style, smoking, meteorological conditions, geography environment, and genetic factors. The present study only investigated the economic adjusted influence of air pollutants to two health outcomes. A comprehensive study integrating all those factors is still to be under taken in further research. This is a pilot study using GWR modelling how the air pollutants and socioeconomic factor influence life expectancy and longevity from spatial perspective. To our knowledge, this is the first research on spatial analysis of life expectancy and longevity in relation to air pollution at the regional scale across China.

CHAPTER 3

Spatiotemporal patterns of ozone and cardiovascular and respiratory disease caused mortality due to ozone in Shenzhen

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Abstract

In order to explore the temporal-spatial patterns and possible health effects of ozone in Shenzhen, daily concentrations of ozone and the daily mortality caused by cardiovascular and respiratory diseases were collected. Using Geographic Information System (GIS) and SPSS, the spatial and temporal patterns of ozone in Shenzhen were illustrated. Using a generalized additive model (GAM), the associations between ozone and cardiovascular and respiratory diseases causing mortality were analysed, adjusted for meteorological factors and other major air pollutants including fine particulate matter ($PM_{2.5}$), nitrogen dioxide (NO_2) and carbon monoxide (CO), and stratified by lag, age, and gender. The results showed that, during 2013, ozone was the second main air pollutant in Shenzhen apart from $PM_{2.5}$, with average daily concentrations of 95.9 μg/m^3 and 76.8 μg/m^3 for the ozone 1-h mean and the daily ozone 8-h maximum concentration, respectively. The daily level of ozone had a higher concentration from September to October, and relatively low concentration from May to June. Obviously, a higher concentration was found in central parts of Shenzhen with the largest population, indicating higher risks. The excess risk (ER) percentage of the cardio-respiratory mortality rate showed a clearly accumulative effect at L03, with the highest ER percentage of 1.08 (0.88–1.27) per 10 μg/m^3 increase in the ozone 8-h maximum concentration for all the population. Males were found to be more sensitive to ozone compared with females, and the elderly were more susceptible to ozone exposure than younger people.

Introduction

Ozone is a secondary pollutant which is not directly emitted into the atmosphere but is created and destroyed by chemical reactions of other emitted species. Ozone is formed in the atmosphere by photo-chemical reactions in the presence of sunlight and precursor pollutants, such as the oxides of nitrogen (NOx) and volatile organic compounds (VOCs). It is destroyed by reactions and then is deposited to the ground. Various other toxic photochemical oxidants arising from similar sources, including nitric acid and hydrogen peroxide, could also influence ozone formation (WHO, 2005).

Through epidemiologic and experimental studies, ground level ozone exposure has been solidly proved to be associated with total mortality, hospital admissions, respiratory symptoms, cough, chest pain, wheezing, asthma, airways inflammation, bronchitis, and cardiopulmonary disease (Hao et al., 2015; Peng et al., 2013; Pride et al., 2015; Shahi et al., 2014). For the association of ozone exposure and cardiovascular disease, the evidence was less conclusive, more heterogeneous, and subject to substantial uncertainty according to a recent review (Petito et al., 2015), and the mechanisms of ozone associated with cardiovascular diseases were also less clear because ozone reacts with respiratory tissues firstly. However, there have been epidemiological studies continually identifying that ozone could enhance cardiovascular related morbidity, probably through its pro-inflammatory effects on the lung (Arjomandi et al., 2015; Brook et al., 2004; Cole & Freeman, 2009; Devlin et al., 2012). Many factors could influence health effects caused by ozone, including the concentration and duration of the exposure (Hazucha et al., 1989), and the susceptibility of the subject itself. Other confounders like the meteorological conditions, other air pollutants and even individual behavior could also influence the association between health impact and ozone (EPA, 2013; Adams, 1987). According to former research, ozone is more likely to reach unhealthy levels under hot and dry weather (Kahle et al., 2015). With global warming, ozone pollution, particularly in hot coastal regions, will become riskier for public health. The association between daily mortality and ozone levels has been proved to be independent of the effects of particulate matter, but not for NOx and CO, which could accelerate the formation or decomposition of ozone and thus influence the concentration (Gryparis et al., 2004). Controlling these confounders in ozone related epidemiological studies is crucial to identifying its health risks.

Ground level ozone has become the secondary ambient air pollutant, following fine particulate matter ($PM_{2.5}$), in many southern cities in China. However, recent studies on air pollution and health have mainly focused on the primary pollutants such as nitrogen oxides (NOx) and fine particulate matter (Chen et al., 2013; Lee et al., 2015; Wang et al., 2014; Xiong et al., 2015; Yang et al., 2014; Zhang, et al., 2011a, 2011b); less focus has been put on ozone research and related health risks assessment. With the increasing emphasis on primary air pollutants control (mainly NOx and SO_2), it is possible to experience an increase in the ozone concentration in China (Anger et al., 2016). Hence, it is necessary to explore the ozone distribution pattern and its health risks to provide scientific evidence on a strategic approach to control ozone pollution, and more importantly to facilitate health precaution strategies.

In this study, we carried out a systemic analysis on temporal-spatial patterns of ozone in Shenzhen and explored the associations between ozone and cardiovascular-respiratory disease-caused mortality, adjusted for meteorological factors and other air pollutants ($PM_{2.5}$, NO_2 and CO), and stratified by lag days, gender and age. The objectives were to identify the spatial and temporal patterns of ozone and to elucidate the health risks caused by ozone pollution.

Materials and methods

Study area and population

Shenzhen is a coastal city in the south of the Guangdong province in China, located in the Pearl River Delta. It has a subtropical oceanic climate, with warm weather and abundant rainfall. The annual average temperature is 22.4 °C, the average monthly temperature is 15.4 °C in January and 28.9 °C in July. Shenzhen has become China’s most crowded city and is the fifth most densely populated city in the world, with a population density of 17,150 per square km. According to the Ministry of Environmental Protection of China, air quality is relatively good in Shenzhen and it is ranked 7th among the 74 first-stage cities implementing the National Ambient Air Quality Standard (NAAQS, GB3095-2012) in 2013. However, Shenzhen has been experiencing elevated levels of air pollution in recent years because of rapid economic development, particularly concerning ozone pollution.

Mortality data

Cardiovascular and respiratory disease-caused mortality data from January 1 to December 31, 2013, was obtained from death certificates recorded at the Shenzhen Centre for Disease Control and Prevention. The causes of death are coded according to the International Classification of Disease revision 10 (ICD-10). In this study, cardiovascular disease-caused death (CVD) (I00-I99) and respiratory disease-caused death (RD) (J00-J98) were identified.

Air pollutants and meteorological data

In 2013, Shenzhen introduced the NAAQS. Air quality data was provided by the Shenzhen Environmental Monitoring Centre and the China National Environmental Monitoring Centre. The daily ambient air concentration of ozone was provided as the daily 1-h mean value and the daily 8-h maximum value, measured from eleven state-controlled monitoring stations in Shenzhen. Daily mean concentrations of $PM_{2.5}$, nitrogen dioxide (NO_2), and carbon monoxide (CO) were also obtained from Shenzhen monitoring stations.

The location of these monitoring stations is presented in Figure 3-1. According to the technical guidelines of the Chinese government, the location of these monitoring stations must not be in the direct vicinity of traffic intersections or of major industrial polluters, and should also be located at a sufficient distance from any other emitting source. Thus, the monitoring data reflect the general background urban air pollution level in the urban area of Shenzhen. It is significant to note that the Nan'ao (NA) station in the east part is in the tourist area with a sparse population and the Overseas Chinese Town (Huaqiaocheng, HQC) station is in the downtown area with the densest population.

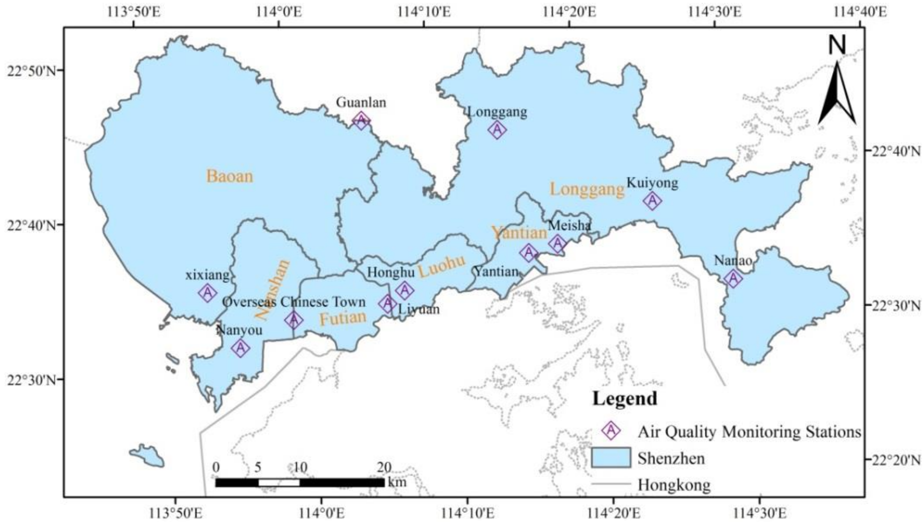


Figure 3-1. Distribution of 11 state-controlled air quality monitoring sites in Shenzhen

To control for the effects of weather on mortality, meteorological data (daily mean temperature, relative humidity, air/barometric pressure and wind speed, etc.) was obtained from the Meteorological Bureau of Shenzhen Municipality. The meteorological data were measured at a fixed-site station located in the study area. This station belongs to the Meteorological Bureau of Shenzhen Municipality, the monitoring standard is consistent with international WMO (World Meteorological Organization) standard, and no data was missing.

Data analysis

In order to quantify the association between daily levels of ozone and daily mortality, adjusted by confounders in the multivariable modelling, consistent with other time-series studies (Bhaskaran et al., 2013; Zhang et al., 2011, 2011), we used the generalized additive model (GAM) with penalized splines to analyse the risk of cardio-respiratory mortality attributable to ozone pollution. Because the daily mortality was small and typically followed a Poisson distribution, the core analysis was a GAM with log link and Poisson error that accounted for smooth fluctuations in the daily mortality.

Before conducting the model analyses, there were two steps in the procedure of the model building and model fit: development of the best base model (without a pollutant) and development of the main model (with a pollutant). The latter was achieved by adding the ozone to the final cause-specific best base model, assuming a linear relationship between the logarithmic mortality number and the ozone concentration.

First, we constructed the basic pattern of mortality number excluding ozone. We incorporated smoothed spline functions of time, weather conditions and the other air pollutants, which can include non-linear and non-monotonic links between mortality and time/weather conditions, offering a flexible modelling tool. The day of the week was also included in the basic models.

After we established the basic models, we introduced the ozone and analysed its association with mortality. To compare the relative quality of the mortality predictions across these non-nested models, Akaike's Information Criterion (AIC) was used as a measure of how well the model fit the data. Smaller AIC values indicated the preferred model. Briefly, we fit the following log-linear generalized additive models to obtain the estimated pollution log-relative rate β in the study district:

$$\log[E(Yt)] = \alpha + \sum_{i=1}^{q} \beta i(Xi) + \sum_{j=1}^{p} fj(Zj, df) + Wt(week)$$

Here E(Yt) represents the expected number of mortality at day t; β represents the log-relative rate of mortality associated with a unit increase of ozone; Xi indicates the concentrations of pollutants at day t; and Wt(week) is the dummy variable for the day of the week. $\sum_{j=1}^{p} fj(Zj, df)$ is the non-parametric spline function of calendar time, temperature, barometric pressure, wind speed and humidity. A detailed introduction of the GAM has been previously described in Wood's book (Wood, 2006). We initialized the df as 9 df/year for time; 6 df for temperature, barometric pressure, and $PM_{2.5}$; 7 df for humidity, NO_2 and CO; and 8 df for wind speed. We also discussed lag effects of the air pollutants, and for the lag effects model we examined the effect of air pollutants with different lag (L) structures of single-day lag (distributed lag; from L0 to L3, L0 corresponds to the current-day pollution, and L1 refers to the previous-day concentration) and multi-day lag (moving average lag; L01 to L03, L03 corresponds to the four-day moving average of the pollutant concentration of the current and the previous three days). The meteorological factors and other confounding air pollutants used in the lag models (distributed lag model, moving average model) were the current day data.

Pearson correlation coefficients among the variables were analysed using SPSS 22.0 (IBM Company 2013, North Castle, NY, USA). Temporal changes of ozone were summarized by Origin 9.0 (Origin Lab, Northampton, MA, USA). In the Macroscopic regional scale, the spatial distribution of the ozone concentration followed the basic assumption of "the first law of geography", namely, the regional concentrations in nearby areas are more similar than in areas farther away. Therefore, inverse distance weighted (IDW) model interpolation analysis was used to analyse spatial distributions of ozone. Spatial differences of ozone were presented by ArcGIS 10.2 (Esri, Redlands, CA, USA) using IDW.

All other statistical analyses were conducted in R3.1.0 (R Foundation for Statistical Computing, Vienna, Austria) using the MGCV package (R Development Core Team, 2014). The results obtained were expressed as the excess risk (ER) percentage change in the number of mortalities caused by cardiovascular and respiratory diseases per 10 μg/m^3 increases of ozone concentrations (ER = $(e^{\delta C} - 1) \times 100$, where δC is the increased amount of air pollutants, in this study we used 10 μg/m^3).

Results

Statistical results

Table 3-1 summarizes the distribution of the annual mean, percentage value on the daily mortality caused by cardiovascular and respiratory diseases, concentrations of ozone 1-h mean and ozone 8-h maximum, confounding air pollutants, and meteorological factors of Shenzhen during the study period.

Table 3-1. Characteristic of air pollutants, meteorological factors and daily mortality

Items	Ave	SD	Min	25%	Mid	75%	Max
c&r	14.4	4.4	4.0	12.0	14.0	17.0	30.0
c&r-m	8.9	3.3	1.0	7.0	9.0	11.0	22.0
c&r-f	5.5	2.5	0.0	4.0	5.0	7.0	15.0
c&r-y	5.1	2.3	0.0	4.0	5.0	6.0	14.0
c&r-o	9.3	3.5	1.0	7.0	9.0	12.0	20.0
T (°C)	23.1	5.2	9.8	19.4	24.2	27.7	31.2
H (%)	74.8	15.5	24.0	67.0	78.0	87.0	100.0
P (hPa)	1005.2	6.2	986.8	1000.5	1005.1	1010.8	1019.2
W (m/s)	2.1	0.8	0.3	1.6	2.0	2.5	5.5
NO_2 (μg/m^3)	39.6	15.7	14.0	28.0	36.0	47.0	111.0
CO (μg/m^3)	1207.2	221.3	700.0	1030.0	1200.0	1344.3	1966.6
O_3-1h (μg/m^3)	95.9	41.3	26.0	60.0	90.0	121.3	234.0
O_3-8h (μg/m^3)	76.8	34.9	17.0	47.0	74.0	100.0	186.0
$PM_{2.5}$ (μg/m^3)	39.6	24.8	9.0	20.0	35.0	52.0	135.0

c&r: cardiovascular and respiratory disease-caused mortality; c&r-m: male group for cardiovascular and respiratory disease-caused mortality; c&r-f: female group for cardiovascular and respiratory disease-caused mortality; c&r-y: 0–65 years age group for cardiovascular and respiratory disease caused-mortality; c&r-o: over 65 years of age group for cardiovascular and respiratory disease-caused mortality; T: temperature; H: humidity; P: barometric pressure; W: wind speed; NO_2: nitrogen dioxide; CO: carbon monoxide; O_3-1h: 1-h ozone concentration; O_3-8h: daily 8-h maximum ozone concentration; $PM_{2.5}$: fine particulate matter (similarly hereinafter).

During the study period, the mean daily temperature and humidity were 23.1 °C and 74.8%, respectively. The mean daily temperature ranged from 9.8 °C to 31.2 °C, and the mean daily humidity ranged from 24% to 100%, reflecting the subtropical oceanic climate of Shenzhen. For the confounding air pollutants, the daily NO_2 concentration ranged from 14 μg/m^3 to 111 μg/m^3, the daily CO concentration ranged from 700 μg/m^3 to 1966 μg/m^3, and the daily $PM_{2.5}$ concentration ranged from 20 μg/m^3 to 135 μg/m^3 with the average being 39.6 μg/m^3. Average concentrations of ozone were 95.9 μg/m^3 for the 1-h mean and 76.8 μg/m^3 for the daily 8-h maximum ozone concentration, and the average values were higher than the median values for both the concentration of ozone 1-h mean and the daily 8-h maximum ozone concentration, indicating a larger contribution of high ozone concentration days to the annual average concentration of ozone. 4646 residents died from cardiovascular diseases and 626 died from respiratory diseases in Shenzhen in 2013. The daily mortality for cardiovascular-respiratory diseases ranged from 4 to 30.

Correlation coefficients

Meteorological conditions can alter the formation and removal of ozone and thus influence the concentration (EPA, 2013). Pearson correlation coefficients among ozone and meteorological factors are presented in Table 3-2. A significant positive correlation was found between ozone and barometric pressure, which is in line with the former research (Austin et al., 2015). Significant negative correlations were found between ozone and other meteorological factors (temperature, humidity and wind speed).

Table 3-2. Correlation coefficients for air pollutants and meteorological factors

Headline	T (°C)	H (%)	P (hPa)	W (m/s)	NO_2	CO	O_3-1h	O_3-8h	$PM_{2.5}$
T (°C)	1								
H (%)	0.377 **	1							
P (hPa)	−0.818 **	−0.534 **	1						
W (m/s)	0.009	−0.003	−0.103	1					
NO_2	−0.381 **	−0.270 **	0.346 **	−0.471 **	1				
CO	−0.493 **	−0.295 **	0.473 **	−0.077	0.345 **	1			
O_3-1h	−0.115 *	−0.574 **	0.298 **	−0.163 **	0.367 **	0.314 **	1		
O_3-8h	−0.139 **	−0.601 **	0.328 **	−0.106 **	0.291 **	0.311 **	0.980 **	1	
$PM_{2.5}$	−0.503 **	−0.589 **	0.544 **	−0.159 **	0.565 **	0.617 **	0.604 **	0.615 **	1

* correlation is significant at the 0.05 level; ** correlation is significant at the 0.01 level (two-tailed).

The health impact of ozone has also been proved to be influenced by meteorological factors. High temperature and ozone might have a synergistic effect on health while the opposite effect occurs for mild temperature when exposed to a high ozone concentration (Kahle et al., 2015). Therefore, the health effect analysis in this study was adjusted by those meteorological confounders. Ambient NO_2 and CO could influence the formation and decomposition of ozone, and significant positive correlations between those two air pollutants and ozone are found in Table 3-2. Although the health effect of ozone exposure was independent from particulate matter (Gryparis et al., 2004), we included $PM_{2.5}$ as a confounder because it was the major air pollutant in Shenzhen and was contributing to significant air pollution-related mortalities (Zhang et al., 2016).

Temporal changes

During 2013, the average daily concentrations were 95.9 μg/m³ ranging from 26 to 234 μg/m³ for the ozone 1-h mean and 76.8 μg/m³ ranging from 17 to 186 μg/m³ for the daily 8-h maximum ozone concentration. According to the NAAQS, the Technical Regulation on Ambient Air Quality Index (on trial) (HJ633-2012) (TRAAQI), and the Technical Regulation for Ambient Air Quality Assessment (on trial) (HJ663-2013) (TRAAQA), ozone was the second main air pollutant in Shenzhen, with 30 days as a primary pollutant and 4 days as a non-attainment pollutant in the year.

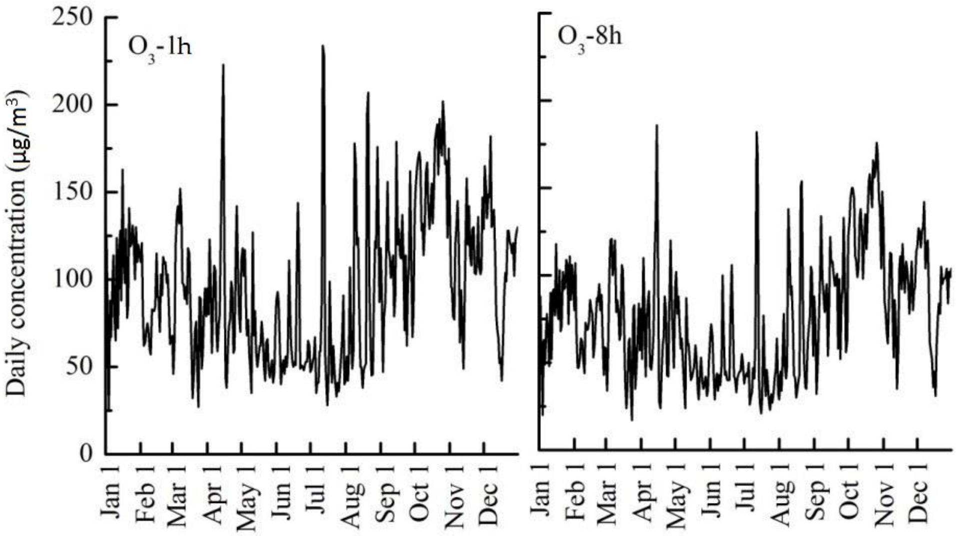


Figure 3-2. Daily concentration of ozone in Shenzhen

Figure 3-2 shows the daily characteristics of the 1-h ozone concentration and the daily 8-h maximum ozone concentration in Shenzhen. The daily level of ozone had a higher value during September to October, while there was a relative lower daily concentration from May to June.

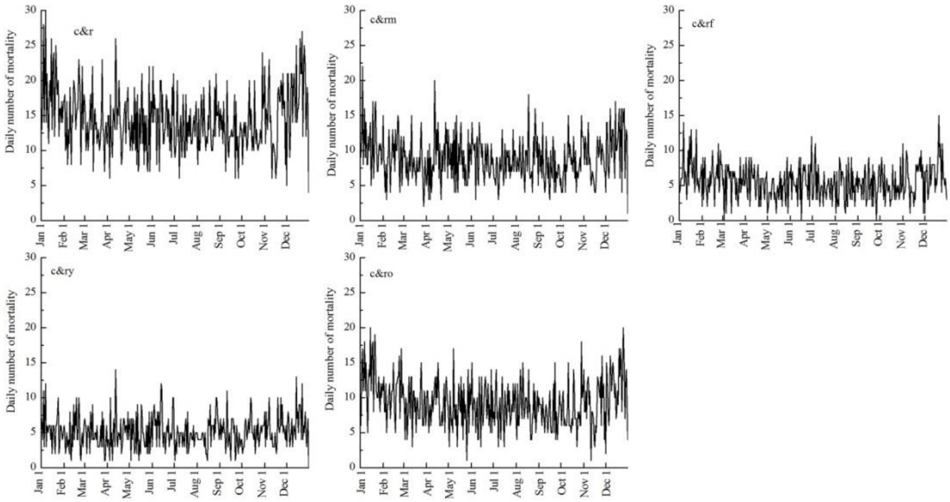


Figure 3-3. Daily mortality

According to the daily mortality in Figure 3-3, males had higher rate cardiovascular and respiratory disease-caused mortality than females, and the elderly group (65+) had significantly higher mortality rate compared to the younger. For the total cardiovascular and respiratory disease-caused mortality, a slightly higher number was found between December to January, while no obvious seasonal patterns of the mortality were found among the males, the females, the younger or the elderly group.

Spatial differences

To represent spatial differences of ozone in Shenzhen more directly, we analyzed monthly and hourly ozone concentrations at HQC and NA sites, in the downtown and tourist areas of Shenzhen, respectively. These two parts of the city serve distinct and quite different urban functions, and differences in air quality might indicate that they were affected by different pollutant emission sources.

Figure 3-4 presents the spatial distribution of ozone in Shenzhen during 2013. The highest concentration could be found in Yantian, which might be attributable to the high emission from the major cargo port in Shenzhen (Yantian port). The Luohu district where Honghu and Liyuan are located is the city centre with intense traffic and human activities, which could explain the high ozone concentration found there. Meanwhile, an obvious higher concentration was also found in the downtown of Shenzhen (HQC) and tourist area (NA). According to NAAQS, TRAAQI, and TRAAQA, annual concentrations of ozone at all the monitoring stations met grade II national air quality standard.

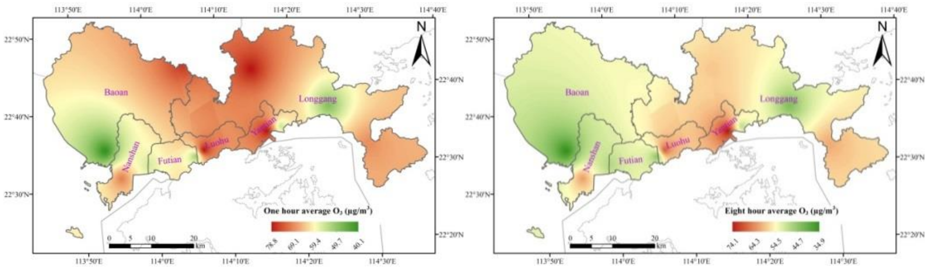


Figure 3-4. Spatial distribution of O_3-1h (left) and O_3-8h (right) in Shenzhen

Temporal Differences between Different Urban Function Areas

In the temporal differences, we considered monthly differences and hourly differences of ozone for the above two different city function areas.

Figure 3-5a shows the monthly average concentration of ozone at HQC and NA from January to November in 2013. Both the downtown and tourist areas had the highest monthly average 1-h ozone level in January and the lowest concentration in July. The daily 8-h maximum ozone concentration showed the highest values in January and October, and the lowest level in July in the tourist area, while the downtown area had the peak value in October and lowest level in July. The ozone concentration in the tourist area was higher than that that in downtown area.

