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Ambient air pollution, climate change, and population health in China

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ABSTRACT

As the largest developing country, China has been changing rapidly over the last three decades and its economic expansion is largely driven by the use of fossil fuels, which leads to a dramatic increase in emissions of both ambient air pollutants and greenhouse gases (GHGs). China is now facing the worst air pollution problem in the world, and is also the largest emitter of carbon dioxide. A number of epidemiological studies on air pollution and population health have been conducted in China, using time-series, case-crossover, cross-sectional, cohort, panel or intervention designs. The increased health risks observed among Chinese population are somewhat lower in magnitude, per amount of pollution, than the risks found in developed countries. However, the importance of these increased health risks is greater than that in North America or Europe, because the levels of air pollution in China are very high in general and Chinese population accounts for more than one fourth of the world's totals. Meanwhile, evidence is mounting that climate change has already affected human health directly and indirectly in China, including mortality from extreme weather events; changes in air and water quality; and changes in the ecology of infectious diseases. If China acts to reduce the combustion of fossil fuels and the resultant air pollution, it will reap not only the health benefits associated with improvement of air quality but also the reduced GHG emissions. Consideration of the health impact of air pollution and climate change can help the Chinese government move forward towards sustainable development with appropriate urgency.

China is the largest developing country, and its economic expansion over the past decades has been one of the strongest in the world history (Fig. 1). Such an economic expansion, however, is largely driven by the use of fossil fuels, which leads to a dramatic increase in emissions of both ambient pollutants and greenhouse gases (GHGs). China is now facing the worst air pollution problem in the world (Kan et al., 2009). Meanwhile, China surpassed the United States as the country emitting the most carbon dioxide (CO_2) in 2007 (International Energy Agency, 2009), although emissions per head in China are still at the global average. China is also a large emitter of methane and black carbon, the other two major GHGs contributing to global warming. Ambient air pollution and climate change are placing Chinese residents at significant health risks.

This article systemically reviewed up-to-date epidemiologic evidence of ambient air pollution, climate change and population health in China. This review focused primarily on literature published since 2000, although some earlier studies were referenced to provide a context. First, we characterized the level and trend of outdoor air pollution in China; second, we extensively reviewed the health effects of short-term and long-term exposures to air pollution, including air pollution from special sources such as vehicle emissions and sand dust storm; third, we reviewed the current evidence of the health impacts of climate change; fourth, we discussed the air pollution health co-benefit studies of reducing GHG emissions in China; lastly, we discussed the challenges China faces in the assessment of the health effects of air pollution and climate change across the country.

1. Level and trend of outdoor air pollution in China

With growing energy consumption and rapid urbanization, an increase in ambient air pollution seemed inevitable. However, ambient air quality in Chinese cities has remained stable or even improved slightly over recent years, through relocation of polluting industries, switching to less polluting fuels, enforcement of zoning regulations, stricter emission standards for mobile and stationary sources, better city planning, and increased investments in city infrastructure construction.

Coal is still the major source of energy in China, constituting about 75% of all energy sources. Consequently, air pollution in China predominantly consists of coal smoke, with suspended particulate matter (PM) and sulfur dioxide (SO_2) as the principal air pollutants. In Chinese cities, however, with the rapid increase in the number of motor vehicles, air pollution has gradually changed from the conventional coal combustion type to the mixed coal combustion/

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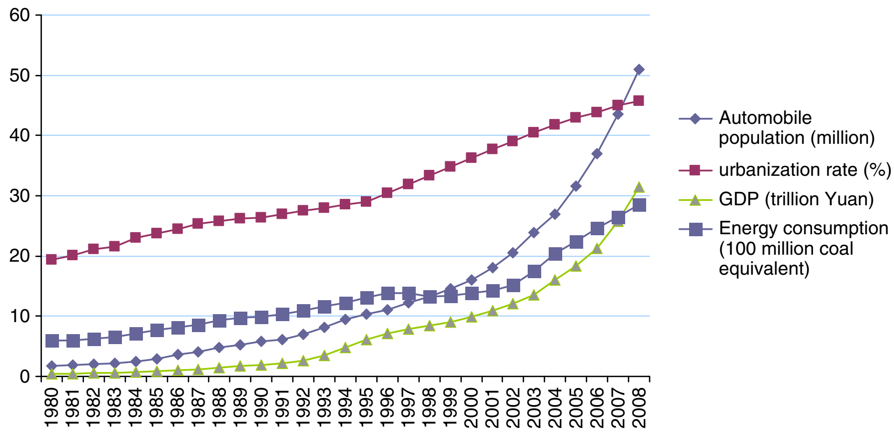

Fig. 1. Automobile population number, urbanization rate, GDP and energy consumption in China in 1980–2008.

motor vehicle emission type. Although ambient air quality in China has slightly improved in the recent decades, China is still one of the countries with the worst air quality globally. Megacities such as Beijing, Shanghai, and Chongqing are frequently among the cities with the highest levels of air pollutants in the world (Watts, 2005).