Figure 3-5b shows the average hourly ozone concentrations at HQC and NA in the study period. The 1-h ozone level showed the same hourly trend in the downtown and tourist areas, with the highest concentration at 16:00 and lowest level at 8:00. The daily 8-h maximum ozone concentration also presented similar hourly patterns in the two different areas, which had peak values at 19:00 and the lowest levels at 11:00.

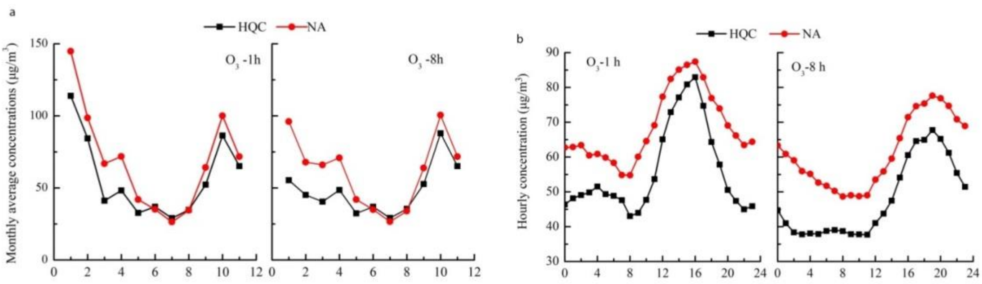


Figure 3-5. Average monthly (a) and hourly (b) concentrations of ozone at Overseas China Town (HQC) and Nan'ao (NA) monitoring stations

Health effects of ozone

Table 3-3 presents the excess risk percentage (ER, 95% confidence interval) of the daily cardio-respiratory mortality with every 10 μg/m^3 increase in ozone concentration. To identify a possible time-delay of ozone exposure-health effects on mortality, we analysed the lag effects of ozone. Changes on ER in cardiovascular and respiratory disease-caused mortality with a 10 μg/m^3 increase of ozone for single-day measures, 1–3 days prior to the mortality (L0–L3), and moving average measures from day 0 and day 1 to day 3 prior to mortality (L01–L03) are also listed in Table 3-3. During the modelling, lag effects of more than 3 days for ozone were also taken into consideration, but little relationship was found, so we only included the lag till lag 3 (L0–L3) and the cumulative lag 0–3 (L01–L03). In this study, we took the daily mortality caused by cardiovascular disease and respiratory disease as one group, and gender and age differences were also taken into consideration. Other major air pollutants and the meteorological conditions were adjusted in the model because these either can influence the health impact of ozone or can simultaneously pose significant health risks (Kahle et al., 2015).

Table 3-3. Excess risk (ER) percentage for the daily cardiovascular and respiratory disease-caused mortality with every 10 μg/m^3 increase in ozone concentration

Items		c&r	c&r-m	c&r-f	c&r-y	c&r-o
		ER (95% CI)	ER (95% CI)	ER (95% CI)	ER (95% CI)	ER (95% CI)
	L0	−0.34 (−0.46–0.22)	0.30 (0.14–0.45)	−1.31 (−1.51–−1.11)	−1.70 (−1.91–−1.40)	0.35 (0.20–0.51)
	L1	0.64 (0.54–−0.75)	0.62 (0.49–0.76)	0.68 (0.5–0.85)	0.72 (0.55–0.90)	0.55 (0.41–0.69)
	L2	0.58 (0.48–0.69)	0.30 (0.18–0.42)	1.07 (0.92–1.23)	0.46 (0.30–0.63)	0.66 (0.53–0.77)
O_3-1h	L3	0.17 (0.07–0.26)	0.15 (0.02–0.27)	0.21 (0.06–0.36)	0.04 (−0.12–0.20)	0.28 (0.16–0.40)
	L01	0.36 (0.21–0.50)	0.76 (0.58–0.94)	−0.24 (−0.47–−0.01)	−0.44 (−0.68–−0.21)	0.72 (0.53–0.90)
	L02	0.71 (0.56–0.88)	0.80 (0.61–0.99)	0.62 (0.38–0.86)	0.07 (−0.18–0.31)	1.01 (0.83–1.20)
	L03	0.69 (0.53–0.84)	0.78 (0.58–0.97)	0.59 (0.34–0.85)	0.03 (−0.23–0.28)	1.00 (0.81–1.19)
	L0	−0.15 (−0.30–0.00)	0.45 (0.26–0.64)	−1.06 (−1.31–−0.85)	−2.02 (−0.23–0.29)	0.79 (0.81–1.20)
	L1	0.59 (0.45–0.72)	0.49 (0.32–0.65)	0.77 (0.55–0.98)	0.88 (0.66–1.10)	0.37 (0.20–0.53)
	L2	0.83 (0.70–0.95)	0.57 (0.41–0.72)	1.28 (1.00–1.48)	0.47 (0.27–0.70)	1.04 (0.89–1.19)
O_3-8h	L3	0.45 (0.33–0.56)	0.43 (0.28–0.58)	0.47 (0.28–0.66)	0.04 (−0.15–0.23)	0.67 (0.53–0.82)
	L01	0.41 (0.24–0.59)	0.73 (0.51–0.95)	−0.04 (−0.32–0.24)	−0.55 (−0.84–−0.26)	0.84 (0.53–0.82)
	L02	0.95 (0.77–1.30)	1.00 (0.77–1.23)	0.91 (0.61–1.21)	−0.01 (−0.31–0.30)	1.40 (1.17–1.63)
	L03	1.08 (0.88–1.27)	1.14 (0.90–1.38)	1.01 (0.70–1.32)	0.03 (−0.29–0.34)	1.59 (1.35–1.83)

Generally speaking, the association between cardio-respiratory mortality and the daily 8-h maximum ozone exposure was more obvious than the ozone 1-h concentration with higher excess risk (ER) percentages; the ER percentage was higher at L2 for single day lag for both 8-h maximum and ozone 1-h concentration, and most of the ER percentages reached the highest points at L03, indicating the cumulative effect. In terms of the gender and age stratification, we found significant higher risks for the male group and the elderly group (65 years and older), and the association between cardio-respiratory mortality and ozone exposure was less evidenced for the females and particularly less for the younger group (0–65 years). The highest risk was found at L03 with the ER percentage of 1.08 (0.88–1.27) per 10 μg/m^3 increase in the 8-h maximum ozone concentration for cardio-respiratory mortality of all population, at L03 with the ER percentage of 1.14 (0.90–1.38) for the male group, at L2 with the ER percentage of 1.28 (1.00–1.48) for the female group, and at L03 with the ER percentage of 1.59 (1.35–1.83) for the elderly group.

Discussions

This study illustrated the spatial and temporal patterns of ozone pollution in Shenzhen, and analysed its health risks focusing on cardiovascular and respiratory disease-caused mortality, adjusted for meteorological factors and major air pollutants. Age and gender were also stratified in the risk study to identify the susceptible group.

The ozone concentration was obviously higher in September and October, and lower from May to June. Anthropogenic activities can largely explain the highest ozone concentrations in the harbour and the city centre, while a higher ozone concentration was also identified in the tourist area (NA) with less population. This was not the only case in Shenzhen. With the increasing emission of the air pollutants in the city centre where the emissions were high, ozone could be decomposed together with its precursors, transferred to downwind areas and then formed into ozone again.

Meteorological factors were found to relate to the ozone concentration through its formation and decomposition (Austin et al., 2015). Barometric pressure was found to positively correlate with both O_3 1-h and O_3 8-h in this study, while, in opposition to former research, temperature was negatively associated with ozone concentration (Lacour et al., 2006). This might be because the months with high temperature were accompanied with high humidity (the rainy season from May to August in Shenzhen), which can influence ultraviolet radiation and thus slow down the formation of ozone. The relationships between meteorological factors and ozone were complex and highly dependent on the range of those factors and the type of the weather clusters, and even the weather frequency change (Austin et al., 2015). With the increase of climate change, the frequency of the weather clusters and extreme weather are predicted to increase and thus the health precaution of ozone pollution could become even more challenging.

In terms of health damage, cardiovascular and respiratory mortality risk of ozone exposure was found among all the population at cumulative lags both for 1-h and daily 8-h maximum ozone concentrations, with the highest ER percentage of 1.08 (0.88–1.27). Ozone is highly oxidant and toxic. Numerous epidemiology studies have shown the association between ozone exposure and respiratory and cardiovascular diseases (Farhat et al., 2013; Hao et al., 2015; Shahi et al., 2014). Inhaled ozone could cause decreased lung function and increased airway hyper-reactivity, particularly for those with pre-existing conditions (Hazucha et al., 1989; Mudway & Kelly, 2000). A recent study using the rat experiment model suggested that ozone exposure could lead to significant perturbations of coronary vascular functions possibly related to intracellular redox disturbances (Paffett et al., 2015). Some other studies, using human volunteers, identified that exposure to ozone could cause adverse systemic inflammation and cardiac autonomic effects through changes in heart rate variability and C-reactive protein, and thus contribute to cardiovascular mortality (Arjomandi et al., 2015; Devlin et al., 2012). Though the mechanism is not conclusive yet, elevated ozone concentration could lead to respiratory and cardiovascular diseases according to many epidemiological studies (de Almeida et al., 2011; Goudarzi et al., 2015; Hao et al., 2015; Jia et al., 2011; Peng et al., 2013; Pride et al., 2015; Xu et al., 2013). Our study came to a similar conclusion, with identified susceptible groups being the elderly and males.

Because of largely existing pre-conditions or deprived immune systems, elderly people are more vulnerable to ozone exposure than the younger generation (Bell et al., 2014). The elderly group (65 years and older) showed the highest cardio-respiratory mortality risk with an ER percentage of 1.59 (1.35–1.83) per daily 8-h maximum ozone concentration increasing by 10 μg/m^3 in this study. From a gender perspective, animal experimental research and meta-analysis have shown that women were more susceptible to inflammatory lung disease induced by air pollution and show worse adverse pulmonary health outcomes than men (Bell et al., 2014; Cabello et al., 2015). By contrast, our research found a more obvious negative association between ozone exposure and cardiovascular and respiratory mortality among males than females. This could be explained by the fact that men are more apt to be exposed to ozone because of their work outside in China. Elevated ozone exposure could affect the health of any individual, but in our research, no obvious exposure-effect correlations between ozone exposure and cardiovascular and respiratory disease-caused mortality among the younger group (0–65 years) were found. We speculated that the excess risk (ER) was estimated with less precision because of the smaller numbers of deaths in this age group compared with the elderly group. For all the sub groups, the associations of elevated ozone exposure and cardiovascular and respiratory mortality were much better proved among the cumulative lags for 8-h exposure. Susceptible individuals for ozone exposure were males and the elderly in Shenzhen.

The health risk caused by ozone exposure is influenced by the emissions of precursor chemical species, meteorology and population themselves (Bell et al., 2014; Cabello et al., 2015; EPA, 2013; Kahle et al., 2015). Precursor chemicals mainly are methane (CH_4) and carbon monoxide (CO), which, with the emissions of nitrogen oxides ($NOx = NO + NO_2$), contribute to a general hemispheric 'background' of ozone. Temperature and humidity are the two major meteorological factors influencing the formation and concentration of ozone, and more directly, intervening the formation of clot through the activation or suppression of the fibrinolytic pathway (EPA, 2013; Kahle et al., 2015; Sanderson, 2003). In this research, we analysed the association between ozone concentration and cardiovascular and respiratory disease-caused mortality confounded by those air pollutants. However, other confounders including socioeconomic position and individual behaviour could also influence the health effects of ozone. Because of the data limitation, we did not include those confounders.

Conclusions

In conclusion, ozone was the second main air pollutant in Shenzhen. The daily concentration of ozone was higher from September to October, while there was a relative low daily concentration from May to June. Obviously, a higher ozone concentration was found in the harbour and city centre, while the tourist area, which was distant from the city centre or industrial area, also had a considerably high ozone concentration, indicating the regional transmission. The ozone level showed same hourly trend in the downtown and tourist areas and the ozone 8-h maximum had peak values around 19:00 and the lowest levels around 11:00. The excess risk (ER) in the cardiovascular and respiratory disease-caused mortality would increase with the concentration level increase of ozone, particularly for the ozone 8-h maximum concentration. When the ozone concentration increased, males in the cardiovascular-respiratory disease mortality group seemed to be more sensitive than females, and people older than 65 years seemed to be affected more easily than younger people. Our findings provide additional information about the ozone distribution and health risk patterns and thus provide scientific evidence for coping strategies for health protection.

CHAPTER 4

Air quality strategies on public health and health equity in Europe—a systematic review

Li Wang, Buqing Zhong, Sotiris Vardoulakis, Fengying Zhang, Eva Pilot, Yonghua Li, Linsheng Yang, Wuyi Wang, Thomas Krafft (2016). Air quality strategies on public health and health equity in Europe: A systematic review. International Journal of Environmental Research and Public Health. doi: 10.3390/ijerph13121196

Abstract

Air pollution is an important public health problem in Europe and there is evidence that it exacerbates health inequities. This calls for effective strategies and targeted interventions. In this study, we conducted a systematic review to evaluate the effectiveness of strategies relating to air pollution control on public health and health equity in Europe. Three databases, Web of Science, PubMed, and Trials Register of Promoting Health Interventions (TRoPHI), were searched for scientific publications investigating the effectiveness of strategies on outdoor air pollution control, public health and health equity in Europe from 1995 to 2015. A total of 15 scientific papers were included in the review after screening 1626 articles. Four groups of strategy types, namely, general regulations on air quality control, road traffic related emission control interventions, energy generation related emission control interventions and greenhouse gas emission control interventions for climate change mitigation were identified. All of the strategies reviewed reported some improvement in air quality and subsequently in public health. The reduction of the air pollutant concentrations and the reported subsequent health benefits were more significant within the geographic areas affected by traffic related interventions. Among the various traffic related interventions, low emission zones appeared to be more effective in reducing ambient nitrogen dioxide (NO_2) and particulate matter levels. Only few studies considered implications for health equity, three out of 15, and no consistent results were found indicating that these strategies could reduce health inequity associated with air pollution. Particulate matter (particularly fine particulate matter) and NO_2 were the dominant outdoor air pollutants examined in the studies in Europe in recent years. Health benefits were gained either as a direct, intended objective or as a co-benefit from all of the strategies examined, but no consistent impact on health equity from the strategies was found. The strategy types aiming to control air pollution in Europe and the health impact assessment methodology were also discussed in this review.

Introduction

Despite efforts to control and reduce air pollution in many countries, ambient (outdoor) air pollution in both urban and rural areas was estimated to have been associated with up to 3.7 million premature deaths worldwide in 2012, with a significant proportion of these deaths in Asia (mainly in China and India) (WHO, 2016). Air pollution has been associated with multiple diseases, such as cardiovascular diseases, asthma exacerbations, lung cancer, and diminished life expectancy (Pope et al., 2002, 2009; Chen et al., 2013; Wang et al., 2014; Shah et al., 2015). Further, these negative health impacts varied according to the socioeconomic position (SEP) and health condition of individuals (WHO, 2016). Research findings showed that people with disadvantaged social-economic status were more likely to be exposed to higher air pollutant concentrations in ambient environments, at home, in school, in occupational environments, in the neighbourhood, and in commuting (Evans and Kantrovitz, 2002; Hoek et al., 2002; Neidell, 2004; Naess et al., 2007; Deguen and Zmirou-Navier, 2010; Bell and Ebisu, 2012; Chi et al., 2016). Epidemiological studies also showed that specific population groups, such as the elderly, young children and people with pre-existing respiratory or cardiovascular conditions, are more likely to be affected by air pollutants, indicating that air pollution could increase health inequity (Deguen and Zmirou-Navier, 2010; Pope, 2000; Peled, 2011).

Air pollution control efforts in Europe extend to more than a century. Some early examples are the Alkali, &c. Works Regulation Act (1906) and the Clean Air Act (1956) following the "Great London Smog" of 1952 in the UK (UK, 1906, 1956). Since then, a series of pieces of legislation and programmes have been put forward, such as the European Union (EU) Directives which set limit values and guidelines for air pollutants (EC, 1999, 2005); the Convention on Long-range Trans-boundary Air Pollution (CLRTAP) and related protocols, which focused on emission reductions for specific air pollutants (UNECE, 1979); the Clean Air for Europe Programme (CAFE 2005) which facilitated the establishment of air pollution control strategies to protect human health(EC, 2005); and local actions such as low emission zones (LEZs) and the introduction of vehicle exhausts catalysts (VECs) to control traffic emissions (Urban access regulation in Europe). With these legislations and programmes, the air quality in EU has improved in recent decades, particularly for the Western EU member countries. However, in more than one third of EU's Air Quality Zones, particulate matter (PM) concentrations exceed the limit values, and the limit values for nitrogen dioxide (NO_2) are not met in about a quarter of the zones (EC, 2013). As a consequence, a large proportion of the urban population, particularly those living close to heavily trafficked roads or industries, and those living in large city centres; remain exposed to air pollutants with concentrations that exceed the European air quality standards for outdoor air quality. More specifically, in 2011, 33% of the urban population in the EU-27 were exposed to PM_{10} levels exceeding the daily limit value; 31% were exposed to $PM_{2.5}$ levels exceeding the annual exposure concentration obligation; still 5% were exposed to NO_2 concentrations exceeding the annual limit value; and 14% were exposed to higher ozone concentration than set in the EU target value (Hoek et al., 2002; EC, 2013; Guerreiro et al., 2014). It is estimated that in 2010, 406,000 premature deaths were attributable to exposure to particulate matter and ground-level ozone in Europe (EC, 2013). $PM_{2.5}$ would be still responsible for 5.5 months statistical loss of life on average across the EU by 2020 and OECD countries are likely to have one of the highest rates of premature death from ground-level ozone by 2050 if there are no more stringent strategies to control air pollution (EC, 2005; OECD, 2012). Although an increasing number of strategies have already been introduced from EU level to local level (EC, 1999, 2005, 2008; DEFRA, 2003, 2007, 2010), and several epidemiological studies on air pollution and its adverse health impact have been carried out (Hoek et al., 2002; Beelen et al., 2008, 2014; Raaschou-Nielsen et al., 2013), there is no comprehensive summary of the effectiveness of air pollution control strategies on public health , and particularly on health equity in the EU.

In order to review the effectiveness of air pollution control strategies and to understand their impacts on public health and health equity, we undertook a systematic review of relevant published studies focusing either on health impact assessment or on health equity assessment in Europe. This review aimed to examine health equity associated with air pollution control strategies, to provide scientific suggestions for further studies on air pollution control strategies, and importantly, to provide evidence on the effectiveness of air pollution control strategies in Europe, which may be transferable to Asian countries where air pollution is posing a very significant public health challenge.

Methods

Definition and searching method

Summarized from WHO glossary of terms used for Health Impact Assessment (HIA), health inequities were defined as uneven health status which may be unnecessary and avoidable as well as unjust and unfair, and these differences in health status are attributable to the external environment and conditions mainly outside the control of the individuals concerned. Health inequalities were differences in health status or in the distribution of health determinants between different population groups, and those differences are attributable to biological variations, free choice, or the external environment and conditions mainly outside the control of the individuals concerned (this also applies to health inequity) (WHO). There are differences in health outcomes from exposure to air pollution, which may affect more socioeconomically deprived groups that often live near busy roads or industrial sites and have fewer opportunities to move to less polluted and usually more expensive areas (Neidell, 2004; Deguen and Zmirou-Navier, 2010; Bell and Ebisu, 2012). Furthermore, air pollution disproportionately affects the more susceptible groups, including the elderly and those with pre-existing illness. In this review, we summarized the strategies on air quality control and their impacts on health and health equity. The objective of this study was to explore the effectiveness of the air pollution control related strategies on public health and health equity, and the strategies in this review were limited to: (1) specific strategies such as policies, regulations, legislation, or directives on ambient air quality control at EU or national level; and (2) specific interventions or actions to reduce ambient air pollution emissions.

We conducted a systematic literature review aiming to assess public health and health equity impact of air quality control strategies based on three databases, Web of Science, PubMed, and Trials Register of Promoting Health Interventions (TRoPHI). In Web of Science, we searched on the scope, which includes title and abstract; in PubMed, we searched on the title and abstract; and in TRoPHI, on keywords. Strategy in our review was defined as interventions, policies or directives aimed at reducing air pollutants or where concentration reduction occurred as an unintended consequence of a strategy. Four key themes, air quality, strategies, health and effectiveness, were selected, and search terms for each theme were selected and defined by consent of all authors. For air quality, we used the following search terms: “air pollution”, “air pollutant”, “outdoor air”, “ambient air”, and “atmospheric air”. For strategies, we used the following search terms, “policy”, “programme”, “project”, “regulation”, “management”, “plan”, “strategy”, “action”, “directive”, “intervention”, “emission control”, “scheme”, and “initiative (in the way of campaign, training, incentive, etc.)”. For health, we used the search terms of “health equity”, “health inequity”, “mortality”, “death”, “morbidity”, and “health”. For effectiveness, we included the following search terms, “evaluation”, “assessment”, “efficacy”, “effectiveness”, “efficiency”, and “impact”. Regarding health equity impact, for those studies with health equity assessment, we summarized the effectiveness of the strategies in improving health equity. For those studies without or with no direct assessment of health equity, we commented on the capacity of the strategies to influence health equity based on whether the studies mentioned health gains from the strategies in terms of differential air pollution reductions (geographical distribution), or different health response among different groups, including age groups, pre-existing health condition groups, gender groups and socioeconomic groups. Those publications containing at least one term of each theme were identified in this search. The inclusion and exclusion criteria are shown in Table 4-1.

Table 4-1. Selection criteria for study inclusion and exclusion

Inclusion	Exclusion
1. English language for the full article	1. Non-English, even with English abstract
2. Scientific peer-reviewed articles, including conference articles	2. Government report, project report, etc.
3. Europe Union member countries	3. Theoretical papers on policies or interventions and related health risks from air pollution
4. Published between January 1 1995 till October 4 2015	4. Papers that only mentioned health in the conclusions or recommendations
5. Health outcome changes are associated with the concentration change of assessed air pollutants	5. Papers assessing interventions that change air pollutant concentrations but not through reduction of emissions from pollution sources (such as green barriers, photocatalytic paints, ventilation, filtration system, etc.)
6. Papers with health assessment from air pollution, indicated by quantitative health indicators, such as mortality, life expectancy, hospital admissions, disease incidence or prevalence, or monetary health benefit, or self-reported health perception, or other indicators which can show the health status	6. Papers on indoor air pollution control interventions
7. Papers focusing on ambient air pollution	

Screening method

For the period January 1 1995 to October 4 2015, 1626 articles were identified from the three databases according to the searching terms, 1522 from Web of Sciences (with country restriction), 103 from PubMed (refined by "Europe" in Mesh) and 1 from TRoPHI.

Among these, 1584 were excluded after the duplication check in Endnote and abstract screening, and 42 selected for full text screening (Figure 4-1). From these 42, 16 articles were excluded because they mentioned health but with no quantitative health impact assessment; 7 articles were excluded because the strategies were not about air pollution source emission control but exposure interventions, such as improved ventilation system or decreased exposure frequency; 3 articles were excluded because the studies were on theory or a synthesis of existing reviews on air quality policies and health impact assessment; and 1 was excluded because it shared the same strategy and air pollution outcome with one included study (Chanel et al., 2014; Letertre et al., 2014). At the end, 15 articles were included after the full text screening.

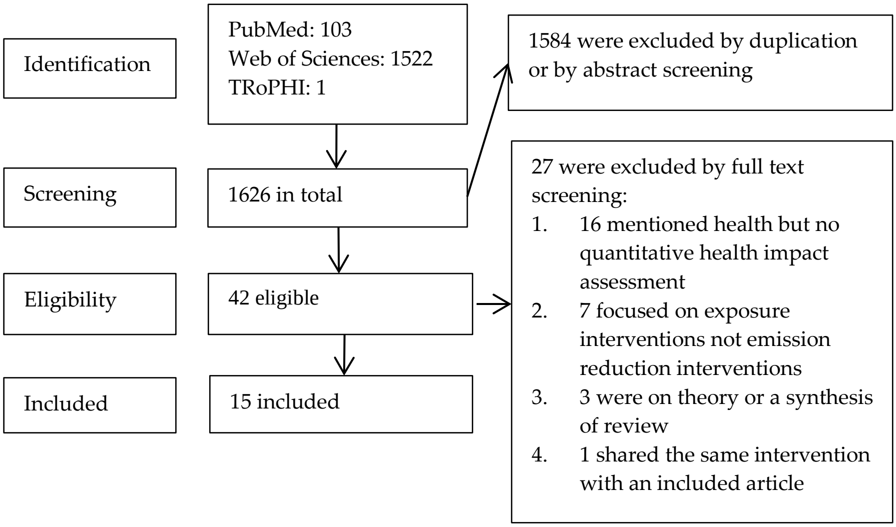


Figure 4-1. Flow chart of the searching and screening procedure

Results

Based on the study types of the 15 articles included, we divided the articles into three categories (marked with I, II and III, see Table 4-2). The first category comprised articles tackling air pollution under the scope of general guidelines at WHO, EU or national level, by means of policies, directives, legislation, standards, guidelines or targets (I); the second category comprised articles on specific interventions, by means of actions or experimental studies (II); and the third category covered articles assessing air quality changes and health benefits under different scenarios (III).