Currently, inhalable particles (particles less than 10 μm in aerodynamic diameter, or PM_{10}), SO_2 and nitrogen dioxides (NO_2) are the criteria pollutants in China. Results from routine monitoring of 621 cities in 2009 revealed that the air quality in 107 cities (17% of the total) did not meet the country's national ambient air quality standards (NAAQS) (Chinese Ministry of Environmental Protection, 2010). According to China Ministry of Environmental Protection, the annual average concentrations in 113 major Chinese cities in 2009 were 87 μg/m^3 for PM_{10}, 42 μg/m^3 for SO_2, and 38 μg/m^3 for NO_2 (Chinese Ministry of Environmental Protection, 2010).

Fig. 2 shows the decreasing trend of PM_{10} and SO_2 concentrations in 31 Chinese provincial cities since 2001, while nitrogen dioxides (NO_2) levels have remained stable with minor fluctuations. Compared with the Global Air Quality Guidelines set by World Health Organization (PM_{10} annual average: 20 μg/m3), the PM_{10} levels in Chinese cities are much higher.

Generally, suspended particulate concentration levels in the north China are higher than those in the south, while SO_2 concentration levels do not differ much (Chan and Yao, 2008). Air pollution in winter is generally more serious than that in summer because most residents use coal for heating during winter.

In recent years, the "gray sky" phenomenon caused by fine particle (particles less than 2.5 μm in aerodynamic diameter, or $PM_{2.5}$) is an increasing public concern, and $PM_{2.5}$ predominately existing in urban areas has posed a serious health risk to Chinese residents. $PM_{2.5}$ has not yet been a routinely monitored air pollutant in most Chinese cities. Recognizing the significant health impact of $PM_{2.5}$, some studies on its pollution levels have been carried out. However, these studies were conducted in only a number of cities (Guangzhou, Wuhan, Lanzhou, Chongqing, Shanghai and Beijing) at different times (from 1995 to 2007) (Duan et al., 2006; Guo et al., 2009; Kan et al., 2007a; Zhang et al., 2002). The reported annual average concentrations of $PM_{2.5}$ in the 2000s were in the range of 56 to 122 μg/m^3. In Beijing, for example, the annual average $PM_{2.5}$ concentrations in 2001–2004 ranged from 96.5 to 106.7 μg/m^3 (Duan et al., 2006), which was approximately seven times the ambient air quality standard recommended by the US Environmental Protection Agency (15 μg/m^3) and ten times the WHO Global Air Quality Guideline (AQG) (10 μg/m^3). In Shanghai, the annual average $PM_{2.5}$ concentrations in 2005 reached 56 μg/m^3, which was also much higher than the WHO AQG (Kan et al., 2007a). There is an on-going plan to include $PM_{2.5}$ as a routine pollutant in air quality monitoring network in Chinese cities.

Ozone (O_3) is not a routinely monitored air pollutant in most Chinese cities either. A few studies reported that the 24 h average concentrations of O_3 in Beijing, Tianjin, Guangzhou, Jinan and Quanzhou were in the range of 60–99 μg/m^3 during 1983–2005 (Su et al., 1987; Wang et al., 2003a,b; Wu and Huang, 2006; Yin et al., 2006), while the 8 h maximum average concentrations of O_3 in Shanghai and Wuhan were in the range of 63–78 μg/m^3 during 2001–2008 (Qian et al., 2007a; Wong et al., 2008).

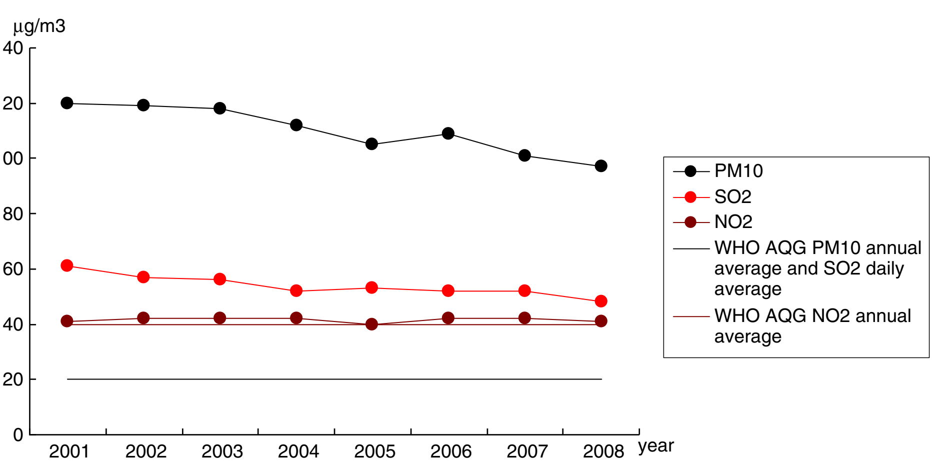

Fig. 2. Ambient air pollution levels in 31 provincial capitals of China (μg/m^3, 2001–2008)* (Data source: China Environment Yearbook 2002–2009). *WHO: World Health Organization; WHO did not set up the annual average standard for SO_2 in the Global Air Quality Guideline (AQG).

In summary, it is quite apparent that during the unprecedented rapid economic development in China, air pollution levels have been kept stable and even declined slightly. However, air pollution levels in China are still at the higher end from a global perspective. Given that ambient monitoring data are often insufficient in China, satellite remote sensing may offer a promising prospect for providing additional information on exposure to air pollution in the country (van Donkelaar et al., 2010).

2. Health impact of ambient air pollution exposure in China

Ambient air pollution is one of the major public health concerns in China. Zhang et al. (2008) calculated the health effects of PM_{10} in 111 Chinese cities which covered most large and medium-sized Chinese cities and accounted for more than 70% gross domestic product (GDP) in China, and estimated that the total economic cost caused by PM_{10} pollution was approximately US$ 29,179 million in 2004.

A number of air pollution health studies have been conducted in China since 1990s (Fig. 3), which include changes in mortality of all causes and of cardiopulmonary disease, and morbidity, as well as number of out-patients and emergency room visits (Chen et al., 2004). The relationships between air pollution and respiratory and other clinical symptoms, lung functions and immune functions have also been assessed. Generally, time-series or case cross-over studies captured the acute effects of air pollution by examining the association between daily mortality (or morbidity) and daily or multi-day changes in air pollution, while the cohort and cross-sectional studies revealed that long-term exposure to air pollution might lead to an increased risk of health hazards in the population. Several panel studies in China examined the short-term association between air pollution and sub-clinical parameters. However, compared to relatively complete air monitoring data, data on the association between air pollution and human health are limited in China. Scarcity of data on $PM_{2.5}$ and O_3 in most Chinese cities further hinders the value of such studies.

2.1. Short-term health effects of air pollution

2.1.1. Air pollution and daily mortality

The total and cause-specific mortality is often considered the most important health endpoint associated with air pollution. To assess the association between short-term exposure to air pollution and daily mortality, a number of time-series and case-crossover studies have been conducted in large Chinese cities, including Beijing, Shanghai, Chongqing, Shenyang, Wuhan, and Anshan etc.

Beijing is the capital of China and is also famous for its air pollution problem. Chang et al. (2003) conducted a time-series analysis to examine the association of air pollution [CO, SO_2, NO_x, total suspended particle (TSP), and PM_{10}] and daily mortality in Beijing. Single-factor Poisson regression analysis showed that there were significant positive associations between the five pollutants and daily mortality except for the relationship between TSP and coronary heart disease (CHD) deaths. In multi-pollutant regression analysis, each 10 μg/m^3 increase of SO_2 corresponded with 0.4% increase of respiratory mortality and 0.4% increase of cardiovascular mortality. Meanwhile, each 10 μg/m^3 increase of TSP was associated with 0.3% increase of respiratory mortality and 0.1% increase of cardiovascular mortality.

Shanghai is the economic center of China. As a component of the *Public Health and Air Pollution in Asia* (PAPA) program (Wong et al., 2008), Kan et al. (2008a) assessed the relationship between outdoor air pollution (PM_{10}, SO_2, and NO_2) and daily mortality in 2001–2004 in Shanghai. Air pollution was found to be associated with mortality from all causes and from cardiorespiratory diseases in Shanghai. An increase of 10 μg/m^3 of PM_{10}, SO_2, and NO_2 corresponded to increases in all-cause mortality of 0.25% [95% confidence interval (CI): 0.14%, 0.37%], 0.95% (95% CI: 0.62%, 1.28%), and 0.97% (95% CI: 0.66%, 1.27%), respectively. This study also provided additional insight into how factors might modify the estimated relative risk of health effects of air pollution. For example, the effects of air pollutants seemed to be more evident in the cool season than in the warm season, and females and the elderly were more vulnerable to outdoor air pollution. Effects of air pollution were generally greater in residents with low educational attainment (e.g. illiterate or primary school) compared with those with high educational attainment (e.g. middle school or above).