Articles under category I, covered larger geographic areas, for example the entire EU or member countries; while for those with specific actions, the area was smaller and more on the level of a selected city or even a smaller area. There were five articles from the United Kingdom (UK), three articles at European level, two articles from Spain, and one article each from Hungary, Sweden, German, Italy and Ireland. All articles focused on urban areas (13 exclusively, while two covered both urban and rural areas). In most of the articles, the target pollutants were particulate matter (PM_{10}, $PM_{2.5}$), followed by NO_x (nitrogen oxides), SO_2 (sulphur dioxide) and ozone, and the pollutant concentrations were assessed by real-time monitoring, model simulation or were set as targeted concentrations according to guidelines or seniors.

In order to explore the impact of the strategies on public health and health equity, we only included articles with health outcome indicators. The health variables used in these articles can be classified into three categories. Most of the articles used attributable mortality (including premature mortality) and morbidity, including hospital admissions and some specific symptoms such as nasal, ocular and respiratory symptoms; some used different ways of relating the health outcome to life years, including life expectancy or years of life gained (YLG); and some used monetized health benefits.

For the health impact assessment, the exposure-response relationships were mostly derived from long-term or both short and long term exposure assessments and only four focused on short-term exposure effects. Most of the articles focused on the entire population, stratified by age group, by gender, by socioeconomic position, or by the distance to the intervention areas within the catchment of the respective study areas. Table 4-3 summarizes the health impact assessments and comments on health equity based on the type of the strategies.

Table 4-2. Summary of the included studies

Study& publish time	Country& geographical scale	Time period covered	Strategy or intervention description and study type (I,II,III)	Methods for measuring air pollution concentration and health outcome, and brief study description	Assessed air pollutants [a]	Health variables	If co-Benefit [b], assessment term, and cofounders	Target group
Aunan, K. et al. 1998	Hungary National level Urban	1992–1993 to the following 5 years	The energy saving program, from National Energy Efficiency Improvement and Energy conservation Programs. (Energy savings of 64PJ/year [c] were expected in a 5 year target period since 1994) II	Monitored Population/recipient data The study simulated the possible reduced damage to public health and other benefits obtained from reducing emissions of key air pollutants	NO_2, SO_2, TSP [d], Dust fallout, PM_{10},	Reduced air pollution attributed annual excess death for >65 and ≤65 years; Reduced air pollution attributed annual excess infant death (0–1 year); Reduced annual acute respiratory symptom days for children and adults; Reduced non-accidental and non-violent mortality; Reduced annual lung cancer cases; Monetary health benefit	Co-benefit Long-term Frequency baseline of the health outcomes	All population, stratified by age group
Clancy, L. et al. 2002	Ireland Dublin, city level Urban	1984–1990 1990–1996	Ban of coal sales. (The Irish Government banned the marketing, sale, and distribution of bituminous coal within the city of Dublin from 1st September 1990) II	Monitored Population-standardised death rates The study compared the air pollution concentrations and health before and after the ban of coal sales in Dublin (1990)	Black smoke, SO_2	Annual total non-trauma death; Respiratory death; Car-cerebrovascular death; Other non-trauma death(total minus cardiovascular and respiratory)	Short-term Temperature, relative humidity, day of week, epidemic, standardised cause specific death rate, and age groups	All population, stratified by age group
Burr, M.L. et al. 2004	UK North Wales, district level Urban	Intermittent 1996–2000	By-pass construction in congested area. (A by-pass was opened in an area with severely congested traffic) II	Monitored Respiratory survey for health The study compared the air pollution concentrations and health outcomes (indicated by the prevalence of respiratory symptoms) between a congested street with a by-pass and uncongested street area	PM_{10}, $PM_{2.5}$	Frequency of symptoms, including wheeze, winter cough, phlegm, consulted doctor, and rhinitis, and peak expiratory flow rate	Short-term Symptom frequency baseline before the intervention	All population, in the experimental area
Hutchinson, E.J. et al. 2004	UK Country level Urban	1993–1998 1998–2005	Vehicle exhausts catalysts (VECs) (UK mandatorily introduced VECs to gasoline fuelled vehicles since 1993) II	Simulated Calculated from mortality rate and hospital admission rate The study evaluated the environmental and health benefits of the emission reduction from VECs with available data for exposure assessment and projection for ex ante assessment (1998)	PM_{10}, NO_2, O_3 [d], VOCs [d], CO [d]	Monetary health value (all-cause mortality and respiratory hospital admission)	Short-term Population change, underlying mortality rate and underlying hospital admission rate	All population
Mindell, J.	UK	(1996–	UK National Air Quality Strategy	Monitored and targeted	PM_{10}	Delayed non-traumatic premature	Short and long-term	All population,

and Joffe, M. 2004	Westminster, district level Urban	1998)—2004, 2009	Objectives for 2004 and 2009 I	Calculated from routine mortality and hospital admission data The study modelled the health impacts of PM_{10} reduction from the current levels(1996–1998) to the UK 2004 and 2009 target levels		death; Emergency hospital admissions and consultations for respiratory diseases, including asthma, COPD, LRTI, and IHD [e]	Mortality number and hospital admission baseline	stratified by age groups
Tonne, C. et al. 2008	UK London Central, city level Urban	February 2003–February 2007	Congestion Charging Scheme (CCS) (London Mayor introduced CCS in Feb. 2003) II	Simulated Calculated from mortality data The study modelled the air pollutant concentrations before and after the implementation of CCS, and then used exposure-response coefficients to predict the health gain indicated by years of life gained.	NO_2, PM_{10}	All-cause mortality, indicated by YLG	Co-benefit Long-term Baseline mortality rate, geographic distribution of population and deprivation	All population, stratified by socioeconomic position
Ballester, F. et al. 2008	26 EU cities EU level Urban		European Directive, European Parliament, U.S. Environmental Protection Agency and the World Health Organization on $PM_{2.5}$ guideline (25μg/m³, 20 μg/m³, 15 μg/m³, and 10 μg/m³, respectively) III	Monitored & calculated Calculated from the total mortality data The study estimated the mortality reduction if the $PM_{2.5}$ concentration reduced to the targeted levels	$PM_{2.5}$	Reduction in all-cause premature deaths; Total burden of all-cause mortality	Long-term Baseline mortality rate	30 years and older
Perez, L. et al. 2009	Spain Barcelona 57 municipalities Urban	Post 2004	Directive 2008/50/EC and WHO guidelines for PM_{10} (annual mean concentration of 20μg/m³ and40 μg/m³) III	Targeted Calculated The study estimated the avoided mortality and morbidity under the scenarios examined the annual mean PM_{10} concentration decreased to the WHO recommended level or to the European Union regulatory level	PM_{10}	Monetary health value, indicated by VOLY [f] from all-cause mortality, morbidity (chronic bronchitis and asthma related symptoms), and hospital admissions of respiratory and cardiovascular causes	Short and long-term Population and baseline frequency of mortality and morbidity	All population, with infant death
Johansson, C. et al.	Sweden Stockholm,	2003–2007	Congestion tax system (Stockholm Trial)(Vehicles	Monitored and simulated Calculated from the mortality rate	NO_x, PM_{10}	Premature death, indicated by YLG [f]	Co-benefit Long-term	All population

2009	city level Urban		travelling into and out of the charge cordon were charged for every passage during weekdays) **II**	The study uses a test trial to measure and model the reduction of road use and then to model the reduction of traffic related PM_{10} and NO_x ; and using epidemiological mortality risk from NO_x, calculates the avoidable premature death			Baseline mortality rate, geographic distribution of population	
Woodcock, J. et al. 2009	UK London, city level Urban	2010–2030	Road transport interventions (Combination of active travel and lower-carbon emission motor vehicles) [g] **II**	Simulated Simulated The study compared business as usual and with the interventions, and modelled the health benefit from reduction in $PM_{2.5}$ concentration	$PM_{2.5}$	Premature deaths from cardio-respiratory diseases and lung cancer in adults and acute respiratory infections for children DALYs [f]	Co-benefit Short and long term Physical activity and road traffic accidents	All population stratified by age groups
Boldo, E. et al. 2011	Spain National level Urban and rural	2004–2011	Spain pollution control policies (Spain's National Emissions Inventory, a baseline 2004 scenario and a projected 2011 scenario on a reduction of primary $PM_{2.5}$, due to technological measures targeting the road transport sector, industry, agriculture, and power generation) **III**	Targeted Calculated from the all-cause mortality and population data The study assessed the health benefit under the assumption that specific air quality policies were implemented successfully.	$PM_{2.5}$	Avoided all-cause mortality	Long-term Population baseline and mortality baseline stratified by age	30–99 years group; 25–74 years group
Cesaroni, G. et al. 2011	Italy Rome, city level Urban	2001–2005	Limited traffic zone (LTZ) (Without policy scenario, optimistic scenario which assumed that all Euro 0 cars were replaced by Euro 4 cars, and pessimistic scenario which assumed that 10% of Euro 0 cars still running, and the rest 90% of Euro 0 were replaced by Euro 1–4 cars) **II**	Simulated Simulated The study calculated the pollution concentration according to the traffic data, and used a concentration-response function to assess the health benefit in two LTZs under the three scenarios	NO_2, PM_{10}	Total mortality, indicated by YLG	Long-term Distance to the intervention, age groups, education levels	People over 30 years old living along high-traffic road, stratified by the distance of 50m, 50–100m and 100–150m, and stratified by SEP
Chanel,	EU	Post	Three European Commission	Monitored & simulated	SO_2	Annual avoided respiratory,	Short-term	All

O. et al. 2014	20 EU cities, EU level Urban	2000	Directives to reduce the sulphur content in liquid fuels for vehicles (1994, 1996, 1999/2000) EC Directive93/12/EEC, EC Directive98/70/EC, Council Directive 99/32/EC (Aphekom project). I	Calculated from the number of deaths The study compared the emission reduction and health gain before and after the intervention		cardiovascular and total premature death (non- external); monetary health benefit indicated by VOLY	Temperature, day of the week, seasonality, time trend and number of death	population, in 20 cities in EU
Cyrys, J. et al. 2014	German Berlin, city level Urban	Post 2010	Low emission zones (LEZs) since 2010 II	Observed & targeted Calculated The study analysed the scientific literatures on the effectiveness of LEZs to PM in German cities and then calculated the avoided death attributable to black smoke due to LEZs in Berlin	Black smoke, PM_{10}	Annual avoided total death	Long-term No confounder	All population
Schucht, S. et al. 2015	EU EU level Urban and rural	2005–2050	EU air pollution legislation and climate policies I	Simulated Simulated The study compared the pollution change and health benefit under the scenario only with air pollution legislation and the scenario with both air pollution legislation and climate policies.	$PM_{2.5}$, O_3	Premature death from acute mortality of respiratory hospital admissions(65+ year) and minor restricted activity days(15–64 year); YLL [f] from chronic mortality of all ages; Monetary health benefit, indicated by cost of GDP [h]	Co-benefit Short and long terms The population change	All population, stratified by age groups

[a] For assessed pollutants, we only included the pollutants that were used for health impact evaluation (excluding CO_2). [b] Co-benefit was defined as the additional benefit of strategies which was above or beyond the direct aim of the strategies. [c] PJ, petajoule. [d] TSP, total suspended particles; O_3, ozone; VOCs, volatile organic compounds; CO, carbon monoxide. [e] COPD, chronic obstructive pulmonary disease; LRTI, lower respiratory tract infection; IHD, ischaemic heart disease. [f] YLG, years of life gained; VOLY, value of a life year; DALYs, disability adjusted life years; YLL, years of life lost. [g] For strategy A, B and A+B, we only included the one with the highest air pollution concentration reduction and health impact. [h] GDP, gross domestic product.

Table 4-3. Summary of health impact assessments and comments on health equity according to the type of the strategies

Strategy type	Major air pollutants	Reference	Pollution control outcome or targeted level	Health outcome *	Was health equity assessed? If not, comment on health equity
General regulations on air quality control in Europe	$PM_{2.5}$, PM_{10}	Mindell, J. and Joffe, M., 2004	PM_{10} concentration with 35 permitted exceedances in 2004 and with 7 exceedances for 2009 for 24 h limit of 50 μg/m³; PM_{10} annual mean of 20 μg/m³	Avoided 2–39 deaths per 100,000 if complying 2009 24 h PM_{10} target; 3.7–9.3 delayed death if complying UK 2009 annual PM_{10} target in Westminster	Yes, reducing air pollution would decrease inequities because exposure would be reduced most in deprived areas and because those who would benefit most were those with worse health, the very young and older people
		Ballester, F. et al., 2008	Annual $PM_{2.5}$ dropped to 25 μg/m³, 20 μg/m³, 15 μg/m³, and 10 μg/m³, respectively	Annual all-cause premature deaths avoided up to 114 (Cracow) per 100,000 if annual $PM_{2.5}$ dropped to 10 μg/m³; Averagely 3% of the total mortality burden among 30 years and older can be reduced	No. Comment: Cracow, Athens and Rome had the most pollution, and benefited the most; London, Dublin and Stockholm had less pollution, and benefited less
		Perez, L. et al., 2009	Annual mean ambient air PM_{10} concentration dropped from 50 μg/m³ to 20 μg/m³(WHO) and to 40 μg/m³(EU)	With WHO target, monetized health benefit was 6400 million Euros per year(1600 euro per capita) from mortality and morbidity	No. Comment: with targeted standards. *No sign* of effect on health equity
		Boldo, E. et al., 2011	An average annual reduction of 0.7 μg/m³ in $PM_{2.5}$ concentration	Annually, 6 per 100,000 population of all-cause deaths avoided for over 30-years group and 5 per 100,000 population avoided for the 25–74 years age group	No. Comment: major absolute health benefits were in Spain's most densely populated cities, such as Madrid, Barcelona, Seville, and relative benefits were the highest in Andalusia and Mediterranean areas
Energy related strategies	SO_2, NO_x, TSP, Black smoke	Aunan, K. et al., 1998	SO_2 concentration dropped by 5.7%, TSP dropped by 9.3%, NO_x dropped by 10.1%, nmVOC (non-methane volatile organic compounds) dropped by 10%, and other greenhouse gases dropped	The program reduced air pollution attributed annual excess death by 9% for the whole population, reduced air pollution attributed annual excess infant death (0–1 year) by 11.4%, reduced annual acute respiratory symptom-days for children and adults by 11.2% and 9.8%, and reduced 25 annual lung cancer cases. The monetized health benefit was 1563 million US dollar	No. Comment: for 65+, infant, and those with pre-existing health conditions, the exceeded cases or exposure days were largely decreased, thus benefited more
		Clancy, L. et	Mean Black smoke concentration dropped by 70%	Adjusted mortality rate decreased by 5.7% for total non-trauma,	No.

		al., 2002	and SO_2 concentration dropped by 33.8%	10.3% for cardiovascular, 15.5% for respiratory, 7.9% for less than 60 years group, 6.2% for 60–74 years group and 4.5% for over than 75 years group	Comment: the Ban greatly decreased mortality, particularly for cardiovascular disease group
		Chanel, O. et al., 2014	Gradual decline in SO_2 concentration	Postponed annual 2212 premature deaths for 20 cities after 2000 comparing with pre 1993; Annual monetized health benefit from mortality was 191.6 million Euro	No. Comment: the lowest number of postponed deaths attributable to the regulation was obtained in Bilbao and the highest in Athens
Traffic emission control related interventions	NO_x, PM	Burr, M.L. et al., 2003	PM_{10} concentration decreased by 23% (8.0 μg /m³) in the congested streets and by 29% (3.4 μg /m³) in the uncongested; $PM_{2.5}$ decreased by 23.5% in congested streets and 26.6% in uncongested streets	Clear improvement around the congested streets for rhinitis symptoms, but no clear differences for low respiratory symptoms	No. Comment: the people living along the intervention area benefited more since the intervention covered specific congested area
		Hutchinson, E.J. et al., 2004	NO_2 concentration dropped by around 20%, PM_{10} dropped by around 10%, O_3 increased slightly, VOCs dropped by around 30%, and CO dropped by more than 70%	Net health benefit of 510 million Pound to 1998, and 2157 million Pound to 2005 with the combined concentration change of NO_2, PM_{10} and O_3	No. Comment: the city people benefit mostly, the rural areas are unlikely to have large health benefit.
		Tonne, C. et al., 2008	NO_2 and PM_{10} concentrations dropped moderately	Total 183 YLG per 100,000 for NO_2 reduction and 63 YLG for PM_{10} reduction per 10 years in CCS area	Yes, more deprived areas had higher air pollution concentration, and these areas also experienced greater air pollution reductions and mortality benefits compared to less deprived areas
		Johansson, C. et al., 2009	NO_x emission dropped by up to 12%, and PM_{10} dropped by up to 7%	Annually 20.6 YLG per 100,000 people for NO_x reduction	No. Comment: the people in the city center (inside the charge cordon) will have the largest reduction in exposure
		Cesaroni, G. et al., 2011	NO_2 and PM_{10} concentrations decreased by up to 23% and 10% by the policy	921 YLG per 100,000 along busy road for NO_2 reduction, average 686 YLG per 100,000 from NO_2, and 116 YLG per 100,000 for PM_{10} within 150m of the High traffic Road with the intervention during 15 years	Yes, because wealthy people lived in city center in Rome. High socio-economic population gained most of the health benefit, thus it increased the SEP inequity
		Cyrys, J. et al., 2014	PM_{10} concentration dropped by up to 10%, and diesel particle dropped by 58%	Annually 144 avoided death per million due to diesel particle decrease	No. Comment: the people living in the zone might benefit more, or people who suffered more from traffic air pollutants benefited more

		Woodcock, J. et al., 2009	$PM_{2.5}$ concentration decreased by up to 9.7%	$PM_{2.5}$ concentration reduction avoided 33 related premature deaths and 319 DALYs per million population	No. Comment: *no sign* of effect on health equity
Greenhouse-gas emission reduction strategies	$PM_{2.5}$, O_3	Schucht, S. et al., 2015	For population weighted annual average $PM_{2.5}$ concentration, with mere air quality policies, 75% decrease from 2005 to 2050, with extra 68% reduction if combining climate policies; For SOMO35 (ozone concentrations accumulated dose over a threshold of 35 ppb), 1% increase without climate policies, and 86% decrease with climate policies	Adjusted by the EU population change, for chronic $PM_{2.5}$ mortality, air quality control policies would reduce YLL attributable to $PM_{2.5}$ from 4.6 million to 1 million from 2005 to 2050, with further 300,000 reduction if combining with climate policy. For ozone, premature deaths from acute exposure to ozone would increase from 31,000 to 48,000 from 2005 to 2050, while they would decrease to 7000 with climate mitigation policies at a global level. The monetized health damage would reduce from3% of the EU GDP in 2005 to 0.4% in 2050 merely with air quality control policies, and to 0.1% if combining with climate policies.	No. Comment: the climate strategies in general decrease the air pollutants ($PM_{2.5}$ and ozone). *No sign* of effect on health equity

* Several studies modelled the health outcomes under different scenarios, but here we only include the one with the largest health benefit.

Summary of the strategy types

As shown in Table 4-2, articles can be categorized into three different study types, I (Chanel et al., 2014; Mindell and Joffe, 2004; Schucht et al., 2015), II (Aunan et al., 1998; Clancy et al., 2002; Burr, 2004; Hutchinson and Pearson, 2004; Tonne et al., 2008; Johansson et al., 2009; Woodcock et al., 2009; Cesaroni et al., 2011; Cyrys et al., 2014) and III (Ballester et al., 2008; Perez et al., 2009; Boldo et al., 2011), respectively. We also classified strategies and interventions into four categories (Table 4-3), namely focusing on general regulations on air quality control, energy efficiency or saving, transport related emission reductions, and greenhouse gas emission reductions. The review showed that, for the real time monitored air pollution studies, the air pollution concentrations or emissions decreased as the consequence of implementing the respective strategies. For the scenario simulation studies, health impact assessment was conducted on the premise that the air pollutants decrease to some extent after implementation of pollution control strategies. Although we have generalized the strategies into four categories, several of these strategies were crosscutting and could fall into several of these categories, for example, the intervention aiming to reduce greenhouse gas emission by introducing lower-carbon emission motor vehicles was also a traffic emission control related intervention (Woodcock et al., 2009).

General regulations on air quality control: For the articles concerning general regulations on air pollution control, the air pollution outcomes were targeted through regulations or guidelines (study type I). These general regulations included the UK National Air Quality Strategy, EU air quality Directives, WHO air quality guidelines, U.S. Environmental Protection Agency guidelines and Spain pollution control policies. All of the studies included focused on particulate matter, which indicates that particulate matter, particularly $PM_{2.5}$, was one of the major concerns for public health associated with air pollution in Europe in recent years. This was reflected in the EU Directive 2008/50/EC on Ambient Air Quality and Clean Air for Europe which first set short and long term targets for $PM_{2.5}$ (EC, 2008). Most of the actions aiming at decreasing air pollution were implemented to meet the targets set up by EU, while climate change mitigation interventions were based on the scenarios of IPCC's Fifth Assessment Report (AR5) to limit global temperature increase to 2 °C by the end of this century (Schucht et al., 2015). However, greenhouse gas emission reductions can be achieved simultaneously with air pollutants emission reductions, since both are often emitted from the same sources, such as from the transport and energy sectors (Aunan et al., 1998; Woodcock et al., 2009).

Energy related strategies: With regard to the energy related strategies, we analysed three studies aiming to reduce air pollution emissions (Chanel et al., 2014; Aunan et al., 1998; Clancy et al., 2002), and one study in which the air pollution decrease was the co-benefit of a climate change mitigation intervention (Woodcock et al., 2009). The strategies were the Energy Saving Program of Hungary's National Energy Efficiency Improvement and Energy Conservation Programs (Aunan et al., 1998), the ban of coal sales in Dublin, Ireland (Clancy et al., 2002), and the European Commission Directives to reduce the sulphur content in liquid fuels for vehicles (Chanel et al., 2014). These strategies mainly focused on the reduction of SO_2 concentrations in ambient air, followed by NO_x, black smoke, and total suspended particles (TSP). The ban of coal sales obtained the most substantial SO_2 reduction by 33.8% during the study period. While for the co-benefit strategies, carbon emission reduction was the main objective and outdoor particulate matter concentrations decrease accordingly as a by-product through the introduction of low carbon emission measures for motor vehicles.

Traffic emission control related interventions: Six articles focused on traffic related emission control. Among these, two focused on Low Emission Zones (Cesaroni et al., 2011; Cyrys et al., 2014); two were about congestion charging schemes for vehicles entering into specific areas (Mindell and Joffe, 2004; Perez et al., 2009); one was about installing vehicle exhaust catalysts (Hutchinson and Pearson, 2004); and one was an experimental study on constructing a by-pass road (Burr, 2004). As a co-benefit from controlling traffic congestion intervention, introducing access restrictions to specific areas resulted in air pollutant reductions and health benefits (Tonne et al., 2008; Johansson et al., 2009). The air pollutants targeted were mainly NO_x and particulate matter for traffic emission control interventions. Congestion Charging and Low Emission Zones were two typical methods in Europe aimed at either reducing traffic congestion or controlling traffic emissions from the most polluting vehicles in European cities, and both of them can reduce traffic related pollution emissions within the zones.

Congestion Charging was first introduced in Singapore in 1975, with the stated objective to reduce traffic congestion and traffic emissions. The Stockholm congestion tax system (similar with CCS) did decrease emissions of NO_x and particulate matter by up to 12% and 7% according to the test trail from 2003 to 2007(Johansson et al., 2009), and for the Congestion Charging Scheme in London, the average ambient NO_2 and PM_{10} concentrations declined moderately within the zone(Tonne et al., 2008).

LEZs are areas where only vehicles with pollutant emission levels lower than a defined limit are allowed to enter, or alternatively, access charges are taken from vehicles that have higher emission levels. More than 200 LEZs have already been implemented in Europe, mainly in major cities, such as Berlin, Amsterdam, London, Lisbon and Rome, aiming to reduce exhaust emission of particulate matter and NO_x, and studies indicated those LEZs in general improved air quality, particularly in the vicinity of busy roads (Ferreira et al., 2015; Panteliadis et al., 2014). Cyrys et al. (2014) reviewed the impact of LEZs on air quality and health, and found that LEZs in Berlin did contribute to the traffic emission reductions, with 10% reduction in PM_{10} and 58% in diesel particle concentrations (Cyrys et al., 2014). While for the LEZ study in Rome, using model simulation, Cesaroni et al. (2011) found reductions in NO_2 (23%) and PM_{10} (10%) concentrations after the implementation of the LEZ, but the reductions were mainly in the intervention area not the whole city(Cesaroni et al., 2011).

Vehicle Exhaust Catalysts (VECs), which are largely used in Europe, were introduced to reduce the NO_x, VOCs and CO emissions from petrol fuelled vehicles. A study from the UK indicated that VECs provided substantial pollutant concentration reductions, 20% for NO_2, 10% for PM_{10}, 30% for VOCs and 70% for CO (Hutchinson and Pearson, 2004). Aside from LEZs, VECs and Congestion Charging, in order to reduce traffic related emissions or in some cases to alleviate traffic congestion, European cities introduced some other traffic control strategies, such as Traffic Limited Zones and Traffic Restrictions (Urban access regulation in Europe). Although the traffic related interventions included in this study reported moderate to significant improvement in air quality, other studies showed less consistent results. The Ecopass zone in Milan (Traffic Restriction) led only to minor reductions of PM_{10} and $PM_{2.5}$ concentrations but to a significant reduction of black carbon in a three-day experimental study (Invernizzi et al., 2011); similarly, nonsignificant reductions in NO_2, NO_x and soot were observed in five Dutch cities after the introduction of LEZs (Boogaard et al., 2012); whereas Panteliadis et al. found clear reduction in traffic related air pollutants after the implementation of a LEZ in Amsterdam (Panteliadis et al., 2014). The inconsistence of the results could be attributable to the differences in the size of the respective study areas, the duration of the intervention/study period, as well as to differences in how strict the respective entrance requirements were and to differences in the implementation of the respective interventions.