Another PAPA study explored the short-term association between air pollution and daily mortality in Wuhan (Qian et al., 2007a,b). Using 4 years of data (2001–2004), Qian et al. (2007a,b) examined the associations of daily cause-specific mortality with daily mean concentrations of PM_{10}, SO_2, NO_2 and O_3 in Wuhan. Each 10 μg/m^3 increase in PM_{10} was significantly associated with an increase in total non-accidental (0.36%; 95% CI: 0.19%, 0.53%), cardiovascular (0.51%; 95% CI: 0.28%, 0.75%), stroke (0.44%; 95% CI: 0.16%, 0.72%), cardiac (0.49%; 95% CI: 0.08%, 0.89%), respiratory (0.71%; 95% CI: 0.20%, 1.23%), and cardiopulmonary (0.46%; 95% CI: 0.23%, 0.69%) mortalities (Qian et al., 2007b). Each 10 μg/m^3 increase of NO_2 was associated with an increase in total non-accidental (1.43%; 95% CI: 0.87%, 1.99%), cardiovascular (1.65%; 95% CI: 0.87%, 2.45%), stroke (1.49%; 95% CI: 0.56%, 2.43%), cardiac (1.77%; 95% CI: 0.44%, 3.12%), respiratory (2.23%; 95% CI: 0.52%, 3.96%), and cardiopulmonary mortalities (1.60%; 95% CI: 0.85%, 2.35%) (Qian et al., 2007a). SO_2 and O_3 were not associated with daily mortality. The exposure–response relationships demonstrated heterogeneity, with some curves showing nonlinear relationships for SO_2 and O_3.

Chongqing is a major city in western China and one of the China's four municipalities directly governed by the central government in China (the other three are Beijing, Shanghai and Tianjin). Chongqing is known for its foggy weather and suffers from heavy air pollution. Daily mortality in a district of Chongqing was analyzed from January through December of 1995 using daily ambient $PM_{2.5}$ and SO_2 data (Venners et al., 2003). The daily mean concentrations of $PM_{2.5}$ and SO_2 were 147 μg/m^3 (n = 213, maximum = 666 μg/m^3) and 213 μg/m^3 (n = 365, maximum = 571 μg/m^3), respectively. Each 10 μg/m^3 increase of SO_2 was associated with 0.4% (95% CI: 0.0%, 0.9%) increase of total mortality, 1.1% (95% CI: 0.2%, 2.2%) increase of respiratory mortality, and 1.0% (95% CI: 0.2%, 2.0%) increase of cardiovascular mortality. The associations between daily mortality and $PM_{2.5}$ were negative and statistically insignificant. Interestingly, the estimated effects of SO_2 on cardiovascular and respiratory mortality risk remained after controlling for $PM_{2.5}$. Compared with SO_2, there were less daily measurements of $PM_{2.5}$, and thereby the researchers had less statistical power to detect the association between $PM_{2.5}$ and mortality. This is also one of the only four population-based studies in China examining the health effects of $PM_{2.5}$ (Guo et al., 2009; Kan et al., 2007a; Venners et al., 2003; Guo et al., 2010a).

Shenyang, a heavily industrialized city, is the capital of Liaoning Province, which is located in northeastern China. Xu et al. (2000)

- ✓ **Short-term exposure studies:**
  - ■ Time-series/case crossover studies
    - ◆ Single-city analysis: Beijing, Shanghai, Chongqing, Shenyang, Wuhan, Anshan, etc
    - ◆ Multi-city analysis: PAPA
  - ■ Panel study: Beijing
- ✓ **Long-term exposure study**
  - ■ Cohort study: China National Hypertension Survey and its follow-up study
  - ■ Ecological study: Beijing, Shenyang, Guangzhou

Fig. 3. A summary of air pollution epidemiologic studies in China.

analyzed daily mortality data in Shenyang to identify possible associations with ambient SO_2 and TSP. During the study period, both TSP concentrations (mean = 430 μg/m^3, maximum = 1,141 μg/m^3) and SO_2 concentrations (mean = 197 μg/m^3, maximum = 659 μg/m^3) far exceeded the WHO's recommended criteria. The association with TSP was statistically significant for cardiovascular mortality, but not for mortality from chronic obstructive pulmonary disease (COPD). In contrast, SO_2 was statistically significantly associated with mortality from COPD, but not with cardiovascular mortality. As the comparison, the mortality from cancer was not significantly associated with TSP or with SO_2.

Anshan is a heavily-polluted industrial city in northeastern China. Chen et al. (2010a) conducted an individual-level time-stratified case-crossover analysis to examine the association between air pollution and daily mortality in Anshan. Time-stratified case-crossover approach was used to estimate the effects of air pollutants (PM_{10}, SO_2, NO_2 and CO) on total and cardiopulmonary mortalities. As the results, significant associations were found between air pollution and cardiovascular mortality. Each 10 μg/m^3 elevation of PM_{10}, SO_2, NO_2 and CO corresponded to 0.67% (95% CI: 0.29%, 1.04%), 0.38% (95% CI: −0.06%, 0.83%), 2.11% (95% CI: 0.22%, 4.00%) and 0.04% (95% CI: 0.01%, 0.07%) increase of cardiovascular mortality, respectively. The associations for total and respiratory mortalities were generally positive but statistically insignificant. The air pollution health effects in Anshan were significantly modified by age, but not by gender. To our knowledge, this is the first individual-level analysis of air pollution short-term effects in China to date.

Few studies in China assessed the health effects of O_3 due to a lack of monitoring data. Given the changes in air pollution patterns from conventional coal combustion to the mixed coal combustion/motor vehicle emissions in China's large cities, it is worthwhile investigating the association between O_3 and mortality in the country. Based on the PAPA database, Zhang et al. (2006) conducted a time-series study to investigate the relation between O_3 and daily mortality in warm and cold seasons in Shanghai using 4 years of daily data (2001–2004). An increase of 10 μg/m^3 of O_3 corresponded to 0.45% (95% CI: 0.16%, 0.73%), 0.53% (95% CI: 0.10%, 0.96%), and 0.35% (95% CI: −0.40%, 1.09%) increase of total, cardiovascular, and respiratory mortality, respectively. In the cold season, the effect estimates increased to 1.38% (95% CI: 0.68%, 2.07%), 1.53% (95% CI: 0.54%, 2.52%), and 0.95% (95% CI: −0.71%, 2.60%), respectively. In the warm season, the authors did not observe a significant association for cardiovascular mortality. Multi-pollutant models indicated that the association between O_3 and mortality was not confounded by PM_{10} or by SO_2; however, after adding NO_2 into the model, the association of O_3 with cardiovascular mortality became statistically insignificant.

$PM_{2.5}$ and coarse particle ($PM_{10-2.5}$) are not yet the criteria air pollutants in China, and their monitoring data are scarce. Few epidemiological studies in China assessed the health effects of $PM_{2.5}$ and $PM_{10-2.5}$ simultaneously. Kan et al. (2007a) conducted a time-series study to differentiate the acute health effects of $PM_{2.5}$ and $PM_{10-2.5}$ in Shanghai from March 4, 2004 to December 31, 2005. The daily mean concentrations of $PM_{2.5}$ and $PM_{10-2.5}$ were 56.4 μg/m^3 and 52.3 μg/m^3 in the study period, respectively, and $PM_{2.5}$ constituted around 53.0% of the total PM_{10} mass. Each 10 μg/m^3 increase of $PM_{2.5}$ corresponded to 0.36% (95% CI: 0.11%, 0.61%), 0.41% (95% CI: 0.01%, 0.82%) and 0.95% (95% CI: 0.16%, 1.73%) increase of total, cardiovascular and respiratory mortalities, respectively. For $PM_{10-2.5}$, the effects were attenuated and less precise. Given the inconsistent findings on $PM_{2.5}$ and daily mortality in Chongqing (Venners et al., 2003) and Shanghai, more studies are needed to investigate the health impact of $PM_{2.5}$ in China.

Ambient air pollution is a complex mixture composed of both solid particles and gaseous pollutants. Identification of the specific pollutants contributing most to the health hazard of the air pollution mixture may have important implications for environmental and social policies. Although the strongest evidence between outdoor air pollutants and adverse health effects is for solid particulates (e.g. PM_{10}) (Pope and Dockery, 2006), many researchers have reported associations for gaseous pollutants in China. For example, in Beijing (Xu et al., 1994) and Chongqing (Venners et al., 2003), it was SO_2, but not TSP nor $PM_{2.5}$, that was significantly associated with daily mortality. This controversy may reflect the different characteristics of the study sites as well as differences in analytic techniques used in various studies. It is also worth noting that the observed health effects attributed to the ambient gaseous pollutants, e.g. SO_2 and NO_2, might result from exposures to particles (Sarnat et al., 2005). Furthermore, in contrast to studies conducted in North America, some Chinese studies reported associations for gaseous pollutants independent of particles (Qian et al., 2007a; Kan et al., 2008a), suggesting that factors other than particle indicators are important for the air pollution mixture in China. At present, we cannot conclude that SO_2 and NO_2 are proxies of particles or the components of particles, and SO_2 and NO_2 may have a direct short-term effect on mortality in China. However, a consistent, significant effect of SO_2 and NO_2 on mortality observed in Chinese literature suggests that the role of outdoor exposure to gaseous pollutants may differ from that in other parts of the world and is worth further investigation.