Greenhouse-gas emission reduction strategies: Among the 15 articles included, there were two articles with strategies aimed to mitigate climate change or to reach climate change targets (Woodcock et al., 2009; Schucht et al., 2015). The climate mitigation goal could be achieved to some extent either from lower-carbon-emission motor vehicles combined with active travel promotion in this case, or from more stringent climate policies at a global level. Considering that the main air pollutants and greenhouse gases share common sources, air pollution emission reductions, mainly of particulate matter and ozone precursors, were also obtained as a result of these strategies. As for the lower-carbon-emission motor vehicles scenario, $PM_{2.5}$ concentration reduction led to substantial health co-benefits (Woodcock et al., 2009). With a more stringent climate policy at a global level, $PM_{2.5}$ concentrations in the EU would receive an extra cut, and further health benefit would be obtained from both $PM_{2.5}$ and ozone reductions.

Impact on health and health equity

All the strategies from the 15 articles included with simulated or monitored pollutant concentrations demonstrated that the strategies could bring a decrease in ambient air pollution and thus would lead to moderate or substantial health benefit. Beside the general regulations on air quality, specific actions mainly focused on traffic access control (LEZs and CCS), technological innovation to reduce emission (VECs, low-carbon-motor), and energy related emission reduction (improving energy efficiency, energy conservation, or energy switching, e.g. ban of coal sales). Climate change strategies on greenhouse gas emission reductions also reduced air pollutant concentrations and provided related health co-benefit. The results provided mixed but generally suggestive evidence of the effectiveness of air quality control strategies in improving public health, but the effectiveness of those strategies in improving health equity was inconclusive as only three of the articles assessed the SEP impact and the results were not consistent.

For the studies of general regulations on air quality control, the most obvious health benefit was gained through the reduction of particulate matter concentrations. For the studies on energy related strategies, health benefits were obtained mainly from the reduction of SO_2 and NO_x concentrations, and the health benefit covered the entire population of the region covered in the assessment. The health benefit from traffic control interventions (mainly from NO_x and particulate matter reductions) was more geographically biased, with a much higher health benefit within the immediate catchment of the interventions. For example, 18.3 YLG per 100,000 population were gained annually in the London Congestion Charge Zone compared with 1.8 YLG in non-Congestion Charge Zones according to Tonne et al. (2008). Furthermore, studies analysing the effects of CCS or LEZs identified a higher reduction of NO_x concentrations and subsequent health benefits as compared to particulate matter (annually 18.3 YLG per 100,000 for NO_2 reduction compared with 6.3 YLG for PM_{10} reduction in the London CCS study; and 45.7 YLG for NO_2 reduction compared with 7.7 YLG for $PM_{2.5}$ reduction in the Rome LEZs study). The two CCS studies in London and Stockholm showed similar health benefit with 18.3 and 20.6 YLG per 100,000 population gained annually for NO_2 and NOx concentration reductions respectively. While for LEZs in Rome, the pollutant reductions and health benefits were significantly higher, with 45.7 YLG per 100,000 gained annually for NO_2 reduction and 7.7 YLG for $PM_{2.5}$ reduction.

Among the articles included, only three articles analysed the impact of the strategies on health equity from socioeconomic position (SEP) perspective. Two articles discussing SEP equity were about traffic control interventions, which were the Congestion Charging Scheme in London and the Limited Traffic Zone in Rome (Tonne et al., 2008; Cesaroni et al., 2011), and one was about the impact on health equity through meeting UK National Air Quality Strategy targets in Westminster(Mindell and Joffe, 2004). However, the health equity impacts of these three studies were inconsistent. For the study in London, the research found modest reduction in socioeconomic inequities associated with exposure to traffic related pollution after the introduction of the Congestion Charging Scheme in 2003 (Tonne et al., 2008). Similarly, as discussed by Mindell and Joffe's discussed, reducing air pollution could decrease inequities because exposure was likely to be reduced most in socioeconomically deprived areas and because those who benefit most were those with pre-existing health conditions, the very young and older people(Mindell and Joffe, 2004). On the other hand, the study in Rome by Cesaroni et al. (2011) indicated that most of the health gains were found in well-off residents after the introduction of the Limited Traffic Zone action, hence potentially exacerbating social inequities caused by traffic related air pollutants (Cesaroni et al., 2011)

Apart from the three studies with SEP assessment, we analysed the effectiveness of the strategies to reduce health inequity using the evidences provided by the reviewed studies. This evidence included differences in the health benefit among socioeconomic groups, age groups, gender groups, pre-existing health condition groups, or geographical groups. In total, among the 12 studies without health equity assessment (Table 4-3), nine studies mentioned that there were varied health gains either because of the geographical variability (Chanel et al., 2014; Burr, 2004; Hutchinson and Pearson, 2004; Ballester et al., 2008; Johansson et al., 2009; Boldo et al., 2011), which can be attributable to SEP, or because of the different susceptibility among subgroups (Aunan et al., 1998; Clancy et al., 2002), or both (Cyrys et al., 2014). Subgroups of more susceptible individuals, such as the elderly, children, pregnant women or groups with pre-existing health conditions, were often affected disproportionally. Because the relative risk and the baseline mortality rate were higher for susceptible groups than for the general population, for the same amount of pollutant exposure reduction, susceptible groups were likely to benefit more, and subsequently, this could improve health equity.

Discussions

This review illustrated that health benefit from air pollution reductions can be gained through all kinds of strategies, actions or plans examined, either as the main goal or as a co-benefit. Because the health benefit was evaluated using different health indicators, the associated pollutants were not always the same, and the exposure–effect terms were often inconsistent (referring to short and/or long term exposure), it was impossible to have a synthesized quantitative evaluation.

Most studies (14) used mortality as the health indicator in the form of avoidable deaths, premature deaths, reduced excess deaths, DALY, YLG, and YLL. Five studies used morbidity in terms of hospitalization or symptoms. Of the 15 studies, four studies monetized health benefits through the willingness to pay (WTP) method using the estimate VOLY obtained from previous studies (Chanel et al., 2014; Aunan et al.,1998; Hutchinson and Pearson, 2004; Perez et al.,2009; Schucht et al., 2015). The methods used (12 out of 15 studies) for health impact assessment involved concentration-response functions (CRF) or exposure-response functions/coefficients (ERF/ERC) obtained either from a series of epidemiologic studies or meta-analysis(Pope et al., 2002; Beelen and Hoek, 2008; Nafstad et al., 2004; Laden et al., 2006; Finkelstein et al., 2003; Health Effects Institute, 2000). Besides that, one study used a questionnaire survey to obtain the frequency of symptoms associated with air pollutants to assess the health impact of the strategy (Burr, 2004), one study used standardised death rate (Clancy et al., 2002), and one study directly calculated the health gain using the attributable estimate from the WHO health report (Cyrys et al., 2014). Though different among specific groups, all of the examined studies using CRF were based on the assumption that the air pollutant concentrations and health outcomes were linearly related, which might not always be the case (Bae et al., 2015; Yu et al., 2016). Furthermore, for the assessment of the health effects associated with reductions in ozone concentrations, Hutchinson et al. (2004) did not use a threshold (0 ppb), while Schucht et al. (2015) used SOMO35 (ozone concentrations accumulated dose over a threshold of 35 ppb) as a threshold (Hutchinson and Pearson, 2004; Schucht et al., 2015), indicating some uncertainty in the concentration-response relationship between exposure to ozone and health outcomes. Although most of the health impact assessments considered the local baseline rate of mortality or morbidity (10 articles), or the population change over time (two articles), only two articles controlled for time trends, influenza and temperature effects (Chanel et al., 2014; Clancy et al., 2002). The only two articles accounting for the geographical variations of population, mortality, and socioeconomic factors included a SEP inequity assessment (Tonne et al., 2008; Johansson et al., 2009). There were other uncertainties regarding the methodologies used for health impact assessment summarized in this review. Firstly, the air pollution mixture of co-pollutants may differ between the included study areas and the study areas where CRFs/ERFs were obtained; secondly, population-specific time-activity characteristics might differ regionally; and thirdly, the CRFs/ERFs could be different for different social strata, age groups, genders or people with pre-existing health conditions.

The focus of the selected studies was on particulate matter, nitrogen oxides, and sulphur dioxide for some regions in Europe. Particulate matter was the major outdoor air pollutant examined in the general regulation studies, while most strategies in the energy or transport sector result in proportionally larger reductions in NO_x and SO_x concentrations (Table 4-3). For example, 2212 premature deaths were estimated to be postponed annually in 20 EU cities because of the SO_2 reduction through the EU Directives to reduce the sulphur content in liquid fuels for vehicles (EC Directive 93/12/EEC, EC Directive 98/70/EC, and Council Directive 99/32/EC) (Chanel et al., 2014), and 18.3 YLG per 100,000 population were gained annually due to NO_2 concentration reduction attributed to the Congestion Charge Scheme in London compared to 6.3 YLG per 100,000 for PM_{10} concentration reduction obtained from the same scheme (Johansson et al., 2009). A large number of the studies only assessed the health impact of one, or few pollutants because of the lack of published concentration-response coefficients (Chanel et al., 2014; Hutchinson and Pearson, 2004). As for the interventions normally decrease not merely one pollutant, and because of the interactions between the pollutants, a comprehensive assessment of health benefit of multiple pollutant reductions taking into account co-benefits, would be more appropriate for effectively assessing the health impact of the strategies caution (Holman et al., 2015). Apart from this, other unintended consequences associated with the interventions could also influence health (Woodcock et al., 2009). For example, active travel (e.g., more walking and cycling) could decrease traffic emissions and improve physical activity levels, but potentially increase injury risks, or could increase the exposure time to traffic related air pollutants depending on travel routes (Woodcock et al., 2009; Rojas-Rueda et al., 2013). As most of the included studies were based on model simulations rather than observations to explore the emission reduction or concentration reduction, results on to what extent the strategies contribute to the pollution reduction and health improvements should be interpreted with caution (Holman et al., 2015).

Only three studies assessed the impact on SEP health equity, with inconsistent result, indicating a lack of studies on health equity assessment of air quality control strategies. Although we provided comments on the potential impact of the examined strategies on health equity, we cannot draw firm conclusions on which one can decrease or increase health equity, considering specific risks among the varied social gradient. Regarding different population groups, with the same amount of decrease in air pollution concentrations, vulnerable groups were expected to benefit more (Aunan et al., 1998; Clancy et al., 2002; Boldo et al., 2011). It should also be noted that specific actions (study type II) focusing on typically high-polluted urban areas showed potential to bring about larger health benefits within the geographic catchment area affected by the actions (Burr, 2004; Hutchinson and Pearson, 2004; Johansson et al., 2009; Cyrys et al., 2014). In summary, air quality control strategies can address air pollution related health inequity by targeting two major pathways: the uneven distribution of concentration of pollutants at various geospatial levels, and the different susceptibilities among population groups. Embedding these two factors into air quality control strategies is advisable for improving the assessment of health equity.

Conclusions

We conducted a systematic review to identify the effectiveness of the recent strategies relating to air pollution control on public health and health equity in Europe. Fifteen studies were included and four major conclusions can be drawn. Firstly, four groups of strategy type were identified, including general regulations on air quality control, road traffic related emission control interventions, energy generation related emission control interventions and greenhouse gas emission control interventions for climate change mitigation. Secondly, all of these strategies brought improvements in air quality and subsequently in public health either as a direct, intended outcome or as a co-benefit. Only three articles assessed the impact of the strategies on the health equity and the results were inconsistent. Thirdly, the reduction of the air pollutant concentrations and the reported subsequent health benefits were more significant within the geographic catchment of the related interventions. Fourthly, particulate matter (particularly fine particulate matter) and NO_2 were the main public health concerns related to ambient air pollution in the studies reviewed.

This review not only highlighted the effectiveness and the need for environmental strategies to improve air quality and health, but also explored the connections between socioeconomic status, vulnerability and air pollution exposure. The health co-benefits obtained from the four groups of air pollution control strategies indicated that there was a strong case for promoting Health in All Policies (HiAP)

(Table 4-2), which WHO is facilitating (Leppo et a., 2013), enabling thus possible health improvement from all perspectives. A previous study reviewed air quality control interventions on equity at urban level (Benmarhnia et al., 2014). To our knowledge, this is the first systematic review of the impact of air quality control strategies on health and health equity in Europe.

This study can contribute to advancing the knowledge related to policies aiming to reduce health risks and health inequity associated with air pollution in Europe. Few limitations still remain. Firstly, language restriction has excluded several national publications from EU member countries; secondly, the search datasets were limited to PubMed, Web of Sciences and TRoPHI; and thirdly, grey literature was excluded.

CHAPTER 5

Taking action on air pollution control in Beijing-Tianjin-Hebei (BTH) region: progress, challenges and opportunities

Li Wang, Fengying Zhang, Eva Pilot, Jie Yu, Chengjing Nie, Jennifer Holdway, Wuyi Wang, Sotiris Vardoulakis, Thomas Krafft (2017). Taking action on air pollution control in Beijing-Tianjin-Hebei (BTH) region: progress, challenges and opportunities. (Submitted)

Abstract

Due to rapid urbanization, industrialization and motorization, a large number of Chinese cities are effected by heavy air pollution. In order to explore progress, remaining challenges, and sustainability of air pollution control in the Beijing-Tianjin-Hebei (BTH) region after 2013, a mixed method analysis was undertaken. The quantitative analysis comprised an overview of air quality management in the BTH region. Semi-structured expert interviews were conducted with 12 stakeholders from various levels of government and research institutions who played substantial roles either in decision-making or in research and advising on air pollution control in the BTH region. The results indicated that the air quality has improved slightly with the recent air quality control strategies. However, improvements vary across the region and for different pollutants. Although implementation has been decisive and was at least in parts effectively enforced, significant challenges remained with regard to industrial and traffic emission control. Air quality limits continued to be significantly exceeded and competing development interests remained mainly unsolved. There were also concerns about the sustainability of the current air pollution control measures especially for industries due to the top-down enforcement, and the associated large burden of social cost including unemployment and social inequity resulting from forced closing down of industries. Better mechanisms for ensuring cross-sectoral coordination and for improved central-local government communication were suggested. Further suggestions were provided to improve the conceptual design and effective implementation of respective air pollution control strategies in BTH. Our study highlights some of the major hurdles that need to be addressed to succeed with a comprehensive air pollution control management for the Chinese mega-urban agglomerations.

Introduction

Air pollution in China is a major concern and it is causing a large public health burden and serious economic losses. According to a recent report, exposure to ambient air pollution has contributed to a death toll exceeding 1.6 million in mainland China, with a total economic loss equivalent to 10.9% of GDP in 2013 (World Bank and Institute for Health Metrics and Evaluation, 2016). Since 2013, fine particulate matter ($PM_{2.5}$, particulate matter with a mean aerodynamic diameter of 2.5 μm or less) exposure has become the fifth leading cause of death in China, and some 900,000 premature deaths a year are attributable to $PM_{2.5}$ exposure (World Bank and Institute for Health Metrics and Evaluation, 2016; GBD MAPS Working Group, 2016), with the highest attributable mortality in Beijing (Liu et al., 2017). Geographically wide spread and long-lasting (totally around 3 weeks with hazardous pollution level in December 2012 and January 2013) extreme air pollution incidents, covering up to one quarter of China's land area and affecting up to 600 million people between 2012 and 2013 drew mounting attention not only internationally but also from the Chinese public (MEP, 2013). As a consequence, the Chinese government launched a series of ambitious laws and policies to prevent the further deterioration of air quality, and intended to initialise an "improvement phase" in air pollution control in China (Feng and Liao, 2015). Together with the commitment to address climate change (The Paris Agreement 2016[1]) (Tambo et al., 2016), and the commitment to reduce air pollution made by the Chinese premier during his opening address to the 2017 National People's Congress in Beijing, the enforcement of air pollution prevention and control measures appear to be now in full swing at the national level.

The Air Pollution Prevention and Control Action Plan (thereafter the Action Plan), the most stringent air pollution plan to date in China, is regarded as a promising strategy to control deterioration and improve air quality. The plan embedded targets on air quality improvement and emission control into government performance and promotion assessment system, which greatly enhances local

[1] The Paris Agreement's central aim is to strengthen the global response to the threat of climate change by keeping a global temperature rise this century well below 2 degrees Celsius above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5 degrees Celsius. Additionally, the agreement aims to strengthen the ability of countries to deal with the impacts of climate change. In 2016, Chinese government ratified the Agreement to curb climate-warming emissions. More details via http://unfccc.int/paris_agreement/items/9485.php.

officials' incentives to pay attention to the implementation of the air pollution control measures (Lin and Elder, 2014; CCICED, 2012; Chen et al., 2013). The Action Plan set nation-wide sub-goals for the current five years' period (2012-2017) with a priority on the three Megalopolises, the Yangtze River Delta (YRD), the Pearl River Delta (PRD) and the Beijing-Tianjin-Hebei region (BTH). Among these, BTH was the most stringently targeted region.

Air pollution control in Beijing traces back to 1998, when it was initiated by the "Blue Sky Project", that however, only focused on point source emissions and pollution control. Since 2004 the preparation for the Olympic Games provided an opportunity to introduce integrated regional prevention and control of air pollution, mainly covering Tianjin, Hebei province, Shanxi province, Shandong province and Inner Mongolia. During the Olympic Games in 2008, the integrated regional prevention and control strategy decreased air pollution to the lowest level one month before and during the games (Zhang et al., 2016). However, just a few years later in 2011, the USA Embassy in Beijing revealed data indicating that the $PM_{2.5}$ concentration in Beijing was "beyond index" of the US EPA's air quality index (United States Environmental Protection Agency) (USA Embassy, 2011), which raised international and national public concern about severe air pollution in China, public awareness of air pollution and the need for effective pollution control strategies.

Since then, long-term integrated regional prevention and control of air pollution has been placed prominently on the political agenda. With strengthened control, air quality in the other two Megalopolises (YRD and PRD) has improved gradually, but air pollution in BTH is still causing major public health concerns, affecting over 100 million people (Jiang et al., 2015). According to the first seasonal report on the air quality of the 74 major cities in China in 2016, seven out of the top ten cities with the worst air quality were in the BTH region (CNEMC, 2016). Exploring the progress and the challenges of the Action Plan in BTH is therefore crucial to allow further progress, and – even more - importantly, helping to formulate a more strategic plan in the next stage and to meet MEP's (Ministry of Environmental Protection of the People's Republic of China) target on controlling annual $PM_{2.5}$ concentration below National Ambient Air Quality Standards Level II of 35 $\mu g/m^3$ in all cities by 2030 (MEP, 2013). According to recent research, this target will barely be met with the current policies, particularly in the BTH region (Wang et al., 2015; Liu et al., 2013; Ma et al., 2013).

Industrial emission was the most important source for air pollution (PM, SO_2 and NOx) in BTH. Source apportionment study indicated that industrial emission accounted for 92.1% of the total sulphur dioxide (SO_2), 68.4% of the total nitrogen oxides (NOx), and 82.6% of the total dust (including $PM_{2.5}$, PM_{10} and coarse particle) emitted in BTH (China Statistic, 2014). The steel, cement and flat glass production were the pillar industries in Hebei province, accounting for one quarter, one twentieth and one sixth of the total production in China, respectively. According to MEP report in 2012, Hebei ranked the first in NOx and dust emission, and the third in SO_2 emission nationally (following Shandong province and Inner Mongolia). SO_2 emissions from Hebei province contributed 80.5% of total SO2 emissions in BTH, indicating that the key to air pollution control in BTH is to control industrial emissions in Hebei province (MEP, 2012; Hebei Economic Yearbook, 2015). Traffic emissions were the second most important emission source in BTH, accounting for 45%, 28.8% and 13.9% of the total NOx emissions in Beijing, Tianjin and Hebei province, respectively (China Statistic, 2014). Particularly for Beijing, road traffic contributed to over 29% of total $PM_{2.5}$ (Zíková et al., 2016).

In this study, we focused on the air pollution control measures from two major emission sources in BTH, industry and traffic. The objectives of this study were (1) to explore the progress of the Air Pollution Prevention and Control Plan using quantitative methods; (2) and to identify the opportunities, challenges and sustainability of the air pollution control measures using qualitative methods. Our study aims to provide a better understanding of the obstacles, problems and risks of the air quality control plan in the BTH region, and to make suggestions on what can be further improved in the near future to make air pollution control strategies more effective and sustainable in China.

Materials and Methods

A combination of qualitative and quantitative methods was used to assess the progress, challenges and opportunities of the air quality Action Plan in the BTH region. First a quantitative analysis of air quality, indicated by concentrations of the key pollutants and the Air Quality Index (AQI), was used to evaluate the progress in improving air quality. Then interviews with experts were used to explore the progress, the opportunities and the barriers during the implementation, and to provide suggestions for further progress.

Quantitative data

Air quality data was obtained from the China National Environmental Monitoring Centre. The Individual Air Quality Index (IAQI) and Air Quality Index were used to identify the pollution level. The calculation methods for IAQI and AQI, and the classification of AQI were defined by the Technical Regulation on Ambient Air Quality Index (HJ 633-2012) and Ambient Air Quality Standards (GB3095-2012), see Appendix A.

Qualitative data collection

Expert interviews were conducted to explore how the control measures of the Action Plan had been implemented and to identify critical challenges that occurred during the implementation within the BTH region with a special focus on industrial restructuring and traffic emission control. As the industrial relocation mainly from Beijing and Tianjin to Hebei province plays a significant role for the industrial restructuring in BTH region, and in particular for the relationship between the regions, we also covered relocation in the interviews. We intended to interview those who played a substantial role in the key government administrations on air pollution control in term of drafting, implementing or supervising the air pollution control measures, and those experts from key institutions who conducted substantial research related to air pollution control and/or provided scientific advice to the governments within the BTH region. After purposive sampling and snowballing, a total of 13 participants were identified of whom 12 responded positively. Eight participants were interviewed face to face, and four provided written statements (Interview guidelines see Appendix B). The semi-structured in-depth interviews were conducted from the 18th July to the 30th August, 2016. The face to face interview lasted between 45 min to 80 min.

Of the participants interviewed face to face, five were from academic institutions, two were from government environmental protection agencies, and one was from a nongovernmental organization (NGO). The four experts answering via written statements were all from academic institutions. Of the five academic interviewees, two were from the environmental policy field, two were from the field of atmospheric environment research and monitoring, and one was from environmental health. Ten participants are from Beijing (BJ), and the other two were from Hebei province (HB). As the interview questions were broad, not every interviewee answered all the questions. The interviewees were numbered in the order in which they were interviewed or written statements were received [ID-01…12]. After the transcription of the interviews, the interviews were translated from Chinese to English. The interview results and written statement were analysed by thematic analysis in two stages (Boyatzis, 1998; Braun and Clarke, 2006). In the first stage we identified four major themes: (1) the interviewees' interpretation on the air pollution control process, (2) industrial emission control, (3) traffic emission control and (4) air pollution control collaboration. In the second stage, related content was coded to select quotations for each of the 4 themes.

How the Air Pollution Prevention and Control Action Plan is assessed?

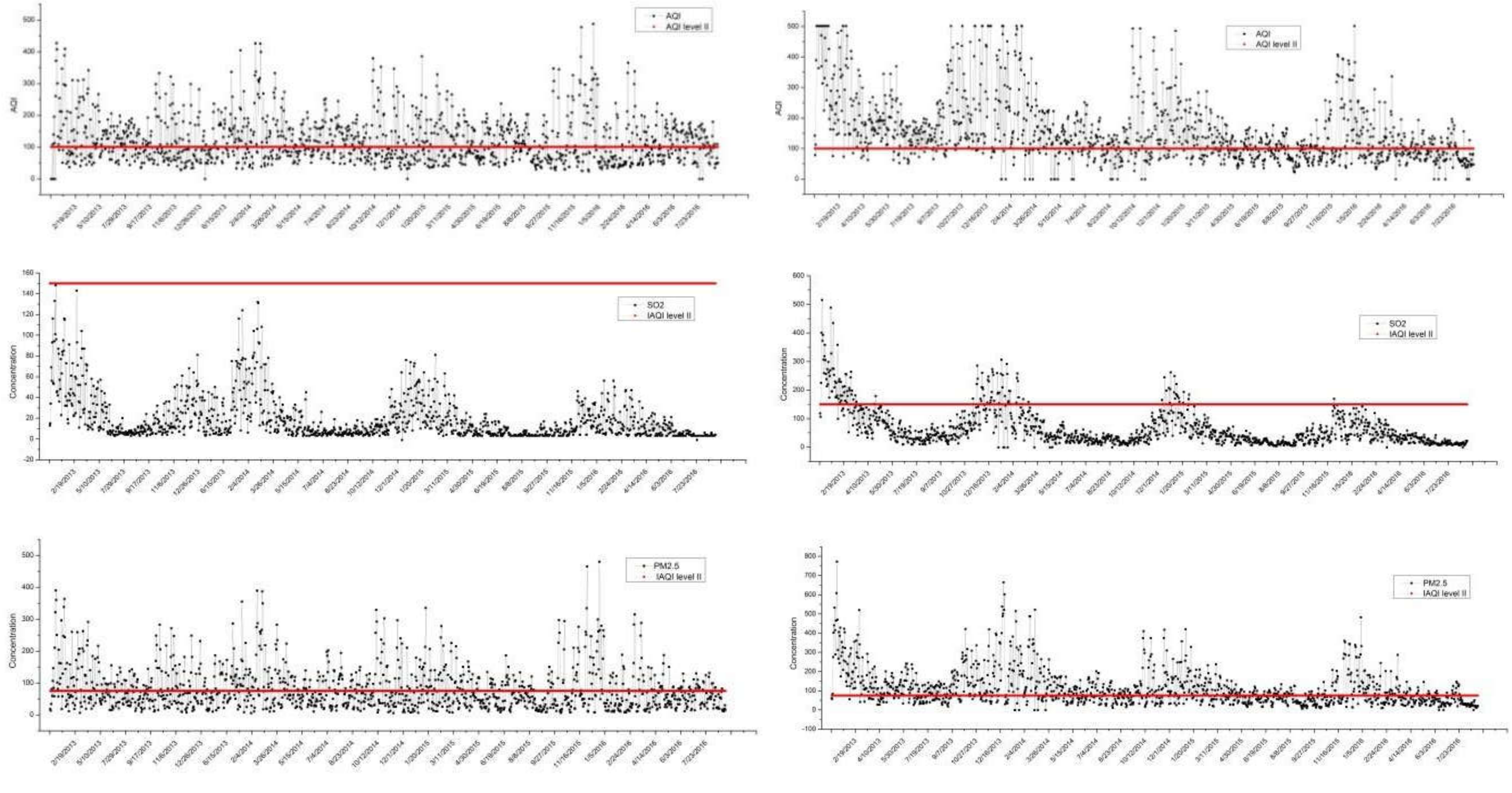
There are two assessment aspects for the evaluation of the Action Plan. The first one is the actual improvement of the air quality, quantified as the reduction in particulate matter (PM) concentrations. The second one is the accomplishment of key tasks for air pollution prevention and control, and these tasks include industrial restructuring, clean energy generation, coal and oil quality management, small coal-fired boiler control, industrial emissions (dust and VOCs), municipal dust control, vehicle pollution control, air pollution control investment, building energy-saving and heat metering management, and atmospheric environment management. The two aspects were evaluated separately for BTH, PRD and YRD, and the lower score of these two aspects was the final score. The time frame for the Action Plan is from 2012 to 2017. More detailed information on performance assessment measures of the Action Plan can be found http://www.cleanairchina.org/product/6349.html.