2.1.2. Air pollution and morbidity

Few Chinese cities have established a city-wide morbidity reporting system, and consequently existing data on the association between air pollution and daily morbidity are quite limited. Several recent studies have made use of the health insurance system data and examined the short-term association of air pollution with hospital admissions, outpatient visits, and emergency room (ER) visits (Cao et al., 2009; Chen et al., 2010b). Other morbidity studies relied on the visit records from a single hospital (Guo et al., 2009, 2010a,b).

In Shanghai, Chen et al. (2010b) conducted a time-series analysis to examine the association of outdoor air pollutants (PM_{10}, SO_2, and NO_2) with both total and cause-specific hospital admissions in Shanghai, using daily data recorded during 2005–2007. Hospital admission data were collected from the Shanghai Health Insurance Bureau. Ambient air pollution was found to be associated with increased risks of total and cardiovascular hospital admissions in Shanghai. A 10 μg/m^3 increase of PM_{10}, SO_2 and NO_2 corresponded to 0.18% (95% CI: −0.15%, 0.52%), 0.63% (95% CI: 0.03%, 1.23%), and 0.99% (95% CI: 0.10%, 1.88%) increase of total hospital admissions; and 0.23% (95% CI: −0.03%, 0.48%), 0.65% (95% CI: 0.19%, 1.12%), and 0.80% (95% CI: 0.10%, 1.49%) increase of cardiovascular hospital admission, respectively. Consistent with the air pollution mortality study in Shanghai (Kan et al., 2008a), the associations between air pollution and hospital admissions were stronger in the cool season (from November to April) than in the warm season (from May to October). To our knowledge, this is the only analysis in China which has examined the effect of air pollution on hospital admissions.

Using the same dataset from the Shanghai Health Insurance Bureau, Cao et al. (2009) examined the association of outdoor air pollutants with hospital outpatient and emergency room visits. The results show that SO_2 and NO_2 were associated with an increased risk of hospital outpatient and emergency room visits. A 10 μg/m^3 increase in concentration of PM_{10}, SO_2 and NO_2 corresponded to 0.11% (95% CI: −0.03%, 0.26%), 0.34% (95% CI: 0.06%, 0.61%) and 0.55% (95% CI: 0.14%, 0.97%) increase of outpatient visit; and 0.01% (95% CI: −0.09%, 0.10%), 0.17% (95% CI: 0.00%, 0.35%) and 0.08% (95% CI: −0.18%, 0.33%) increase of emergency room visit, respectively. Similar to the hospital admission findings, the associations appeared to be stronger in the cool season than in the warm season.

Guo et al. (2009) explored the association between $PM_{2.5}$ and hospital ER visits for cardiovascular disease in Beijing. Daily data of hospital ER visits for cardiovascular disease were collected from the Peking University Third Hospital. A time-stratified case-crossover design was used to evaluate the association. After adjustment for the temperature and relative humidity, a 10 μg/m^3 increase in $PM_{2.5}$, SO_2, and NO_2 was statistically significantly associated with hospital ER visits for cardiovascular diseases, with odds ratios (ORs) of 1.005 (95% CI: 1.001, 1.009), 1.014 (95% CI: 1.004, 1.024), and 1.016 (95% CI: 1.003, 1.029), respectively. However, selection bias might exist in this study because the authors used hospital records only from one hospital, $PM_{2.5}$ from one monitor station, and average concentrations of SO_2 and NO_2 from eight sites.

Hypertension is the most important risk factor for cardiovascular mortality in China (He et al., 2009). However, few studies have examined the impact of air pollution on morbidity for hypertension. Guo et al. (2010a,b) examined the association between air pollution and ER visits for hypertension in Beijing using a time-stratified case-crossover design. As the result, an increase in 10 μg/m^3 of $PM_{2.5}$, PM_{10}, SO_2 and NO_2 was associated with ER visits for hypertension with odds ratios of 1.084 (95% CI: 1.028, 1.139), 1.060 (95% CI: 1.020, 1.101), 1.037 (95% CI: 1.004, 1.071), and 1.101 (95% CI: 1.038, 1.168), respectively.

2.2. Long-term health effects of air pollution

Daily time-series and case-crossover studies continue to suggest short-term acute effects of air pollution but provide little information about the degree of life shortening, pollution effects on long-term mortality or morbidity, and role of pollution in inducing or accelerating the progress of chronic diseases (Kunzli et al., 2001). Several prospective cohort studies in North America and Europe have evaluated the effects of long-term exposure to outdoor air pollution on mortality (Pope and Dockery, 2006). However, it is unknown whether the findings from low air pollution exposure settings in developed countries are applicable to China, where characteristics of outdoor air pollution and socio-demographic status of local residents are different from those in developed countries.

Compared with association studies of short-term effect, there are even fewer studies in China examining the association between long-term exposure to air pollution and human health. So far, there has been only one published air pollution cohort study in China (Cao et al., 2011). Meanwhile, some ecological mortality evidence exists from which we can also draw some preliminary conclusions about potential long-term health effects of air pollution (Tie et al., 2009; Wang et al., 2003a,b; Zhang et al., 2000). Of course, the results of these ecological analyses are difficult to interpret, due to the lack of information on some key potential confounders (e.g. smoking, diet, or socioeconomic status).

2.2.1. Air pollution cohort study

Cao et al. (2011) conducted a cohort study to examine the association between outdoor air pollution and mortality in 70,947 middle-aged men and women of the China National Hypertension Survey and its follow-up study (Cao et al., 2011). The baseline survey and follow-up evaluation were conducted in 1991 and 2000. Air pollution exposures, including TSP, SO_2 and NO_x, were estimated by linking fixed-site monitoring data with resident zip code. Significant associations were found between air pollution levels and mortality from cardiopulmonary diseases and lung cancer. An increase of 10 μg/m^3 of TSP, SO_2, and NO_x corresponded to 0.3% (95%CI: −0.1%, 0.6%), 1.8% (95%CI: 1.3%, 2.3%), and 1.5% (95%CI: 0.4%, 2.5%) increase of total mortality, respectively. Compared with air pollution long-term effects studies in developed countries (Pope and Dockery, 2006), this Chinese cohort study reported relatively lower effect estimates per unit increase of pollutant concentrations. This cohort study strengthened the assumption that lower exposure–response functions may exist in Chinese air pollution studies compared with those conducted in North American and Europe (Aunan and Pan, 2004). Interestingly, significant effects of SO_2 on mortality were found even after adjustment for TSP. The sensitivity analysis using quartiles of air pollutants concentrations showed that exposure–response relationships between TSP/NO_x and cardiovascular mortality tended to become flat at high concentrations, while SO_2 had an almost monotonic relationship with cardiovascular mortality.

Lung cancer is a serious health problem in China, as in many parts of the world. Since the 1970s, lung cancer mortality has drastically increased in China (He et al., 2005). Although cigarette smoking is the principal risk factor for this epidemic, a body of epidemiological evidence indicates an association between outdoor air pollution and lung cancer (Cohen, 2000). In this cohort study, an increase of 10 μg/m^3 in TSP, SO_2, and NO_x corresponded to 1.1% (95%CI: −0.1%, 2.3%), 4.2% (95%CI: 2.3%, 6.2%), and 2.7% (95%CI: −0.9%, 6.5%) increase of lung cancer mortality, respectively, after adjustment for potential confounders including smoking.

This cohort study contributes to better understanding of the long-term health effects of air pollution in high exposure settings — typical in developing countries. One major limitation of the study was that the air pollutants considered were limited to TSP, SO_2, and NO_x only, due to the limitation of monitoring data in the research period. Future cohort studies in China should consider the long-term health effects of $PM_{2.5}$ and ozone.

2.2.2. Ecological studies

In Beijing, Zhang et al. (2000) conducted a cross-sectional analysis to examine the relationship between long-term exposure to ambient air pollution and mortality. Data on environmental pollution levels and related factors, population size and number of deaths were collected from the eight districts in Beijing from 1980 to 1992. SO_4^{2-} was selected as a main indicator of air pollution, because SO_4^{2-} levels were significantly correlated with daily mean concentrations of SO_2 and NO_2, annual coal combustion, number of households using gas fuel, counts of motor vehicles and population density in Beijing. Statistically significant correlations were found between SO_4^{2-} concentration and mortality from cardiovascular disease, malignant tumor and lung cancer (correlation coefficients$>$0.50 in all cases). Moreover, the correlations were not only found for the current SO_4^{2-} concentration, but also for SO_4^{2-} levels up to 12 years prior to death, which may suggest long-term effects of air pollution.

In Shenyang, Wang et al. (2003a,b) examined the chronic effects of air pollution on cardiovascular mortality with an ecologically cross-sectional analysis. Across the whole city, the annual daily averages for TSP in the high-, medium-, and relatively low-pollution areas were 518, 477, and 361 μg/m^3, respectively; and for SO_2 were 235, 128, and 64 μg/m^3, respectively. The result showed that there were significant differences in mortality of cerebrovascular and cardiovascular diseases among these areas.

In Guangzhou, Tie et al. (2009) analyzed 52-year historical surface measurements of haze data, and found that the dramatic increase in the occurrence of air pollution events between 1954 and 2006 had been followed by an increase in the incidence of lung cancer. When a time lag of 7 years was adopted, there was an increased correlation between air pollution and lung cancer mortality.