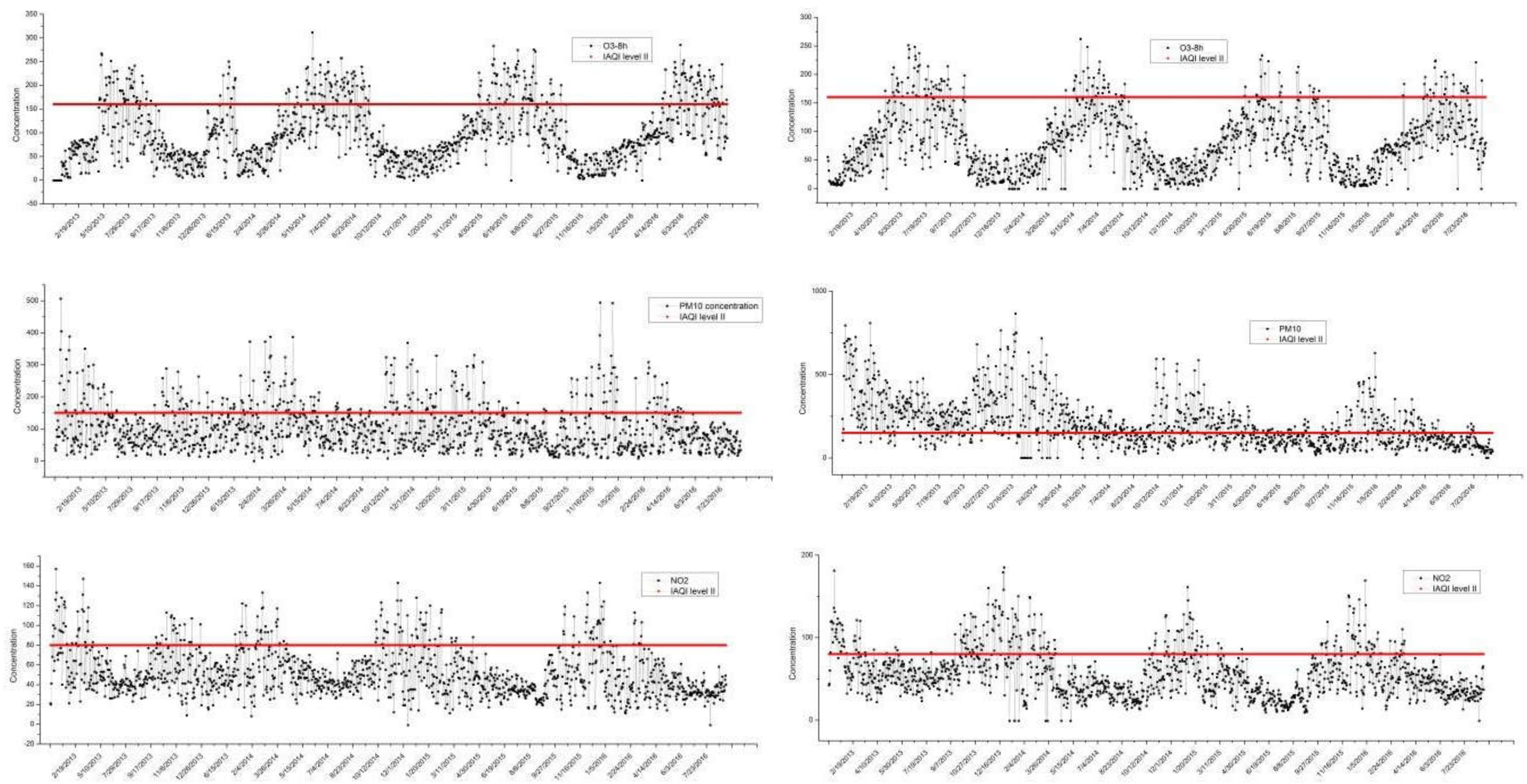
Results

At the end of 2012 and the beginning of 2013, heavy smog covering the BTH region rose public concern about air pollution. Immediately after the incident, the government launched a series of air quality control strategies including guidelines, laws and other measures. These are listed in Appendix C. Among these strategies, the Air Pollution Prevention and Control Action Plan, which included specific measures and assessment methods, acted as the guideline for air pollution control measures. The air pollution reduction targets at provincial or municipal level can be found in Appendix D.

Quantitative result-air quality in BTH in the past 3 years

Figure 5-1 shows the Air Quality Index (AQI) and other five major air pollutants in Beijing and Shijiazhuang (the capital city of Hebei province) from the January 2013 to August 2016 and the limit value II (red line, based on the Ambient Air Quality Standards GB3095-2012) for daily average concentrations of SO_2, $PM_{2.5}$, NO_2, and PM_{10}, and 8h-daily maximum concentration for O_3 (8h-O_3). Table 5-1 shows the changes in dominant pollutants (definition see in Appendix A) and their concentrations in the three cities of Beijing, Tianjin and Shijiazhuang.


AQI
AQI level II
SO2
IAQI level II
PM2.5
Concentration



*, according to the Ambient air quality standards (GB3095-2012) and Technical Regulation on Ambient Air Quality Index (HJ 633-2012), below the limit value II, the air quality is good (II) or very good (I); above the limit value II, the air quality is slightly polluted (III), moderately polluted (IV), heavy polluted (V), and sever polluted (VI).

Figure 5-1. Trends of the daily AQI, SO_2, $PM_{2.5}$, NO_2, PM_{10} and 8h-O_3 concentrations in Beijing (left) and Shijiazhuang(right)

Figure 5-1 shows clear seasonal change for all the pollutants. The concentrations of PM, NOx, and SO_2 are higher in winter and lower in summer, while O_3 seems to anti-correlate with primary pollutants such as PM and NO_2, with higher concentration in summer and lower in winter. The progress on pollution control has occurred in both Beijing and Shijiazhuang but it has been uneven. A clear decline can be found for SO_2, NO_2, PM_{10} and $PM_{2.5}$ in Shijiazhuang city, and for SO_2 in Beijing. The AQI in Beijing showed a slight improvement in the past three years, with the number of mildly polluted days (defined as AQI level higher than level II, Appendix A) decreasing from 192 days in 2013 to 179 days in 2015; while for Shijiazhuang, the number of mildly polluted days decreased remarkably from 318 days in 2013 to 185 days in 2015 (Figure 5-1). These observed reductions are due to a number of factors, including reductions in emissions and inter-annual variability in meteorological conditions.

Table 5-1. The number of days as the dominant pollutants and the annual mean concentrations for Beijing, Tianjin and Shijiazhuang from 2013 to 2015*

	Dominant pollutant**	2013/d	2014/d	2015/d	2013/μg/m³	2014/μg/m³	2015/μg/m³
BJ#		212	178	161	89.4	86.0	80.7
TJ#	$PM_{2.5}$	261	213	175	95.7	83.3	70.3
SJZ#		105	208	198	157.3	122.2	88.8
BJ		64	74	94	86.9	98.5	96.9
TJ	8h-O_3	20	51	46	78.6	81.5	76.9
SJZ		16	24	32	82.3	75.4	76.0
BJ		14	32	22	108.3	115.5	101.5
TJ	PM_{10}	66	67	77	150.0	133.1	115.8
SJZ		237	101	72	310.3	196.2	146.7
BJ		30	40	36	56.1	56.6	50.0
TJ	NO_2	2	18	22	53.6	54.4	42.1
SJZ		2	3	32	68.9	51.2	50.6
BJ		0	0	0	26.5	21.8	13.5
TJ	SO_2	10	8	0	58.9	48.9	29.2
SJZ		5	0	0	106.29	60.9	47.2

* for $PM_{2.5}$ and PM_{10}, annual concentration is the average concentration of the daily average concentration; for 8h-O_3, the annual concentration is the average concentration of the daily maximum 8h concentration. ** when the AQI is over 50, the pollutant with the highest IAQI among the six pollutants is the dominant pollutant. #BJ, Beijing; TJ, Tianjin; SJZ, Shijiazhuang.

Table 5-1 indicates that there has been improvement in air quality across all three cities mainly for $PM_{2.5}$ and PM_{10} over the period examined. By July 2016, Tianjin and SJZ had already reached the annual $PM_{2.5}$ concentration reduction target of

25%; but Beijing was still under high pressure to reach the target of bringing the annual $PM_{2.5}$ concentration below 60μg/m^3. However, large variation could be observed across pollutants and cities. SO_2 showed a significant decrease in both cities. For Beijing, SO_2 concentration has met the limit value II since 2013, and for Shijiazhuang, SO_2 concentration has also met the limit value II in the past years except for one day. The annual mean $PM_{2.5}$ concentration has decreased slightly in Beijing but more significantly (almost 50%) in Shijiazhuang and Tianjin (around 20%). Shijiazhuang experienced the sharpest decrease in PM_{10} concentrations (more than 50%) in the past 3 years, followed by Tianjin, while there was only a minor change in Beijing with a much lower baseline. Annual NO_2 concentration also slightly decreased in the past three years in three cities. Ozone was the only pollutant showing no steady decline in the past three years, with annual average of the daily maximum 8h concentration increasing in Beijing, and fluctuating in Tianjin and Shijiazhuang. As a secondary pollutant, the concentration of ozone was strongly but not always positively correlated with the concentration of ozone precursor gases, particularly NOx and VOCs (Liu et al., 2016; Li et al., 2016; Ji et al., 2016).

Although concentration has decreased in Beijing and Tianjin, $PM_{2.5}$ was still the dominant pollutant in both cities, with 161 days as the dominant pollutant in Beijing and 175 days in Tianjin. For Shijiazhuang, the dominant pollutant changed from PM_{10} (with 237 days as the dominant pollutant) in 2013 to $PM_{2.5}$ (with 198 days as the dominant pollutant) in 2015. This trend reflected a change in the emission sources, which was strongly related to industrial restructuring in Hebei. The number of days as dominant pollutant for NO_2 was increasing in Tianjin and Shijiazhuang although the concentration was slightly decreasing. PM_{10} pollution was still high in both Hebei and Tianjin, and it was also important to note that with the enforcement air pollution control measures in BTH, the concentration of ozone barely changed or even slightly increased.

Analysis of the interviews

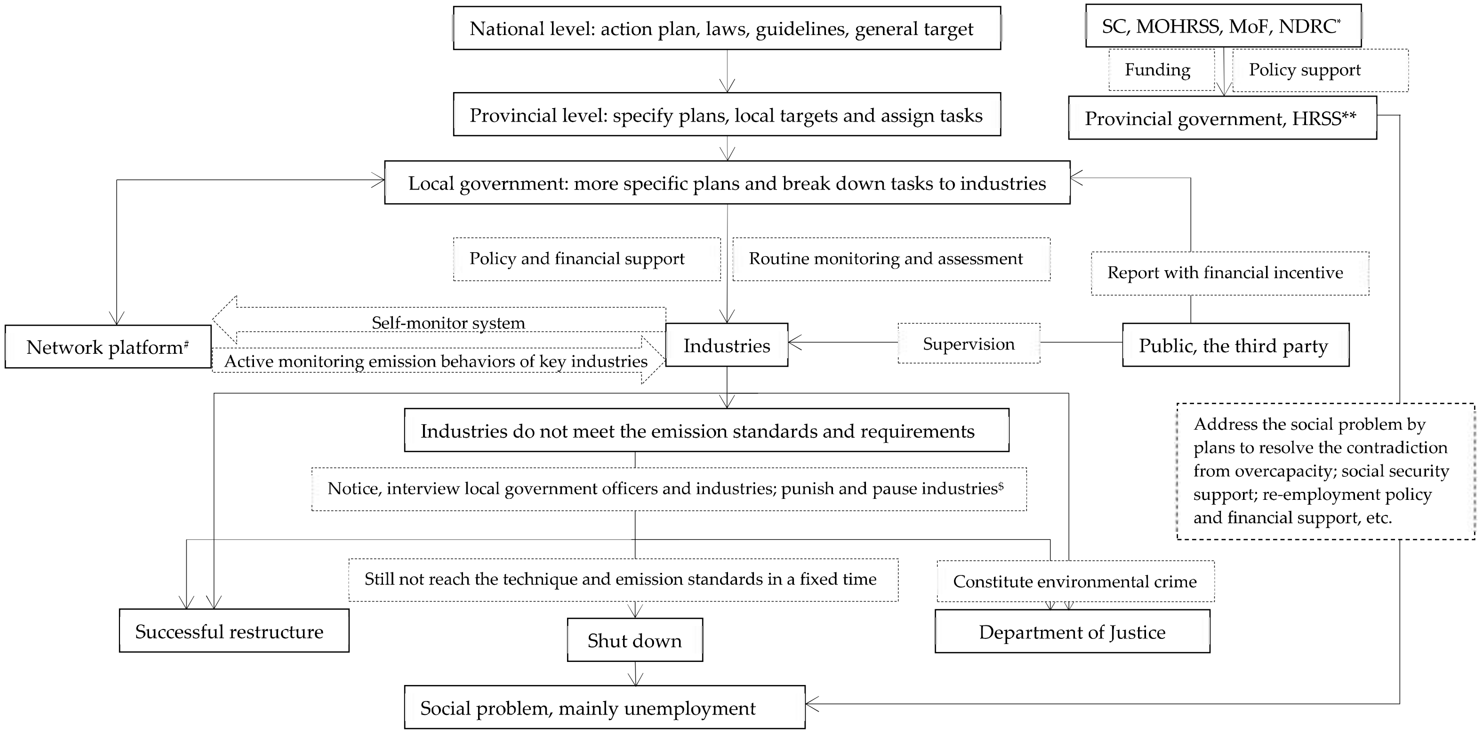
In the following we present how the policies that have targeted emissions may have shaped the outcomes above, how the emissions from different sources in the region were controlled, and what kind of challenges and consequences those policies have, based on interviewees' responses. By means of thematic analysis method, we categorized the interview results into 4 themes ”air quality control progress”(3.2.1), “industrial emission control”(3.2.2), “traffic emission control”(3.2.3), and “collaboration on air pollution control”(3.2.4).

Air quality control progress

The air pollution control strategies were introduced in response to concerns about public health and climate change. Although the air quality was still far from reaching the daily limit value II for most regulated pollutants, all the interviewees were optimistic about the air pollution control strategies in BTH, particularly after the Chinese government’s commitment to the Paris Agreement in 2016 (United Nations, 2016). All interviewees indicated that with the implementation of the more stringent air pollution control strategy in the past few years, air quality had improved. Interviewees were asked about Beijing being still under pressure and far from reaching the target annual mean level of 60μg/m^3 for $PM_{2.5}$, and also that all of the three regions that compose BTH were far from reaching the national level II standards (GB 3095-2012; annual mean 70μg/m^3 for PM_{10} and 35μg/m^3 for $PM_{2.5}$). According to the interviewees, this was due to the baseline emissions both from the transport and the industrial sectors continuing to being too high because of the rapid economic growth counterbalancing the control measures. Although vehicle emission standards had been raised to national V or VI level for both gasoline and diesel light duty vehicles in China, which is the same as Euro V or VI for light duty vehicles (EC, 2007), the total number of vehicles in the BTH region, and particularly in Beijing, had further increased to 5,650,000 vehicles by mid-2016. Similarly, in the case of heavy industry emission, Hebei had the largest steel industry in China, accounting for a quarter of all steel production nationally. Although the compliance with emission standards has been gradually improving and the government was controlling steel production capacity, heavy emissions from the industrial sectors were still the largest contributor to air pollution in Hebei and Tianjin *[ID-03,05]*. Second, cross-regional transport of pollutants contributed to the high pollution level *[ID-04]*, which can be supported by recent findings indicating that around 28-36% of $PM_{2.5}$ in Beijing was attributable to cross-regional atmospheric transport (Zhang et al., 2016). Thirdly, the specific climate and topography of Beijing and its surrounding areas were also influencing the dispersion of air pollutants, contributing to high pollution episode *[ID-02]*. Fourth, even with the stringent control measures, many industrial and vehicle emissions were still violating the emission standards.

Industrial emission control

Since the preparation for the Olympic Games, the central government has engaged in relocating heavy industries from Beijing to its surroundings, mainly to Hebei. Faced with high energy consumption, high pollution emission, and exacerbating environmental degradation, in 2013, the central government launched a national call to decrease the production capacity and to transform and upgrade the equipment and production processes in Hebei and other provinces. The concern about public health impacts of high air pollution has accelerated industry restructuring in the BTH region. Figure 5-2 indicates the industrial restructuring enforcement procedure in Hebei province.



Solid line indicates institutions or the endpoints of the actions; Dotted line indicates the action process. * SC, State council; MOHRSS, Ministry of Human Resources and Social Security; MoF, Ministry of Finance; NDRC, National Development and Reform Commission. ** HRSS, Department of Human Resources and Social Security. # The network platform is from the national/provincial/local environmental sector, and can actively real-time monitor the emission behaviour of the key polluting industries (not open to public); The industries (only large ones) have their own emission monitoring networks (selectively open to public); The National Monitoring Centre conducts spot-checks of the local industries (not exclusively the key pollution industries) and compares the emission data with the industry self-monitoring data, and then reports to the MEP (Ministry of Environmental Protection). $ Department of Pollution Prevention and Control of MEP is in charge of this action; The six Environmental Protection Supervision Centres (more details see appendix E), here the North China Environmental Protection Supervision Centre, also conduct supervision in BTH region.

Figure 5-2. The implementation process of industrial restructuring in Hebei province

The implementation of the industrial re-structuring followed a top-down approach from central government to local government. The central government launched the general legislations on the emission standards (including technical standards) and plans on emission reduction, the provincial government set up the targets on the emission control and assigned the implementation tasks to local governments, and the local governments set up more specific plans and assigned specific implementation tasks to local industries. In parallel, the local governments conducted routine monitoring and assessment of industrial emissions (including technical innovation) through three major pathways: routine emission monitoring, emission monitoring platform and public reporting involving third parties such as NGOs. The government monitoring platform was merely for internal evaluation, and for the industrial self-emission-monitoring system, the emission data can be made selectively accessible to the public depending on the consent of the respective industry. For the industries that did not meet the emission standards, the government tried to enforce the improvement of emission standards mainly by confronting local administrators and industry representatives personally and/or suspending licenses and applying heavy fines. If the industrial emissions would still not meet the standards in due time, the government forced them to close down permanently. This applied especially to fragmented low-technology and high emission industries. Social issues, mainly unemployment, emerged from closing down a significant number of industries as there was a lack of immediate alternative employment opportunities for often low skilled labour. The process to solve the social issues attributable to industrial restructuring also followed a top-down pathway, through specific plans, social security support, financial support, and prioritized employment policies (Figure 5-2).

With the analysis of the interviews, we intended to explore the expert's view on the following issues: (a) opportunities and challenges during the implementation of industrial restructuring, (b) the potential consequences including regional relationship in terms of air pollution control, and unintended social consequences that emerged from the industrial restructuring, and (c) the middle and long term sustainability in terms of industrial emissions reduction in BTH region.

Opportunities and challenges for implementation*:* The "*fast*" and "*decisive*" implementation of industrial restructuring showed the government's resolve to control air pollution, but this short-term success on air pollution control could also be partially attributed to the decline in demand for steel (or overcapacity in the global market), as one interviewee stated. On the one hand, the government could take this opportunity to upgrade the technology and raise emission standards, but on the other hand, it had to be cautious for potential future increases in emissions if the international demand for steel should recover.

Challenges that are posing difficulties to the full enforcement of the emission control measures largely lay in the management and supervision of the process. There are still companies violating pollution emissions standards, which may be partly due to the "selective action" from local government. When it came to large state-owned companies, the authority and capacity of a local government were limited and it was hard to fully implement laws and policy measures (cf. also CCICED, 2012). Furthermore, some industries evaded routine government inspections; for example, industrial units that operated just during the night or were located in more remote rural areas, were often energy-intensive and had very high emissions. Suggestions by interviewed experts for improving implementation included enhancing the enforcement of industrial restructuring and stepping up monitoring. Further it was considered to be of importance to explore the relevant barriers to industry restructuring, for example the industries' technical and financial capacity to upgrade in order to meet emission standards and to provide financial or policy incentives for industries to comply. Using economic measures such as developing an emission trading systems instead of merely command and control regulations, were also regarded to be helpful to push forward emission control.

Table 5-2. Interview quotes on industrial restructuring and related emission control

Nr.		The quote	Quote ID
		Progress in Implementation	
1	Progress	*"Close, suspend, or restructuring are the main themes to control industrial emissions"*	[ID-01,03]
2		*"Implementation enforcement is very fast and the target is very clear"*	[ID-03]
3		*"According to our investigation, the local government just either closes the high polluting industries or suspends them until they meet the emission standards within a certain time period. It is very decisive"*	[ID-01]
4		*"the international overcapacity in the steel industry in the past few years provided a very good opportunity for the industrial re-structuring in BTH region"*	[ID-05]
5	Problem	*"Monitoring and supervision issues remain as emissions are still exceeding the standards"*	[ID-01,03]
6		*"The government management pattern for industrial emissions has shifted from inaction to selective action", and "most of the closed or suspended industries are small-sized and inferior"*	[ID-01,10]
7		*"Personally, I think the 'marginal effect' of the policy is decreasing, … some local governments focus more on economic development and government performance, verbally paying attention on the industrial emission control, but ignoring it in practice. They pay attention formally, but not in practice, and it is difficult to tell how serious it is. Some industries run during the night and close during the daytime"*	[ID-04]
8	Suggestion	*"…we also should study industries' behaviour to explore the reasons for the excessive emissions; whether they (industries) do not care about environment protection or they just cannot afford to upgrade their installations"; "we also need to consider their emissions reduction capacity…"*	[ID-03,10]
9		*"More research on the pollution source, the diffusion, and the interaction mechanism needs to be done to support policy"*	[ID-03]
10		*"Improve the emission's charging system, and establish an emissions trading policy"*	[ID-12]
11		*"Enhance the monitoring, law, punishment…"*	[ID-01,02,03]
12		*"Provide incentive strategies to promote restructuring"*	[ID-03]
		Potential for regional contradiction	
13	Not necessarily	*"The relocation will inevitably lead to the emission and pollution relocation, but not necessarily lead to regional contradiction as the local government (HB) is willing to welcome industries that can generate GDP growth. The relocation is a top-down political mission from the higher government, a kind of a mandatory mission"*	[ID-02, 08]
14	Yes	*"Yes, it will cause regional contradiction"*	[ID-06]
15		*"Current action on air pollution control is more a political mission but not enforced by law. In the long run, there will be inevitable contradictions of interest between regions"*	[ID-09]
16	Suggestion	*"…the central government should provide mechanism to settle the contradiction, such as set up regular meetings among the regions…"*	[ID-09]
17		*"Embedding environmental carrying capacity, when re-locating industries (to*	[ID-07]

	Hebei)"	
18	*"Increase the environmental protection and energy consumption standards, promote recycling economy and clean production; in the meantime, Beijing should increase support to control pollution in Hebei and Tianjin, including increase financial subsidies, specific policies on market access and government procurement, etc."*	[ID-06]
	Social problems	
19	*"The restructuring (mainly closing the small industries) impacts the local job market seriously"*	[ID-11]
20	*"The control target and the economic growth sometimes is not balanced among regions, and we can see that the social cost is huge"*	[ID-02]
21	*"Many people are unemployed; while formal employee have some insurance, the situation is harsh for temporary employees (most are in the small industries), who normally are low-educated, low-skilled, and not insured"*	[ID-01,03,11]
22	*"Closing down the small and supporting the large industries, [but] who is paying the bill? How to balance the interests between different population groups? Should it be considered during the drafting, implementing and assessment of air pollution control actions? "*	[ID-11]
23	*"How to improve social security (for workers laid off due to restructuring)?"*	[ID-02,03,11]
	Sustainability	
24	*"Obliged suspending or closing of industries, for short period during an (air quality) emergency or special event, is acceptable, but not as a normal or permanent action unless there is reasonable compensation"*	[ID-03]
25	*"A reasonable compensation among the regions should be provided; monitoring of the compensation needs to be introduced to make sure the money is used in pollution control/industrial restructuring related things"*	[ID-09]
26	*"It is fairly sustainable, because the guidelines, emission standards, industrial technique have already improved to certain level; if the monitoring and supervision continues to be strict, it is unlikely to return to the pervious problems"*	[ID-05]
27	*"… particularly when the steel market is recovering, supervision and inspection will inevitably become more difficult, and the likelihood for excessive emissions will increase. To maintain the sustainability of the action plan, it is imperative to step up penalties, and normalize and popularize the reporting mechanism"*	[ID-04]
28	*"Related laws and regulations need to be fully implemented to ensure sustainability, such as enhancing the monitoring of fuel quality, building up a third party-monitoring institution, empowering environmental agencies and clarifying their rights; more emphasis has to be give on environment protection in the government performance evaluation"*	[ID-12]

Potential regional contradiction: It became obvious that regional contradiction could be caused by the relocation of industries due to the more stringent environment emission standards enforced in certain regions. As Beijing upgraded its industry, the relocation of less technologically advanced production facilities to neighbouring regions brought job opportunities and economic growth in these peripheral areas but also led to more pollution. The disparity in interviewees' views regarding the impact of industry relocation stemmed from the different emphasis they placed on economic and environmental achievements. From an economic growth perspective, high-energy consumption industries can bring more employment and tax income to the Hebei province, which was economically favourable for the whole region. But from an environmental perspective, the economic development in BTH region, particularly in Beijing, was at the expense of environmental quality in Hebei (cf. also Liu et al., 2016), and the top-down enforcement on air pollution emission control, described as "*political mission*" (*Table 5-2, quote #13, #15*), largely restricted the negotiation options between Beijing and Hebei, thus exacerbating the dissatisfaction in Hebei province. Either driven by the economic growth or/and by the political mission, those industries would bring extra pressure on air pollution emission control to the local government in the long term. Suggestions were to adopt a more effective platform for negotiation, to embed eco-environmental carrying capacity in the requirements for relocating industries and to provide "*financial subsidies, specific policies on market access and government procurement*" *(Table 5-2, quote #18).*

Social problems: Industrial restructuring has generated serious impacts on employment. It was estimated that industrial restructuring could directly lead to more than 1,000,000 job losses by 2017 in Hebei province (Bian, 2015). Although the State Council launched "Guiding Opinions on Solving the Contradictions from Serious Overproduction" in 2013 to address the social problems, and followed by the Hebei provincial "Action Plans on Solving the Contradictions from Serious Overproduction" in 2014, unemployment is still a major social problem. Recent researched showed that, in Xingtai - a city in Hebei province with 40% of local GDP from heavy polluting industries, 36.7% of the unemployment people laid off because of the industrial restructuring still could not find new job after the government resettlement plan (Su et al., 2016). Most of the unemployed were from small industries with less competitiveness in the job market because they were often "low-educated, low-skilled, and not insured". This made their resettlement or re-employment even more difficult. Apart from unemployment, social inequity was another issue that the government was facing, as one interviewee remarked, "*Closing down the small and supporting the large industries, [but] who is paying the bill?*" *(Table 5-2, quote #22)*. Several interviewees maintained that Beijing government should provide substantial financial subsidies to Hebei province and particularly specific policies on market access in Hebei province, as the economic and industrial synergy support from Beijing to its nearby provinces was very limited (CCICED, 2012).

Sustainability: Forced closing down of industries which are operating under legitimate business licenses would - from a legal point of view - require a "*reasonable compensation*" to those industries (*Table 5-2, quote #24, #25*). From a pollution emission perspective, as the technology and emission standards were updated, it was sustainable *(Table 5-2, quote #26)*. However, in the long term, if regional dissatisfaction, social costs and legality issues cannot be alleviated, the full implementation of related air pollution control strategies would be less effective.

Traffic emission control

Restrictions on vehicle registration, higher emissions standards and promoting clean energy vehicles are currently the three major approaches to decrease traffic emission in the BTH region (Table 5-3).

Table 5-3. Major traffic related emission control measures in BTH#

Measures	Region and description
Improve emission standards for vehicles	(BTH)National V emission standards (same as EU standards) for all vehicles
Improve gasoline and diesel quality	(BTH)Improve gasoline and diesel quality to meet the National V emission standards
License-plate lottery	(BJ, TJ) Limiting the number of new license plates per year, to reduce the registration of additional cars
Vehicle restriction rule	BJ, TJ and some cities in HB restrict the use of private cars for one work-day per week according to the last number of the license plate, or during rush hour; for specific events or on extremely polluted days, alternatively odd or even license plates only are allowed to enter urban areas. This is also aimed to alleviate congestion problem
Promoting clean energy and new energy vehicles	(BTH)The government (Ministry of Finance) provides financial incentives for buying clean-energy vehicles; provides tax discounts for purchasing clean-energy vehicles; builds up charging facilities for electric vehicles; exempts clean energy vehicles from the lottery for license plates; and increases the annual quota* for clean energy vehicles in BJ and TJ
Phasing out old and yellow label vehicles**	(BTH)Provide financial subsidies for phasing out yellow label vehicles which have not reached the retire years; yellow label vehicles are banned from entering urban core areas

#BTH, Beijing-Tianjin-Hebei; BJ-Beijing, TJ-Tianjin, HB-Hebei; * in order to control the total vehicle number, local governments set up annual ceilings for the total amount of vehicles, and control the vehicle number through license plates; **yellow label vehicles, namely the gasoline vehicles that fail to meet the National I emission standard (the same with corresponding Euro I emission standard), and diesel vehicles that fail to meet the National III emission standard (the same with corresponded Euro III emission standard). Those vehicles are labelled with yellow environmental protection certificates.

Challenges for implementation: According to the interviews (Table 5-4), the implementation of traffic emissions control was generally effective. Major challenges during the implementation were related to the comprehensiveness of identifying and controlling trucks and service vehicles that exceed emission standards, particularly at night and in rural areas. Further, some filling stations continued to provide low quality petrol or diesel. The interviewees' suggestions to optimize control of road transport emissions can be summarized into three groups: further control to increase coverage of the total number of vehicles, promote active and public travel options (cycling, walking and public transport), and use environmental economic measures instead of command-control measures. Although the share of public and active transport in daily travel has been increasing, there remains much more scope to further increase its share, for example, by optimizing the allocation and exclusive reservation of routes to different modes of transport (e.g. bus or cycle routes) and improving comfort and convenience of public transport.

Table 5-4. Interview quotes on traffic emission control

Nr.		The quote	Quote ID
		General opinions	
1	*"Most of the transportation emission control measures are going relatively well"*		[ID-02,03]
2	*Challenge*	*"Diesel and gasoline quality varies in different gas stations, some of which still do not meet the diesel and gasoline standards."*	[ID-02]
3		*"Vehicle emissions in rural area are still high because vehicles do not reach the emissions standard"*	[ID-01,03]
4		*"The vehicles, particularly trucks, which are only limited to enter BJ/TJ at night, do not meet the emission standard"*	[ID-01]
5	Suggestion	*"Further control the total vehicle number"*	[ID-03]
6		*"Further improve diesel and gasoline quality and vehicle emissions standard"*	[ID-02,03]
7		*"Optimize the allocation and the use of the public transport, and also improve the comfort of public transit"*	[ID-03,04]
8		*"Build up bicycle paths in some areas and promote green travel"*	[ID-02]
9		*"I do not recommend compulsory emission control actions like traffic restrictions, but go for economic measures like increasing parking fees and oil prices, etc."*	[ID-04]
10		*"We could use environment economic measures to regulate travel behaviour,… Which is affecting the pollution? The emission factor, mileage and the number of the vehicles…for example, price measures can obviously change the mileage, emissions and short-distance travel patterns… at the early stage of pollution control, the net benefit of these kinds of command and compulsory policies are significant, but with the improvement of the pollution control targets, behaviour change induced by environmental economic are more manifest"*	[ID-03]
		Sustainability	
11	*"[but] if the vehicle restriction becomes normal, for example, for a half year or one year, it obviously goes beyond the individual property rights according to the law"*		[ID-02,09]
12	*"As we all know, there is no time limit (except for mileage) to retire private cars, so if you want to phase out the old cars, you can only encourage people to do so through for example new for old trade or providing subsidies, but not saying the car has to be retired after 10 years, this is inappropriate"*		[ID-09]
13	*"The traffic emission control actions (traffic restriction) contribute to the decrease of the air pollutants, like military parade blue and APEC blue, but we cannot deny that even with the traffic restriction, the heavy smog still exists. We should also notice the side effect of the traffic control, which is the inconvenience for the public, it is not sustainable and should not be used as a routine measure to control air pollution"*		[ID-04]
14	*"Traffic restrictions and license lottery cannot reasonably decrease the total number of vehicles, which in the meanwhile, impose dissatisfaction from the public. It is not sustainable and I suggest to take economic measures like parking tax"*		[ID-02,03,04]

Sustainability: Several interviewees mentioned that vehicle restriction measures are violating personal freedom and property rights, and causing inconvenience for the general public, indicating that they were not sustainable as a long-term traffic control measures. Although phasing out old and yellow label vehicles (namely the gasoline vehicles that fail to meet the National I emission standard, and diesel vehicles that fail to meet the National III emission standard) was proceeding well in BTH, the way it was implemented was also arguably a violation of the individual's property rights, for example, yellow label vehicles are forced to phase out even when those vehicles have not reached the end of the economic or technical life-time. Interviewees suggested alternative ways to phase out those type of old and yellow label vehicles including new-for-old trade or providing reasonable financial compensation.

Collaboration on air pollution control

There were regional collaborations with different focuses on air pollution control in BTH, the names and the functions see appendix E.

Table 5-5. Interview quotes in regional and institutional collaboration

Nr.	The progress, challenges and suggestions	Quote ID
1	*"There is regional collaboration, but still not close enough; the air pollution control measures in BTH are always 'prosperity or loss'; it is necessary to build up a tight collaboration with the collaboration mechanism more mature; and now in most of the cases, the surrounding regions together 'save Beijing' "*	[ID-04]
2	*"The regional collaboration is not smooth, each government cares about its own interests and constituency, and it is very difficult to communicate among the institutions involved."*	[ID-08]
3	*"Very limited collaboration with the other surrounding, like Shandong, Shanxi province, but it is needed; for BTH, the conventional collaboration. The BTH collaboration is more for the special events or emergency but not for regular collaboration, which needs to be enhanced. Beijing, Tianjin and Hebei are three politically parallel governments, it is still lack of coordination mechanisms and a political institution or organization which is separate from or above the three to coordinate the implementation of the action plan in BTH"*	[ID-03]
4	*"Suggest to set up a regional environmental centre (commission) for joint prevention and control [also ID-03,06], and empower independent right (with judicial independence), and with fixed fund source and independent right to allocate the funds and subsidies (for example, certain percentage of GDP from each province/city), and have the right of carrying out punishment and one-vote veto, and etc."*	[ID-12]
5	*"For the three major organizations* recently set up for regional air pollution prevention and control, we need to be keep in mind that, if they are temporary organizations, then the authority and stability are questionable, and the lack of continuity of the policy can also influence the authority and stability"*	[ID-09]
	Regional emergency response system	
6	*"The emergency system is already in place, and can provide timely information, but the corresponding measurements are mainly limited to temporarily pause the production and vehicle restriction, both are not a sustainable measures"*	*[ID-03,04]*
	"… but the forecast is too late, the measures can only be taken in the same day when heavy pollution happens, thus the measures cannot decrease the pollution until a while. The prediction timeliness should be improved to provide ample time for preparation and reaction"	*[ID-06]*

The mechanism on regional collaboration to control air pollution was already well-established in the way of working groups, platforms and committees. The Olympic Games experience indicated that air quality improved dramatically with the short-term combined control measures, but the effects disappeared gradually afterwards (Zhang et al., 2016). According to our interviews, the greatest concern regarding long-term regional collaboration lies in how to ensure the adequate balance of interests among different local administrations. For example: Beijing, Tianjin and Hebei set up their own respective action plans according to their own interests as response to the economic growth and air pollution control pressure. This led to the decoupling of collaboration between regions when it came to the respective economic or environmental interests. Prioritized interests during implementation made it difficult to communicate among the three regions; for example "*save Beijing*" in the special events like APEC or hazardous pollution days *(Table 5-5, quote #1)*. The three regional authorities are administratively at the same government level (provincial level), but Beijing, as capital and at the heart of the political centre, had more political clout and always received more attention nationally and internationally. An option suggested by the interviewees was to set up a judicially independent institution or coordinator with long-term authoritative strategy on air pollution control in the BTH region to ensure regional coherence and sustainable collaboration in the long run (*Table 5-5, quote #4*).

For the institutional collaboration, a decoupled relationship still existed between the policy makers and the technical advisors, mainly researchers, and between policy makers and the public, as one interviewee indicated: *"(although) many studies on the air pollution and health have been carried out; there is disconnection between government and research, and the public have limited knowledge of the air quality control strategies and health impacts. I suggest enhancing the public awareness on air pollution and health, pollution control plans, progress, etc. The related policy officers can participate in the research report and academic meetings to extend their knowledge. I also suggest regular training on related research for the government officers" [ID-05]*

Discussions and recommendations

We summarized the progress on air pollution control in BTH, and explored the challenges for integrated air pollution control strategies in the region, focusing on industrial and traffic emission control measures. The measures used to control industrial emissions (mainly through industrial restructuring) and road traffic emissions have resulted in some air quality improvements in the region stopping the negative trend. To reach the air quality targets set by the Air Pollution Prevention and Control Action Plan, further improvements are required in Beijing to meet the annual target of 60 μg/m^3 for $PM_{2.5}$. Hebei and Tianjin have already met the target of decreasing annual $PM_{2.5}$ concentration by 25%. The current Action Plan has specific focus on $PM_{2.5}$ control; while NO_2 showed slight decline and O_3 could potentially increase. A comprehensive emission control strategy is strongly recommended for the next air pollution control stage. The Action Plan has been in place for only few years with data available for three years. The result from a 3-year dataset might be less representative, because the air pollution levels can be influenced by natural variability in weather and atmospheric conditions. This is one important limitation of our study.

Zhang indicated that air pollution control during the Olympic Games of 2008 did not result in long term improvement due to the short-term nature of most policies implemented at that time (Zhang et al., 2016). However, under the current circumstances, the central government seems determined to control and reduce the air pollution, and has shown commitment to further engage on climate protection (Tambo et al., 2016). The continuity and consistency of air pollution control strategies is encouraging and a cause for cautious optimism. Still, the economic development and industrial production (mainly iron and steel industry in BTH) plays a crucial role in terms of air pollution control performance. With regard to the industrial restructuring, the local governments' incapacity to enforce regulations, and the illegal emissions from certain polluters, were the major challenges during the implementation of the air quality plans. The weak institutional capacities of local government, when dealing with large companies and/or tax contributors hindered the full enforcement of the measures (CCICED, 2012), and thus potentially increased social inequity, as small industries were forced to shut down. In addition, the air pollution control measures were introduced suddenly with a "command and control" approach, and the regional market in Hebei was far from being ready to absorb the redundant labour force (Yuan et al., 2012). Even with the policy and financial support from national to local government, unemployment is still the major social consequence of industrial restructuring in the Hebei province.

The sustainability of the air quality strategies based on industrial restructuring is debatable, mainly because of the top-down, command and control approach, and the failure to compensate for the huge social cost (unemployment). Unlike PRD and YRD having better market-regulated economic development mechanisms, the economic development in BTH region is strongly influenced by the political enforcement. Consequently, Beijing has very limited influence on the economic development of its neighbouring areas such as Hebei (Mu, 2012, CCICED, 2014; Yu, 2015). As the economic and environmental development in the region, particularly in Beijing, was at the expense of Hebei's environmental quality (Liu et al., 2016), financial subsidy and substantial market support at central-local and cross-regional level, would be needed to reduce unemployment and mitigate the potential regional dissatisfaction in the long run (Yu, 2015).

In terms of traffic emission control, the interviews indicated that the related actions were effective, while the sustainability - at least in the long run - was questionable. Some of the actions were violating the individual's property right and freedom. Individual resisted by covering parts of the license plates or borrowing license plates from other car owners thus undermining traffic restriction policies and thus the effectiveness on pollution emissions control (Wang, 2014). There are three major factors that influence emissions: emission intensity of a vehicle, mileage driven and the number of vehicles. Although vehicle traffic growth has been sharply curtailed, and congestion has been addressed through the total number control (vehicle license-plate lottery) and traffic restriction based on license-plate number, total vehicle fuel consumption was not reduced as much as anticipated (Yang et al., 2014). The traffic restriction in Beijing had small immediate effect in the beginning of its implementation, with the annual average vehicle distance travelled (VDT) by private cars decreased by 24%; however, this percentage dropped to less than 4% since then, indicating the traffic restriction has little effect in the long run (Beijing transportation annual reports, 2013, 2014, 2015). Although these measures, particularly for vehicle license-plate lottery, limited the total vehicle numbers, and contribute to the air quality improvement, this kind of command and control rationing measures have a small immediate effect on traffic control and emissions, but the effect was short-lived and provided loopholes to circumvent the policy.

Few collaboration mechanisms were already in place, but the regional collaboration on air pollution control in BTH mainly focused on short-term control (emergency response or special events like APEC). Liu indicated that the bottleneck of regional collaboration lies in the administrative management system (Liu et al., 2016). For this Beijing played a more active role while Hebei and Tianjin played more passive role in the collaboration. The quote *"save Beijing"* (*Table 5-5, quote #1*) indicates the contradiction between the central government which develops the broad policies and the local government which was responsible for implementing the policies. A long-term regional collaboration involving BTH and the surrounding regions is however indispensable, as the surrounding regions also contribute a large proportion (28-36%) of the pollutants observed in BTH (Shi et al., 2016; Yang et al., 2016).

The challenges for the success of long-term emission control mainly lie in the appropriate design of strategies themselves and in the way they were enforced, i.e. the overall governance of the strategies (United Nations, 2009). Although the government formulated laws and regulations on "public supervision mechanism" to promote transparency (Figure 5-2), public participation had a very limited role in reality (Johnson, 2014; Gao et al., 2017). A more substantive participation of the public and the third sector (e.g. NGOs) can facilitate the implementation of the measures. Research indicated that a transparent governance system can encourage companies to comply with environmental regulations even in the absence of adequate government enforcement in China (Haddad, 2016). A transparent supervision mechanism in BTH can prevent "selectively action" during the industrial restructuring, and transparent information disclosure mechanisms on industrial emissions from both industry and government can facilitate regional information sharing, enhance accountability, and increase public participation in both decision making and supervision (Wang et al., 2016; Sun et al., 2016; Sun et al., 2016). In addition, although there is sufficient environmental legislation, this study indicates that a legal basis for the implementation and enforcement of the emission control measures is still wanting. This has major consequences for the sustainability of the strategies, and resulted in regional contradiction and conflicts between stakeholders.

Apart from the lack of appropriate governance mechanisms, the pre-dominant emphasis on GDP growth, and still subordinated and limited attention on environmental protection in the government's performance evaluation encourages the local officials to focus on economic growth, rather than environmental protection, as their priority (Zhang et al., 2016). Strong political supervision in the BTH region largely shaped the existing administrative barriers, including the exclusivism management system and limited information sharing, resulting in local protectionism.

Conclusions

Using both quantitative and qualitative methods, we explored the progress and challenges of the air pollution control in the BTH region in terms of industrial and traffic emissions. In general, air quality in the BTH region improved slightly with the Air Pollution Prevention and Control Action Plan since 2013. The implementation of both industrial restructuring and traffic emission control has provided environmental benefits, but more stringent monitoring and supervision is needed to improve enforcement. Social inequity and unemployment were the main unintended consequences of the policy that require attention from national, regional and local authorities. In the long term, the mandatory top down enforcement with little self-regulation mechanism could make the strategies unsustainable. Current collaboration on air pollution control mainly focuses on emergency haze episode control, but not on routine long-term air pollution control. Better mechanism to provide a multi-sectoral communication between regions is still lacking. The interview results revealed the challenges that can hinder the effectiveness and sustainability of the air pollution control plans, and also shed light on the lack of appropriate governance mechanism in terms of decision-making and implementation. More active stakeholder involvement could help mitigate unintended consequences like social inequity, unemployment, and regional contradiction. Further, it could improve the intrinsic motivation for the local government to implement the measures, to increase the implementation and monitoring, and thus increase the sustainability of the strategies. A sound information exchange system for decision-making, policy implementation and monitoring, would improve supervision and increase the accountability. Finally, strengthening the legal basis for emission trading, compensation mechanisms and enforcement in the region and more importantly between regions, can improve consistency and fairness of policies, and ensure the interests can be reasonably balanced between regions.

CHAPTER 6

General discussion

General discussion

The objectives of this dissertation are to explore the public health risks caused by air pollution and to identify the challenges of air pollution control strategies in China. The first part (chapter 2 and chapter 3) of the dissertation is designed to contribute to an understanding on the characteristics of health risks, including regional differences and risks among sub-groups, which could provide a theory-based support for formulating strategic prevention and control plans. The second part, using a case study in Beijing-Tianjin-Hebei (BTH) region, where air pollution is the worst in China and is getting the most political attention, explores the challenges that might hinder the full implementation of air pollution control strategies. This contributes to the evidence-base for suggestions on what can be further done in the BTH region and beyond. An analysis of experience from the EU on air pollution control strategies and health benefit is also included to provide reference for decision-making. Three issues are addressed through this thesis: 1) the extent to which air pollution is providing a risk to public health in China; 2) the factors that are impeding, or could impede, the effectiveness and the sustainability of air pollution prevention and control strategies; and 3) supported by a systematic review on Europe, an analysis on health benefits and air pollution control policies, that has so far barely been studied in China. Each of these three research aspects can contribute to the formulation of more coherent and effective air pollution prevention and control strategies in China. Vice versa, as the EU continues to be confronted with sever air pollution issues in many urban agglomerations, the further exchange and collaboration with China can also provide new insights into pollution control and improve international collaboration on environmental health and climate protection.

China's air pollution in the globalization world

Air pollution in China is a mixture of primary pollutants (directly emitted from a source) and secondary pollutants (synthesized in the environment by chemical reactions involving primary pollutants, or emitted chemicals) with multiple sources. The interactions among the pollutants make the source-appointment more complicated and make the health impact assessment more difficult. Therefore, more multi-channelled science-based strategies are needed to control air pollution effectively. Chapters 2 and 3 address the gaps in the research on air pollution and public health: spatial differences of health impact and ozone pollution that has been neglected in China despite its serious health impact. However, despite the complexity, urbanization and globalization are also opening opportunities to address air pollution in a more effective way, such as more advanced emission control technologies and more experienced research and management resources.

Added value I: air pollution and public health

Chapters 2 and 3 answer the first question on the extent to which air pollution is influencing health in China, with two dimensions: spatial and temporal. A few European studies explored the differences on health damage of air pollutants stratified by the socioeconomic position, and the pollution concentration and socioeconomic position are normally geographically distributed (Cesaroni et al., 2011; Tonne et al., 2008). The result in general revealed that groups with lower socioeconomic position suffered more from air pollution exposure. This might be attributable to the geographical distribution of the air pollutants, as many people in lower socioeconomic conditions tend to work and/or reside at places with higher pollution exposure, for example, close to main traffic routes (highway or railway) or to industrial areas (Neidell, 2014; Bell and Ebisu, 2012). A further reason might be the underlying poor health conditions, as often people with lower socioeconomic positions have poorer health conditions and poor health care for pre-existing conditions (respiratory, cardiovascular, etc.). This can also make them more susceptible to air pollution. There are hardly any studies exploring the health effects of air pollutants among social strata at geographical level in China. Our study (Chapter 2) provided light on this issue. The first conclusion, in terms of regional differences of the health response to air pollution, is that the association is more obvious in the south part of China. This is possibly because of the non-linear relationship between air pollution and health, particularly for the extreme high pollution concentrations in the northern cities in China. The regression in Chapter 5 reveals that per unit SO_2 concentration increase seems resulting in higher life expectancy loss in the South China. Still, it is too arbitrary to speculate the real exposure-response effect in this context, because the associations between SO_2 and life expectancy in the central and the north China are less significant. The results from Chapter 5 might help to explain why, despite the fast economic growth, China has seen only mild life expectancy increase in recent generations. Air pollution has functioned as – at least one of – the countervailing roles (Ebenstein et al., 2015; Chen et al., 2014).

Ozone pollution is emerging and replacing fine particulate matter as the dominant pollutant in many southern cities in recent years, but perhaps because, unlike particles, it is invisible (the "invisible killer"), much less emphasis has been put on this in terms of research and control policy. Chapter 3 explores the geographical distribution pattern of ozone and its health risks. The result highlights the ozone distribution pattern in mega cities like Shenzhen. Unlike the general geographic distribution patterns of the other pollutants (like particulate matter and NOx), a higher ozone concentration can also be found in the suburbs. As a secondary air pollutant, ozone is very unstable, and can be formed and decomposed according to the precursors. With increasing emissions of the air pollutants in city centre, ozone can be decomposed. Its precursors can be transferred to downwind areas and then form into ozone again. This has been documented also for other regions (Allen, 2002). The health risk assessment indicates the highest risk groups being the elderly and male, and the excess risks caused by ozone can be even higher than for fine particulate matter or SO_2. This clearly indicates that more focus should be put on controlling the emission of ozone precursors (mainly NOx and VOCs), and that health precaution strategies should be implemented not just for the inner city area but also in the surroundings and even rural areas.

Added value II: connecting health studies with air pollution control policies

Due to a somehow decoupled relationship between health research and decision making in China, environmental health research has made very limited contribution to policy. As also indicated in the expert interviews (Chapter 5), despite considerable research that has been conducted in China regarding health and air pollution (for example, on health risks and disease burden), there are still very few studies that analyse the transfer of knowledge into policies. Zhang (2010) estimated economic burden from health loss in a heavily polluted city and provided policy suggestions based on scenario-simulation. According to our interviews in Chapter 5, the relationship between policies and corresponding health assessment has rarely been analysed in China. Without bridging this gap, it is ambiguous to know if the policies are beneficial for health, and it is difficult to compare which policy is more efficient to improve health. Still, considering the scale of health risks caused by air pollution and the equity issues resulting from the variations in geographical exposure and the vulnerability and susceptibility among various groups of the population, it is necessary to set up some immediate and prioritized strategies to protect those who are more vulnerable.

As air pollution control has just reached an "improvement phase" in China, there is very limited research on the effectiveness of air pollution control policies (Wang et al., 2014), and barely any research on the effectiveness of air pollution control strategies on health. Using a systematic review, Chapter 4 links recent air pollution control strategies in Europe to health benefit. This provides a research reference for conducting similar studies in China, including health impact assessment and health equity assessment of air pollution control strategies. This review also contributes to the scientific bases on how to embed health studies into policies and how to evaluate the effectiveness of policies for health protection from a methodology perspective. Relevant health outcome indicators and the health impact assessment methods are also discussed. Monetized health effect has become the dominant way in cost-benefit analyses of ambient air pollution control policies (Williams, 2015; Wang et al., 2016). Air pollution control strategies involve multi-disciplinary approaches in the EU including direct strategies like improving emission technology, elevating emission standards (national or regional) for specific or high risk areas and controlling the energy market; and indirect strategies like embedding air pollution emission reduction in climate change mitigation policies. The EU experience described in Chapter 4 indicates the categories of air pollution control strategies, which are not merely national or EU legislations or actions but include more local actions targeting specific pollution control under the EU framework. And the experience underlines the relevance of the concept of Health in All Policies (HiAP) that the WHO is promoting (Leppo et al., 2013).

Added value III: air pollution control strategies

The 11th Five-Year Plan (FYP) (2006-2010) is the first FYP aiming to reduce atmospheric pollution, mainly SO_2, and this is expanded in the 12th FYP (2011-2015) to include NOx. With the increase in heavy smog incidents, the focus on atmospheric pollution control has moved from NOx and SO_2 to particulate matter, particularly to $PM_{2.5}$. The past two FYPs have (almost) achieved the targets of reducing SO_2 and NOx emission by 2010 and 2015, respectively (Wang et al., 2014). The "Air Pollution Prevention and Control Action Plan" issued in 2013 is aimed to decrease air pollution emission, particularly for PM with clear decrease target for each province. During the 2017 National People's Congress, the urgency to address air pollution and to meet the Action Plan targets was underlined and received prominent mentioning during the speech of Premier Li Keqiang. Based on the content of this – so far the strictest – Action Plan, Chapter 5 investigates the challenges and sustainability of the air pollution control strategies in the Beijing-Tianjin-Hebei region, where air pollution is the worst and is getting the most attention in China. The current air pollution policy related research largely involves prospective projections (Wang e al., 2014), but there is no systematic study assessing the challenges of the strategies. As air pollution control involves multiple stakeholders' interests, exploring the roles and interactions among stakeholders can provide a clear picture of how those interests can be balanced to further smooth the strategies, in particular, under the circumstances that the government wants to keep the economic growth above 6% at the same time trying to fight the sever air pollution.

Since the heavy smog in 2011 that was followed by a government credibility crisis regarding air pollution control, several crucial laws and standards have been promulgated and up to now there are sufficient pollution control legislations. But the ineffectiveness of the enforcement of these strategies largely persists, including violations of the emission limit from both transportation and industries (Zhang et al., 2015). Insufficient supervision partially leads to this ineffectiveness. Prioritizing economic development over environmental protection still dominates the ways the local government enforces the strategies, only slowly switching from "inaction" to "selective action" to protect their regional industries (Wang et al., chapter 5). In addition, the unbalanced relationship between regional governments in terms of the roles that they are playing during the implementation of the strategies, and the unbalanced interests led by a top-down political mission, cause a lack of intrinsic motivation for the disadvantaged groups (here the local governments) in the execution of these action plans. This is partially attributable to the lack of legal basis in terms of rights and responsibilities for coordinating the key stakeholders. Consequently, it leads to huge social cost, which, if not properly and urgently solved, could also threaten the full implementation of the action plans. Underlying is the problem of insufficient and/or ineffective governance concepts and tools. Although the government already tried to increase transparency and participation in the drafting of the current air pollution control related legislations (including the Law for Air Pollution Prevention and Control, the Air Pollution Prevention and Control Action Plan), this played a very limited role in reality (Johnson, 2014). As discussed in Chapter 5, a sound participation from different stakeholders (multi-sectoral and multi-stakeholder levels), transparency and clear accountability with legal support could further increase the enforceability of strategies to a more efficient, sustainable, and interest-balanced direction. These can also help to minimize the social cost and decrease social inequity. One important aspect that becomes increasingly apparent during the trajectory of this dissertation is the need of bridging the gap between air pollution related health studies and decision-making. Narrowing this gap would already contribute to more strategic air pollution control plans in terms of health protection. It is important to note that, the implementation of air pollution control strategies is – more or less – improving the air quality, and consequently beneficial for public health and health equity. But the social cost of these strategies, like unemployment – if not handled properly in China – might offset this benefit, and even worsen the health status of the laid-off workers, at least in a short period.

On a final note, although a big step has already been made towards environmental protection in terms of legislations and actions in China, this thesis suggests that there may be more room to further improve the strategy and improve the way it is implemented.

Some experiences from the EU in terms of knowledge and decision-making

The analysis of the complex relationship between air pollution, public health and strategic policies has to be under taken with caution and especially drawing easy and superficial comparisons between the different development in the EU should be avoid. Still, through the trajectory of writing this thesis, some experiences can be derived spanning from science to policy.

From a policy perspective, the EU's air pollution control policies have some notable successes to its name and the structure of how they were formulated could be seen as a good practice. It mainly involves rounds of scientific reviews on the historical policies, guidelines and related researches, and a broad consultation process including a wide range of participants from Member States, industries, NGOs and international stakeholders. Taking the latest (the 7th) Environmental Action Programme as an example, stakeholders (including BUSINESSEUROPE[2], CONCAWE[3], EEB[4], EURELECTIC[5], EUROCITIES[6], UITP[7]), regional committees, public consultation (an online survey targeting general public, experts and practitioners), press releases and documents provided support including rounds of reviews on the recommendations from stakeholders and different sections (EC, 2016). These retrospective reviews assessed the effectiveness of existing policies, and together with the recommendations, contributed to a more strategic future plan. We can see that the guidelines and policies on air pollution control are highly evidence-based, and scientific research plays a backbone role for those strategies. Policy drafting in China, however, is still much isolated from scientific research, and highly isolated from stakeholders' participation. This has also be pointed out by the experts in our interviews (chapter 5). This largely cultivates the challenges that hinder the full enforcement of air pollution control strategies in the BTH region, including the inadequate enforceability of the action plans and the difficulties during the implementation. Apart from participation during the formulation of policies, the stakeholders also contribute to the supervision following the EU experiences. For instance several air pollution lawsuits from NGOs (like ClientEarth) focusing on few European cities were and are underway, and are pushing forward for a stricter air pollution control.

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[2] Business Europe is the leading advocate for growth and competitiveness at European level, standing up for companies across the continent and actively campaigning on the issues that most influence their performance. https://www.businesseurope.eu/

[3] Environmental Science for the European Refining Industry. The scope of CONCAWE's activities has gradually expanded in line with the development of societal concerns over environmental, health and safety issues. These now cover areas such as fuels quality and emissions, air quality, water quality, soil contamination, waste, occupational health and safety, petroleum product stewardship and cross-country pipeline performance. https://www.concawe.eu/

[4] European Environmental Bureau, Federation of Environmental Citizens Organisations. http://www.eeb.org/

[5] The Union of the Electricity Industry. EURELECTRIC is the sector association which represents the common interests of the electricity industry at pan-European level, plus its affiliates and associates on several other continents. http://www.eurelectric.org/

[6] EUROCITIES is the network of major European cities. The objective is to reinforce the important role that local governments should play in a multilevel governance structure. http://www.eurocities.eu/

[7] Union Internationale des Transports Publics (UITP) is the International Association of Public Transport. http://www.uitp.org/

The EU has an experienced history of transferring health studies into air pollution control policies, and making the policy more health-oriented. In the early 1990s, a series of what proved to be ground-breaking research relating health to air pollution emerged. Those studies played a crucial role to the resurgence in a strategic way of a coherent strategic approach, which underpinned the follow-up air pollution control strategies, such as the Environment Act 1995 in UK (Williams, 2015). All of these studies have been tremendously influential at the EU and international level, both for research and decision-making. Vice versa, the scientific support paved the way to embed health benefits as the aim of the policies. For example it defined the long term objective as "to achieve levels of air quality that do not result in unacceptable impacts on, and risks to, human health and the environment" in the Thematic Strategy on Air Pollution (the 6th Environmental Action Programme), and the Thematic Strategy set up the aim of mitigating the life loss, quantified by life expectancy and acute mortality.

With regard to air quality management, there are substantial variations across the EU. Under the uniform guidelines and standards (or Directives) from the EU, the Member States are required to set up the targets accordingly. History indicates that those strategies produced great progress in Europe. Still, considering the facts that the pollution characteristics and the background of the air pollution (including the globalization context, the urbanization process, socioeconomic status, and the industrialization development level) are largely different between Europe and China, experiences in addressing air pollution from Europe can only be cautiously used as a reference but not as a copy.

Suggestions for research

First, research on spatial distribution characteristics of the air pollutants needs to be further enhanced, including the source-appointment and, more importantly, the dynamic transformation and migration patterns among the regions and across the regions. This can help facilitate more cost-effective and regionally prioritized control plans. Spatial study also includes a comprehensive concentration-response relationship study at different geographical scales, which can range from community to national levels. This could help to identify the specific vulnerable groups under the background of different socioeconomic positions, demographic structures, climate conditions, and geographical environment conditions.

Although with numerous time-series studies, the cause-effect relationship is still insufficient as many cofounders, such as individual behaviours (like smoking) and socioeconomic conditions, can influence the accuracy. Further, toxic substances from air pollutants can accumulate in the body. Until now, there are very limited long-term cohort studies on the accumulative health effect of air pollution in China (Cao et al., 2011; Liu et al., 2016; Deng et al., 2016; Aschengrau and Seage, 2013). Further, most of the health risk assessments used linear models to explore health risks from air pollution, while it is most likely sufficient for the European or the US situation (as the concentration is much lower, see Daniels et al., 2000; Martuzzi, 2002). Is the linear relationship still sufficient at the extreme high concentration levels in China? The recently introduced Ambient Air Quality Standards (GB3095-2012) is referenced from the WHO and the US guidelines. But whether the exposure-response function from the WHO and the US guidelines is just applicable to the extreme high concentrations in China is still uncertain and require further study.

Besides, most of the air pollution related health studies have focused on one pollutant, adjusted for the exposure to other pollutants and confounders. But urban population are exposed simultaneously to multiple pollutants, the health burden from simultaneous exposure to multiple pollutants may differ from the sum of individual effects estimated from single pollutant. There could be synergistic-effects of multi-pollutants influencing health (Dominici et al., 2010). Therefore, new approaches including deep insights into health effects of multi-pollutants exposures, and more advanced statistical modelling to estimate the health effects from multi-exposure, should be developed to further understand the total health risks. This can help facilitate a more integrated manner of emission control and air pollution standards and regulations.

In addition, a national agenda-setting for transforming knowledge to decision-making is urgently needed. This could include a sound evidence-based support in terms of theory and methodology. A thoroughgoing review of the existing research to identify the regional differences and interactions of the air pollutants influencing health could help to define more suitable concentration-expose relationships, and could help to formulate more targeted precaution strategies. Health impact assessment of the control strategies can further guide the policy in a more effective and targeted direction. This would also include a weighing between the gain and loss of the policies. Currently, the severity of air pollution in China is highly driven by the imperative of economic growth and the assumed generation of wealth; monetization of the health cost and environmental cost is crucial to evaluate the net economic achievement or loss, and can provide a more obvious picture on the balance between economic and environmental considerations.

From the social science perspective, it is necessary to set up cross-regional and cross-sectional studies to explore the intrinsic interactions and connections among those stakeholders. This could provide a platform to balance the interests between the regions and between the sections.

Last but not least, successful experiences in Europe indicate that a thorough and comprehensive review of former policies can help to foster coherence and synergies in a strategic approach, which I think is also essential for decision-making in China. The current global scientific achievement has provided an advantage base from both theoretical and methodological perspectives. A nationwide research for a thoroughgoing assessment of the former policies from national level to local level is strongly recommended.

Suggestions for practice

Nearly all populations in China and India have experienced (or are experiencing) the most extreme (PM_{10} over than 65 μg/m^3) atmospheric particle pollution (World Bank, 2016). Although air pollution control has reached an "improvement phase" in China, it will definitely take time to achieve the "APEC BLUE" in daily life, even with appropriate control strategies. "Appropriate" here means efficiency and sustainability within the reach in the context of China. Even the air quality in China is highly economic-dependent, a successive and fast improvement is urgently needed because the pollution level is reaching an "intolerable" level nationally. Science, thus, is of vital importance to provide a prospective projection based on theoretical and empirical experiences. Accordingly, one of the foci of this dissertation has been to evaluate the challenges and opportunities that occurred during the implementation of the air pollution control strategies. Challenges lie in the way that these strategies are enforced, and challenges lie in the strategies themselves. A number of implications can be derived from this point of view.

Firstly, substantial good governance, in terms of decision-making and policy implementation, could improve the efficiency and sustainability of the strategies. The central government has tried to introduce good governance into its legislation formulation mechanisms in the past decade. For example the government has provided legal channels for public's participation and supervision, and has increased the transparency, but it was more (mis-)interpreted as rhetoric to enhance the governance and to bolster regime legitimacy (Johnson, 2014). The public participation and supervision mechanism have played little role in the reality. Our research also shows a lack of sufficient public supervision during the implementation of the strategies. Therefore, we suggest enhancing the promulgation of legislation to facilitate public participation. A top-down air pollution control mission under a non-participatory decision-making system could lead to consequences like potential regional contradictions because of unbalanced interests. It can also rise unreasonable social cost (unemployment and social inequity), which could hinder the sustainability and the efficiency of the strategies. In the meantime, the weak accountability during the implementation, which is attributable to a shortage of clear legal bases when there is contradiction, is problematic according to our study. The unequal administration between regions also weakens the capacity of full enforcement of air pollution control measures at the bottom level.

Secondly, introducing "good health from all perspectives" into decision-making is necessary to direct air pollution control strategies into a coherent and health-based way. Experience from the EU indicates that, with the support of strong health related scientific evidences; air pollution control policies can reach a more strategic approach, and until then, air pollution standards can be established in a coherent manner. This would also include a comprehensive assessment of the cost-benefit relationship between economic achievement and environmental health cost. Combining Chapter 4 and Chapter 5, an example on how to embed health-related research into air pollution control policies can be drawn. Transferring the current health-related studies into decision–making can help to make more targeted air pollution control strategies. It can also maximize the health benefit from those strategies through putting extra emphasis on high risk regions (population-dense regions and high pollution concentration regions) and on more susceptible groups (groups with pre-health conditions, groups at extreme ages, and others).

Thirdly, the emission control should be enhanced by emphasizing multiple pollutants rather than single pollutant. Research indicated that the pollution reduction plan (the 12th FYP) to reduce NO_2 by 10% and SO_2 by 8% till 2015 could possibly lead to a more than 10% increase in ozone concentration (Anger et al., 2016). Current legislations focus more on fine particles at large scale in China while ozone (and precursors like NOx, VOCx) is emerging in many places, and the health damage from ozone cannot be ignored.

In addition, cross-regional control should be further improved. Many researchers have indicated that cross regional transportation of air pollutants greatly contributes to local pollution. A cross-regional collaboration is of vital important. Although collaboration facilities are already well established, according to our investigation, the mechanisms of how to collaborate, and the legal bases for coordinating the stakeholder's interests are still missing.

Last but not least, research has shown that with ambitious climate change policies, a large improvement in air quality and health quality can be achieved (Wang et al., 2016; Schucht et al., 2015). Achieving the climate change mitigation targets, such as the Paris agreement on climate change (COP 21, COP 22), could create a national and even international co-benefits in terms of air pollution control, in particular for China with its huge greenhouse gas emission. Strong commitment on climate change policies can also contribute to air pollution reduction and thus ultimately health benefits.

Final remarks

It is difficult, in a Ph.D., to have a comprehensive answer to the extraordinarily complicated problem of extent to which air pollution is causing health damage as many other confounders also influence the risks. Even when provided with quantitative result, many limitations still remain; it is difficult to provide a precise answer to the question "why is air quality still so bad and not improving in China after the implementation of such strict air pollution control strategies?" However, by combining theoretical research and empirical studies, this dissertation has made some systematic contributions to further the understanding of air pollution and health. It has also provided some reasons why the implementation of air pollution control strategies is making subtle change, and last but not least, has shed light on the next steps that need to be made to transfer these studies into more effective and sustainable policies.

VALORISATION

Valorisation

Valorisation is defined as "the process by which knowledge created by research is made available to society and by which it is transformed into economic and social impact" (National Valorisation Committee, 2011). This impact can be in all kinds of forms depending on the nature of the research, with a broad distinction made between fundamental and applied research. Based on the understanding of this thesis, which has strong relevance to the social, environment and health development, we can say that the experience and scientific impact yield from this thesis and beyond, in terms of scientific publications, can serve as a basis for further research, a tool for interdisciplinary education, and a reference for decision-making.

General innovations

The more experiences we draw from other samples, the less fragile when facing the similar problems and the better we prepare. By collectively using data, research results, systematic review, it is possible to triangulate on what and how the health changed under the background of urbanization and environmental change, and more specifically how the health is affected under the various policies coped with the negative effect of urbanization. On these grounds, this research has great value for trying to bridging the gap between health related studies and decision-making, particularly in China. Firstly, we use geographical regression and time series study to identify the characteristics of health risks caused by air pollution. An additional explore is made to evaluate the progress and the challenges for the sustainability of the air pollution control strategies in China. While for the EU, although air pollution is still risking the public health, numerals of effective air pollution control strategies are already in place. Using systematic review, we comprehensively analyse the recent air control strategies in the EU and the health and health equity benefit, which in one way, give a general summary of the effectiveness of the strategies, and in another way, shed a light on how to embed health studies into policies and vice versa, how to maximum the health benefit from air pollution control strategies.

Approach for valorisation from this thesis

Three general implications of this study can be summarized; 1) the population's vulnerabilities to air pollution varies geographically and varies among the individuals; 2) there are challenges for the fully enforcement and the sustainability of the ongoing air pollution control strategies; 3) and it is necessary to embed the health related research to decision making, and vice versa, to transfer the policies into health benefit. The valorisation thus can be achieved through the following perspectives.

In an academic setting, awareness has been and still can be developed by publishing the study results in national and international journals and presenting the results at national and international conferences. The relationship between air pollution to health is a complicated issue because of the confounders both internally and externally. Three chapters from this dissertation have been reported in international conferences and inspired a debate on the association between air pollution and public health, in terms of how to improve the methodology and how to combine confounders in health related studies to make the health risk-estimate more accurate. Still, more has to be done. A comprehensive and systematic explore on the progress of air pollution control strategies, particularly for the strategies targeting the most vulnerable groups, and their health impact still require further studying. A broad range of academic debate will be aroused as the result of this thesis will go back to the key stakeholders, including the government officials and researchers participated the interviews and beyond.

For education, although environmental health has been an old topic for decades, which in most of the cases is embedded in either global health or environment sciences, an enhanced understanding for students on how the environment, more specifically deteriorated environment, is influencing the health and the interactions between human development and environment protection is largely needed, particularly under the rapid urbanization setting like China, India but also including those developed countries who are facing with same issues. In addition, this enhancement should not be limited to the groups who are studying environmental health, but also to the related disciplines, including health care, medicine, policy, management, business, etc. This would link to the further knowledge dissemination to the public, which will be achieved through the third party like FORHEAD in terms of report and public propaganda.

In terms of decision-making, the recent (2017) China's National People's Congress committed to a “faster progress” on air pollution control in China. Although plenty of studies have been done including source apportionment and health impact assessment, transferring these knowledges into policy is still largely missing during the decision-making according to our investigation in China. Challenges that are hindering the sustainability of the air pollution control strategies do not only include the gap between research and decision-making, but also a lack of participatory, an unbalanced interests among the stakeholders, emphasizing less on the environmental protection, etc. Bringing those issues to the table with relevant suggestions can provide a clear picture on what has to be done during the decision-making and implementation. This does not just target to the government, who is the decision maker, but also to the researchers, the industries, the publics, and any others who are and should be involved in the decision-making, implementation, and supervision. This thesis will provide a bridge connecting policy makers and main stakeholders. Debate on the issues that is facing in terms of air pollution control and what can be expected from the government will be aroused.

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APPENDICES

Appendices

Chapter 5: Appendix A - The calculation method and classification of IAQI and AQI

Technical Regulation on Ambient Air Quality Index (HJ 633-2012) and Ambient Air Quality Standards (GB3095-2012) defined the calculation and classification of the IAQI and AQI. The AQI is calculated through Individual Air Quality Index (IAQI), and the calculation base for IAQI and AQI is explained as following.

The corresponding concentration limit value for individual air quality index (IAQI)

IAQI	Concentration limit value									
	SO_2-24h μg/m³	SO_2-1h(1) μg/m³	NO_2-24h μg/m³	NO_2-1h(1) μg/m³	PM_{10}-24h μg/m³	CO-24h mg/m³	CO-1h(1) mg/m³	O_3-1h μg/m³	O_3-8h μg/m³	$PM_{2.5}$-24h μg/m³
0	0	0	0	0	0	0	0	0	0	0
50	50	150	40	100	50	2	5	160	100	35
100	150	500	80	200	150	4	10	200	160	75
150	475	650	180	700	250	14	35	300	215	115
200	800	800	280	1200	350	24	60	400	265	150
300	1600	(2)	565	2340	420	36	90	800	800	250
400	2100	(2)	750	3090	500	48	120	1000	(3)	350
500	2620	(2)	940	3840	600	60	150	1200	(3)	500
Note	(1) 1h average concentrations of SO_2, NO_2, and CO are used merely for real time report. 24h average concentrations are used for the daily air pollution report. (2) When the 1h average SO_2 concentration is over 800 ug/m³, it is not used for IAQI calculation anymore. Only 24h average SO_2 concentration is used for IAQI calculation. (3) When the 8h average O_3 concentration is over 800 ug/m³, it is not used for IAQI calculation anymore. Only 1h average O_3 concentration is used for IAQI calculation.									

Then, the IAQI is calculated by the following formula,

$$\mathrm{IAQI_P} = \frac{IAQI_{hi} - IAQI_{lo}}{BP_{hi} - BP_{lo}}(C_p - BP_{lo}) + IAQI_{lo}$$

Where, $\mathrm{IAQI_P}$ is the IAQI for pollutant p; C_p is the concentration of pollutant p; BP_{hi} is the high limit value for C_p according to table 1; BP_{lo} is the low limit value for C_p in table 1; $IAQI_{hi}$ is the corresponding IAQI for BP_{hi}; and $IAQI_{lo}$ is the corresponding IAQI for BP_{lo}.

In the end, the AQI is calculated by the following formula,

$$AQI = \max\{IAQI_1, IAQI_2 \ldots IAQI_n\}$$

Where, AQI is the air quality index, n is the number of the included pollutants. When AQI is over than 50, pollutant has the largest IAQI is the dominant pollutant (can be two or more dominant pollutants). When IAQI is over than 100, it is the non-attainment pollutant.

The level of AQI is classified as following: 0~50, level I, descripts as excellent quality; 51~100, level II, descripts as good quality; 101~150, level III, descripts as mildly polluted; 151~200, level IV, descripts as moderately polluted; 201~300, level V, descripts as heavily polluted; >300, level VI, descripts as severely polluted.

Chapter 5: Appendix B - Interview guidelines

Overall aim of the interview: to explore the stakeholder's view on the 'air pollution prevention and control action plan' in Beijing-Tianjin-Hebei region (BTH)

Expected outcomes

1) The challenges and experiences during the implementation of the action plan (collaboration, interests conflict, management and others);
2) Apart from existing actions, standards, measurement, and laws, what else can be further done to control air pollution.

Interview Guide

1. Personal context
2. Have you been involved in any of the strategies on air pollution control, in the way of drafting, researching, propagating, implementing, evaluating, monitoring, or some other way? (in another way, if you familiar with the action plan)

❖ **General question**

1. What do you think of the 'air pollution prevention and control action plan'(progress, the challenges, sustainability and further suggestions)?

❖ **Industrial relocation/restructuring**

2. What are the major challenges during restructuring? Do you think the restructuring has led to the expected emission control?
3. According to the report, the industrial-restructuring is going well, particularly in Hebei province, and the air quality improved, but for some regions, the air pollution is still far from reaching the target, what do you think the reasons are?
4. Do you think industrial relocation in the Integrated-BTH will add additional burden to Tianjin and Hebei on air pollution control, and thus lead to conflict between BJ and T-H? Why and how to alleviate the burden for Tianjin and Hebei?
5. Regarding the industrial emission reduction, do you suggest further control? What kinds of measures do you suggest?

❖ **Traffic emission control**

6. How do you evaluate of the current transportation emission control measures? (progress, the challenges, sustainability)

7. Do you suggest further transportation control? What kinds of measures do you suggest?

❖ **Regional and institutional collaboration**

8. What do you think of the current collaboration on air pollution control in Beijing-Tianjin-Hebei? What are the challenges and what do you suggest to improve?
9. Is there any close collaboration between BTH and other surrounding regions, like Shandong province, Shanxi province, and Inner Mongolia in terms of air pollution control? If not, do you think it is necessary, and in which way?
10. Based on your work/research, can you give some suggestions on air pollution control for the next "five year plan"(13th-five year plan)
11. Are the heavy pollution weather monitoring and warning system in place? Can they provide timely and useful information for emergency response?

Chapter 5: Appendix C - Major air quality control strategies since 2012

Measures	Issued by*	Issue/execute date	Type
The 12th Five-Year Plan (FYP)	State council	2011-2015	Plan
The 13th Five-Year Plan	State council	2016-2020	Plan
Environmental protection law	NPC	Amended 2014.04	Law
Air pollution prevention and control law	NPC	Passed 2014.04 Executed 2016.01	Law
Clean Production Promotion law	NPC	Executed 2012.07	Law
The 12th FYP on Prevention and Control of Air Pollution in Key Regions	MEP, NDFC, MoF	Issued 2012.10	Plan
Air pollution prevention and control action plan	State Council	Issued 2013.09	Plan
National 10 measures	State Council	Published 2013.06	Plan attachment
Performance Assessment Measures for Air Pollution Prevention and Control Action Plan	State Council	Issued 2014.07	Plan attachment
National Ambient Air Quality Standard	MEP	Executed 2016.01	Standard
Emission standard of air pollutants for industries#	MEP, AQSIQ	Varied	Standard
Limits and measurement methods for emissions from light-duty vehicles (V)	MEP, AQSIQ	Issued in 2013.09 Fully executed 2018.08	Standard
Gasoline for motor vehicles Automobile diesel fuels(V)	AQSIQ, SA	Executed 2013.12/06	Standard
Rules on the standard for compulsory retirement of motor vehicles	MoC, NDFC, MoPS, MEP	Executed 2013.05	Standard

*Abbreviations: NPC, National People's Congress; MEP, Ministry of Environmental Protection of the People's Republic of China; MoF, Ministry of Finance; NDFC, National Development and Reform Commission; MoPS, Ministry of Public Security; Ministry of Commerce; AQSIQ, General Administration of Quality Supervision, Inspection and Quarantine; SA, Standardization Administration. #mainly includes the cement industry, iron and steel industries, brick and tile industry, electronic glass industry, iron smelting industry steel rolling industry, etc.

Chapter 5: Appendix D - Particulate matter decrease targets for the Action Plan at provincial or municipal level

Province	$PM_{2.5}$ decrease by*	Province	PM_{10} decrease by**	Province	PM_{10} decrease by
Beijing	-25%/limit to 60ug/m^3	Henan	-15%	Sichuan	-10%
Tianjin	-25%	Shaanxi	-15%	Ningxia	-10%
Hebei	-25%	Qinghai	-15%	Heilongjiang	-5%
Shanxi	-20%	Xinjiang	-15%	Fujian	-5%
Shanghai	-20%	Hubei	-12%	Jiangxi	-5%
Jiangsu	-20%	Gansu	-12%	Guangxi	-5%
Zhejiang	-20%	Liaoning	-10%	Guizhou	-5%
Shandong	-20%	Jilin	-10%	Hainan	Continuously decrease
Guangdong	-15% PRD*	Anhui	-10%	Yunnan	Continuously decrease
Chongqing	-15%	Hunan	-10%	Tibet	Continuously decrease
Inner Mongolia	-10%	Guangdong	-10%		

*,**, for $PM_{2.5}$, the baseline is the provincial/municipal annual $PM_{2.5}$ concentration in 2013, when the Ambient air quality standards (GB 3095-2012) were first introduced in China; for PM_{10}, the baseline is the provincial/municipal adjusted annual PM_{10} concentration in 2012 (GB 3095-1996).

Chapter 5: Appendix E - The major regional collaboration mechanisms on air pollution control in BTH region

Name	Key functions
Environmental protection supervision centre *	The main tasks for Environmental protection supervision centre are: to supervise the implementation of national environmental policies, plans, laws and other legislations; to investigate major environmental pollution incidents; to coordinate major environmental disputes between regions; to supervise the emergency response for major environmental incidents; to inspect the enforcement of environmental laws and sewage charges; to provide suggestion on limited batch for different regions and different industry types; to inspect the state-controlled emission sources#; to inspect the environmental protection enforcement in environmental function area, national nature reserve area and national key ecological protection area; to undertake or coordinate the cross-provincial environmental pollution or ecological destruction cases.
Working group office air pollution prevention and control of BTH region and its surrounding	The working group includes the Ministry of Environmental Protection, the National Development and Reform Commission, the Ministry of Industry and Information Technology, the Ministry of Finance, the Ministry of Housing and Urban-Rural Development, the Meteorological Bureau, the Energy Bureau, and the Ministry of Transport. The working group makes the annual plans on emission decreasing tasks and implements the tasks; and makes the medium and long term planning on regional air pollution control.
Coordination group office of vehicle emission control in BTH and its surrounding	The functions include cross-regional punishment for vehicle excessive emission, regional vehicle emission data sharing, joint spot-check for new vehicles in BTH, Shanxi province, Inner Mongolia and Shandong province.
Experts committee on regional air pollution prevention and control	The main tasks are: to identify research focus on the air pollution prevention and control; to provide guidance on composing the air pollution prevention and control plans; conduct fundamental research on source appointment, regional transmission, provide suggestion on advanced and applicable air pollution emission control technology
Air pollution early warning and forecast platform	This platform is mainly for severely polluted episodes or special events. It can provide synchronous monitoring of the regional air quality and provide real-time video meeting within the BTH and its surrounding.
Information sharing platform for air pollution prevention in BTH and its surrounding	The platform is to provide air quality data and key polluted emission sources information sharing in BTH, Shanxi province, Inner Mongolia and Shandong province

*There are 6 centres, Northern, Eastern, Southern, Northwest, Southwest and Northeast. The Northern Environmental protection supervision centre is in charge of the BTH region and its surrounding. Normally, the surrounding of BTH region in terms of air pollution control includes Shanxi province, Shandong province, Inner Mongolia, and Henan province; #Based on the amount and the type of the emissions; the Ministry of Environmental Protection classifies the emission sources into state-controlled, provincial-controlled and municipal–controlled.

SUMMARY

Summary

China has experienced a high-speed urbanization and socioeconomic development in the past three decades, which brought severe environmental issues. The air pollution issue got people's attention since the outbreak of a few heavy pollution episodes covering large part of China since 2011, which boosted a range of health related research and enhanced the formulation of unprecedented air pollution control strategies. Evaluating the progress and the challenges of those strategies and their health benefit can help to improve the efficiency of the strategies for the next stage, and to formulate more strategic health based prevention and precaution policies. On the other hand, this highly depends on a deep understanding on the association between air pollution and health, particularly on how the socioeconomic and individual characteristics influence this association and thus to protect the more vulnerable groups.

This dissertation provides a series of separate scientific articles that address the relationship between air pollution and health, and air pollution coping strategies in the context of China. The overarching aims and objectives of this dissertation are three-fold:

1. to explore the influence of air pollution to health, with the stratification of regional economic development and individual characteristics, and thus to identify the regional differences and the susceptible groups;
2. to assess the contribution of air pollution control policies to public health and vice versa based on European experiences;
3. and in the end, to identify the progress and the challenges that hinder the fully enforcement of the air pollution control strategies in China, with specific focus on the two major emission sources, industry and transportation.

Chapter 1, the general introduction to this thesis, presents a general background of the urbanization, air pollution and related health risks in China and the EU. This includes a brief review of the air pollution and control strategies with special focus on China, a summary of the health consequences of air pollution and the major mechanisms of the air pollution influencing health, and the parallels and potential solutions to address air pollution and protect health in both China and the EU.

Research aims and the content of this dissertation are also displayed in this chapter.

Identifying the regional differences and the susceptible groups are crucial for health protection and precaution strategies as those groups are exposed with higher risks. Accordingly, **Chapter 2** and **Chapter 3** answer the questions on "how" and "to what extent" air pollution is influencing health and what are the differences of those influences under the varied regional socioeconomic backgrounds; and clarifies the regional differences and the vulnerable groups. Using the geographical weighted regression model (GAM), **Chapter 2** identifies the regional differences of air pollution influencing health, and discussed the potential influence of socioeconomic factor to the association between air pollution and health. Spatial correlations between life expectancy and air pollutants were more obvious in south China. Methodology-wise, this was the first study analysing the relationship between air pollution and health at spatial level in China. **Chapter 3**, on the other hand, explores the health risks of ozone using time-series study. Susceptible groups for mortality caused by cardiovascular and respiratory diseases to ozone exposure were identified as the elderly (65 years and older) and the male.

Chapter 4 indicates the necessity of knowledge transferring between research and policy, and provides the possible methodologies for health impact assessment of air pollution control policies. Using a systematic review, the health benefit of the interventions used to control air pollution in the EU was assessed and its influence to health equity was discussed. Four groups of strategy types were identified: general regulations on air quality control, road traffic related emission control interventions, energy generation related emission control interventions, and greenhouse gas emission control interventions for climate change mitigation. All of those strategies resulted in improvement in air quality and subsequently in public health. Health benefits were gained either as a direct, intended objective or as a co-benefit from all of the strategies, indicating that there was a strong case for promoting Health in All Policies (HiAP), which WHO is facilitating. The methodology for health impact assessment and related health indicators were also discussed to provide reference for further research.

In 2013, the Chinese government launched the – so far - strictest air pollution control plan "Air Pollution Prevention and Control Action Plan" (2013-2017), represented a new stage of air pollution control of “improvement phase”. Under this circumstance, exploring the implementation progress of this action plan and the sustainability of the plan is crucial for a more coherent strategic approach in the next stage. **Chapter 5** illustrates the progress and challenges that hinder the full implementation and the sustainability of the air pollution control strategies. The results indicate that the air quality has improved with the recent air quality control strategies but the improvement is geographically uneven, and significant challenges remain with regard to transportation, industrial emissions control and regional collaborations. More specifically, these challenges are: incapacity for the supervision and monitoring, inter-regional contradictions caused by strong top-down enforcement, and the huge social cost such as unemployment and social inequity. There are many factors causing these challenges. Firstly, the challenges deeply lie in prioritizing the economic development over the environmental protection, which is still the case in many local places. Furthermore, the challenges lie in the insufficient participation and supervision from research and related stakeholders, including central-local government levels and sectional levels. Finally, the challenges lie in the lack of a powerful and explicit legal system, for the contradictions between environmental protection and economic development, between the regional and central government interests, and between the local government and industries. Suggestions are provided in terms of better formulating and implementing of air pollution control strategies in China.

Chapter 6 provides a general summary and discussion of the findings from the former chapters, discusses the added value of the thesis and the potential directions for next step in terms of research, and then illustrates the implications of this thesis to both research and decision-making on air pollution control and air pollution related health studies.

Samenvatting

China heeft de afgelopen drie decennia een grote verstedelijking en sociaaleconomische ontwikkeling doorgemaakt, wat een ernstig verslechterd milieu heeft opgeleverd. Sinds de uitbraak van een aantal periodes van zware vervuiling in een groot deel van China vanaf 2011, heeft het probleem van luchtvervuiling de aandacht getrokken. Dit heeft meerdere gezondheids-gerelateerd onderzoeken gestimuleerd en er zijn niet eerder voorgekomen controlestrategieën ten aanzien van luchtverontreiniging geformuleerd. Het evalueren van de voortgang en de uitdagingen van deze strategieën en hun gezondheidsvoordeel kan bijdragen aan zowel het verbeteren van de efficiëntie van de strategieën voor de volgende fase, als aan het formuleren van meer strategische op gezondheid gebaseerde preventie- en voorzorgsmaatregelen. Dit is echter sterk afhankelijk van het begrijpen van het verband tussen luchtvervuiling en gezondheid, met name over hoe de sociaaleconomische en individuele kenmerken dit verband beïnvloeden om kwetsbare groepen te beschermen.

Dit proefschrift omvat een reeks afzonderlijke wetenschappelijke artikelen die betrekking hebben op de relatie tussen luchtvervuiling en gezondheid en beheersingsstrategieën ten aanzien van luchtvervuiling in China. De overkoepelende doelstellingen van dit proefschrift bestaan uit drie onderdelen:

1. het onderzoeken van de invloed van luchtvervuiling op de gezondheid. Met stratificatie van regionale sociaaleconomische posities en individuele kenmerken, om de regionale verschillenen de gevoelige groepen te identificeren;

2. het onderzoeken van de kennisoverdracht tussen beleid en onderzoek en het beoordelen van de bijdrage van het controlebeleid ten aanzien van luchtverontreiniging aan gezondheid en vice versa op basis van Europese ervaringen;

3. en als laatste, het identificeren van de vooruitgang en de uitdagingen die de volledige uitvoering van de controlestrategieën ten aanzien van luchtverontreiniging in China belemmeren, met een focus op de twee belangrijkste bronnen van verontreiniging, industrie en vervoer.

Hoofdstuk 1, de inleiding van dit proefschrift, presenteert een algemene achtergrond van de verstedelijking, luchtvervuiling en gezondheid in China en de Europese Unie (EU). Dit omvat een korte bespreking van de strategieën ten aanzien van luchtvervuiling en controle, specifiek gericht op China, een samenvatting van de gevolgen voor de gezondheid van luchtvervuiling en de belangrijkste mechanismen van luchtverontreiniging die de gezondheid beïnvloeden, en de parallellen en mogelijke oplossingen om luchtvervuiling aan te pakken en gezondheid in zowel China als de EU te beschermen. Ook worden de onderzoeksdoelstellingen en de inhoud van het proefschrift in dit hoofdstuk weergegeven.

Het identificeren van de regionale verschillen en de gevoelige groepen is cruciaal voor zowel de bescherming van de gezondheid als voor voorzorgsmaatregelen, omdat deze groepen aan hogere risico's worden blootgesteld. **Hoofdstuk 2** en **hoofdstuk 3** beantwoorden daarom de vragen over "hoe" en "in hoeverre" luchtvervuiling de gezondheid beïnvloedt en wat de verschillen van die invloeden zijn tussen de verscheidene regionale sociaaleconomische achtergronden, en verduidelijkt de regionale verschillen en kwetsbare groepen. Hoofdstuk 2 identificeert de kwetsbare regio's en bespreekt de mogelijke invloed van sociaaleconomische factoren op de relatie tussen luchtvervuiling en gezondheid. Ruimtelijke correlaties tussen levensverwachting en luchtverontreinigende stoffen waren evident in Zuid-China. Methodologisch gezien was dit de eerste studie die de relatie tussen luchtvervuiling en gezondheid op ruimtelijk niveau analyseerde, gebruik makend van het "*geographical weighted regression model*" (GAM). Hoofdstuk 3 onderzoekt juist de gezondheidsrisico's van ozon met behulp van een tijdreeksstudie. De groepen die gevoelig waren voor sterfte veroorzaakt door hart- en-vaatziekten en ademhalingsziekten vanwege de ozonblootstelling werden geïdentificeerd als ouderen (65 jaar en ouder) en mannelijk.

Hoofdstuk 4 duidt de noodzaak van kennisoverdracht tussen onderzoek en beleid aan en biedt mogelijke methodologieën om de impact van het controlebeleid ten aanzien van luchtvervuiling op gezondheid te beoordelen. Met behulp van een systematische review werd het gezondheidsvoordeel van de interventies om luchtvervuiling te beheersen beoordeeld en de invloed ervan op de (on)gelijkheid op gezondheidsgebied besproken. Vier verschillende groepen van strategieën werden geïdentificeerd; algemene regelgeving omtrent controle van luchtkwaliteit, controle interventies ten aanzien van uitstoot van verkeer, controle interventies gerelateerd aan de uitstoot door het genereren van energie, en controle interventies omtrent de uitstoot van broeikasgas voor vermindering van klimaatverandering. Al deze strategieën hebben geleid tot verbetering van de luchtkwaliteit en daarmee tot verbetering van de volksgezondheid. Gezondheidsvoordelen werden verkregen ofwel als directe, beoogde doelstelling ofwel als bijkomend voordeel van al deze strategieën. Dit laat zien dat er een sterke zaak was voor het promoten van "*Health in All Policies*" (HiAP), gefaciliteerd door de Wereldgezondheidsorganisatie (WGO). De methodologie voor het beoordelen van de gezondheidsimpact en verwante gezondheidsindicatoren werd ook besproken om meer naslag te bieden voor verder onderzoek.

In 2013 lanceerde de Chinese regering het strengste controleplan tegen luchtverontreiniging "*Air Pollution Prevention and Control Action Plan*" (2013-2017), dat een nieuw stadium van controle op luchtverontreiniging vertegenwoordigde als "verbeteringsfase". Onder deze omstandigheden is het voor een meer samenhangende strategische aanpak in de volgende fase cruciaal om de voortgang van de implementatie van dit actieplan en de duurzaamheid ervan te onderzoeken. **Hoofdstuk 5** illustreert de voortgang en uitdagingen die de volledige implementatie en de duurzaamheid van de controlestrategieën ten aanzien van luchtverontreiniging belemmeren. Uit de resultaten blijkt dat de luchtkwaliteit verbeterd is met de recente controlestrategieën, maar dat de verbetering geografisch ongelijk verdeeld is. Er blijven aanzienlijke uitdagingen met betrekking tot vervoer, uitstoot door industrie en regionale samenwerking. Meer specifiek gaat het om de volgende uitdagingen: onbekwaamheid in toezicht en monitoring, interregionale tegenstellingen veroorzaakt door sterke top-down uitvoering, en de enorme sociale lasten zoals werkloosheid en sociale ongelijkheid. Er zijn vele factoren die deze uitdagingen veroorzaken. Allereerst zijn de uitdagingen diep geworteld in het prioriteit geven aan de economie ontwikkeling in plaats van bescherming van het milieu, hetgeen in vele lokale plaatsen nog steeds het geval is. Verder liggen deze uitdagingen in de onvoldoende deelname en toezicht van onderzoek en gerelateerde belanghebbenden, waaronder centrale-lokale overheidsniveaus en sectieniveaus. Tenslotte liggen de uitdagingen in het ontbreken van een krachtig en expliciet rechtsstelsel, ten aanzien van de tegenstrijdigheden tussen milieubescherming en economische ontwikkeling, tussen de regionale en centrale belangen en tussen de lokale overheid en de staatsbedrijven. Er worden suggesties gegeven voor het beter formuleren en implementeren van controlestrategieën ten aanzien van luchtverontreiniging in China.

Hoofdstuk 6 geeft een algemene samenvatting en bespreking van de bevindingen uit de eerdere hoofdstukken, bespreekt de toegevoegde waarde van het proefschrift en de mogelijkheden voor vervolgonderzoek. Ook worden de implicaties van dit proefschrift voor zowel onderzoek als besluitvorming over luchtverontreiniging gerelateerde gezondheidsstudie.

总结

城市化是与社会经济和环境的发展融为一体的。过去的三十年，中国经历了快速的城市化和社会经济的发展，同时也带来了严重的环境问题。自 2010 年底以来，几次大范围的严重的空气污染事件，将中国空气污染问题带入了人们的视线。伴随着大量的空气污染健康有关研究，这些污染事件同时也加速了我国在空气污染预防与控制方面的政策出台。对这些政策的进展和面临的挑战进行评估能够对下一阶段（十三五）提高我国的空气污染控制效率提供良好的借鉴。评估这些大气污染控制政策带来的健康效益，能够促成更具有战略意义的健康预防和保护措施。而这些评估的实施很大程度上依助于对空气污染健康效益的深入研究。更具体来说，大气污染与健康的关系在不同的社会经济水平和个体特征背景下存在差异性，研究这些差异性能够帮助确定脆弱区域和脆弱人群，进而对这些高风险人群采取特殊预防和保护措施，进而获得政策健康收益的最大化。

本论文通过一系列独立的科学文章来阐述空气污染与健康的关系，并探索了中国（以京津冀为研究案例）近阶段大气污染防治行动计划的执行进展和面临的挑战。此论文共有三个总体目标：

1. 研究空气污染与健康的关系。通过纳入区域社会经济水平等因子，确定空气污染与人群健康风险关系在空间上的差异性，确定脆弱区域；通过时间序列模型，确定空气污染和人群健康风险关系在个体特征方面的差异性，确定脆弱人群;
2. 确定我国近期出台的空气污染预防与控制策略的进展和挑战。对京津冀地区在主要污染排放源（工业和交通）方面进行的污染排放控制措施进行评估，分析了其存在的问题、面临的挑战和政策的可持续性并提出建议;
3. 探索空气污染决策的健康效益。基于欧洲的经验，评估空气污染控制策略的健康收益和健康均衡收益。并探讨空气污染政策的健康收益评估方面的研究方法和健康指标，为空气污染控制政策提供更好的科学依据。

第一章首先介绍了中国和欧洲城市化进程和其背景下的空气污染状况，随后参考大量流行病学研究，介绍了空气污染对健康的影响并展示了不同空气污染物对健康的主要影响机制。同时进一步阐述了我国在大气污染控制方面采取的措施。鉴于欧洲曾经（甚至现在）面临严重的空气污染问题，且在空气污染控制方面积累了较多的经验，本章节同时提出了中国和欧洲在空气污染控制方面和健康风险应对方面存在的差异性和相似性。章节的最后提出了本论文的研究目的和研究内容。

确定脆弱区域和脆弱人群对于制定空气污染预防和控制措施来说至关重要。相应的，第二章和第三章回答了空气污染在空间和时间维度如何影响健康及其对健康的影响程度。第二章采用了地理加权回归模型，确定了空气污染健康风险在空间维度的差异性，并探讨了社会经济水平对此差异性的影响。结果表明，空气污染对预期寿命和长寿人群的影响在中国西南部更为明显，而这些地方的污染水平相对较低，社会经济发展水平相对较低。从方法学上来说，这是初次研究空气污染与健康在空间上的相关性。第三章以深圳为研究区域，采用时间序列分析了臭氧对呼吸系统和心脑血管死亡率的影响。通过校正气象条件和其他污染物因子后，结果表明老年人（65 岁以上）和男性对臭氧的敏感度明显高于其他人群。

第四章采用系统综述，评价了欧洲近期大气污染控制政策的健康效益和健康均衡收益。指出了将科研成果转换为政策并将政策服务于健康的研究的必要性和重要性。该研究将近期欧洲主要的大气污染控制划分为总体污染物排放控制政策、交通污染排放控制政策、能源有关污染排放控制政策和缓减气候变化控制温室气体排放政策。无论作为直接效益还是间接效益，此四类政策均获得了中度和良好的空气质量提升和相应的健康收益。表明在大气污染控制中，有潜力也有可能采纳世界卫生组织提倡的"所有公共政策皆将健康纳入考量（Health in All Policies）"。该章节进一步讨论了空气污染控制政策进行健康效益评估研究中的健康指标选取和研究方法。该章节通过对欧洲近期空气污染治理政策及健康效应的系统研究，为中国空气污染治理提供理论和实践的借鉴。

自 2013 年以来，中国政府颁布了自此为止最为严格的大气污染控制方法“大气污染防治行动计划（2013-2017）”，将中国大气污染防治带入了一个“提高阶段”。在此背景下，探索该行动计划的执行进展和其持久性对我国下一阶段的大气污染防治至关重要。第五章阐述了行动计划在京津冀地区的执行情况和遇到的挑战。研究结果表明：空气污染防治行动计划改善了区域空气质量，但其效果有限且区域分布不均衡。在交通和工业污染排放控制方面和区域协作污染控制方面，仍存在大量挑战。更具体来说，这些挑战包括：执行层面的监测和监督不力；因利益不均和强制执行而导致的潜在的区域冲突；巨大的社会成本，包括失业和社会不公平。导致这些挑战的因素有很多。首先，地方政府在执行污染控制行动中将经济发展远凌驾于环境保护之上。其次，政策的制定和执行过程中，利益相关方（包括各级政府层面和部门层面）的参与度不够。最后，虽然空气污染控制直接的法律法规都已充足，但缺乏强有力且细化的法律法规来明确不同利益相关方的权责，特别针对经济发展与环保的冲突、地方政府之间的利益冲突、政府与企业之间的利益冲突。文章最后为制定良好的决策和执行方式提供了意见。

第六章总结并讨论了前五章的研究成果，阐述了各章节在空气污染和健康研究领域的附加价值，并提出了本论文对空气污染和健康领域在科研和决策方面的影响和意义。

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PERSONAL CV

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Li Wang was born on the 21st September 1985 (Chinese lunar calendar) in Shaanxi province, China. She obtained her Bachelor of Science degree in Beijing Forestry University in 2008, and in 2011, she achieved her Master of Sciences degree in the Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing, China. From 2011 to 2014, she was working as a research assistant in the Institute of Geographical Sciences and Natural Resources Research. In between, she applied a PhD program in Maastricht University, got the funding from Maastricht University for one year, and started her PhD. In 2014, she received a 3-year funding from the Chinese Scholarship Council (CSC), and moved to Maastricht University. Throughout her PhD trajectory, she was involved in several research projects including air pollution and health in China, health equity from environment perspective, and Sino-Dutch collaboration on infectious diseases syndromic surveillance. In the meanwhile, she participated and organized various international conferences.

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