High polycyclic aromatic hydrocarbons (PAHs) air concentrations have been shown to induce heritable mutations. Zhang et al. (2009) estimated ambient air concentrations of BaP at ground level nationwide using the validated Euler atmospheric transport model, and then estimated that the overall population attributable fraction (PAF) for lung cancer caused by inhalation exposure to PAHs was 1.6%, corresponding to an excess annual lung cancer incidence rate of 0.65×10^{-5}.

2.3. Air pollution intervention study

Air pollution intervention study provides evidence regarding the potential health benefits from specific intervention-induced reduction in air pollution. A unique opportunity emerged during the 2008 Beijing Olympic Games when the air quality in Beijing was significantly improved due to unprecedented efforts taken at that time in Beijing and surrounding regions. Health benefits gained from the improvement of air quality were observed not only in high-risk vulnerable groups but also in young, healthy adults.

Li et al. (2010) analyzed outpatient asthma visits at Beijing Chaoyang Hospital during the 2008 Beijing Olympic Games. The daily average $PM_{2.5}$ concentrations were 46.7 and 78.8 μg/m^3 during the Olympics and baseline period, respectively. There were 7.3 outpatient asthma visits per day during Olympic Games as compared with 12.5 visits per day at baseline [relative risk (RR) 0.54; 95%CI: 0.39, 0.75]. The authors concluded that even in a heavily-polluted city, decreased concentrations of $PM_{2.5}$ were associated with certain reduction in asthma visits in adults.

During the drastic air pollution changes accompanying the 2008 Olympics, a major panel study was conducted before, during and after the Beijing Olympics to examine air pollution effects on oxidative and nitrosative stress and other mechanistic pathways (Kipen et al., 2010). This on-going study may lead to a clearer and more precise role of oxidative and nitrosative stress, as well as other mechanisms, in determining acute morbidity and mortality from exposure to air pollution.

Wu et al. (2010) conducted a panel study to evaluate the relationship between traffic-related $PM_{2.5}$ exposure and heart rate variability (HRV) in a highly-exposed panel of young healthy adults (taxi drivers) for a 12-hour work shift before, during and after the 2008 Beijing Olympic Games. The daily averages of real-time $PM_{2.5}$ exposure before, during and after the Olympics were 95.4, 39.5 and 64.0 μg/m^3, respectively. The authors observed marked changes of HRV in these taxi drivers in the three time periods. The reduced PM air pollution in Beijing during the Olympic Games improved the HRV even in young healthy adults. The changes suggested a complicated mechanism through which the cardiac autonomic system responds to $PM_{2.5}$ exposure.

2.4. Health effects of air pollution from special sources

2.4.1. Traffic-related air pollution

Accompanied with the rapid socioeconomic development, the number of motor vehicles increases drastically in urban China, and exhaust gas emissions are becoming one of the major contributors to urban air pollution (Kan, 2009).

Evidence from epidemiological studies on the health effects of traffic-related air pollutants [nitrogen oxides (NO_x), carbon monoxide (CO), $PM_{2.5}$, O_3 and its precursors] has accumulated in China. However, most of these studies focus on occupationally exposed populations (e.g. traffic policemen, drivers or conductors) and vulnerable population (e.g. children). No Chinese studies examined mortality in relation to transport-related air pollution, which has been well investigated in Western countries (Kan et al., 2008b).

In Shanghai, Zhou et al. (2001) investigated the health effects of occupational exposure to vehicle emissions in 745 bus drivers, conductors, and taxi drivers, compared with 532 unexposed controls. Logistic regression analysis showed that the prevalence rates of respiratory symptoms and chronic respiratory diseases were significantly higher in the exposed group compared with the controls. The adjusted ORs were 1.95 (95% CI: 1.55, 2.46) for throat pain, 3.90 (95% CI: 2.61, 5.81) for phlegm, 1.96 (95% CI: 1.11, 3.46) for chronic rhinitis, and 4.19 (95% CI: 2.49, 7.06) for chronic pharyngitis. Exposure–time–response relationships were found for the prevalence of phlegm and chronic respiratory diseases. However, pulmonary function and blood lead levels were not significantly associated with traffic exposure. These results suggest that occupational exposure to vehicle emissions may induce detectable adverse respiratory disorders.

Children are more susceptible to traffic-related air pollution because of their fast growth and development. Many chemicals from traffic exhaust, such as CO, NO_2, and lead, have been reported to have adverse effects on neurobehavioral functions (Ye et al., 2007). Several studies in China have suggested that traffic exhaust might affect neurobehavioral functions of adults who have been occupationally exposed to traffic exhaust (Liu et al., 2001). Wang et al. (2009) further explored the association between traffic-related air pollution and neurobehavioral function in children in Quanzhou of Fujian Province. Second grade (8–9 years of age) and third grade (9–10 years of age) children of two schools ($n = 928$) participated in a questionnaire survey and manual-assisted neurobehavioral testing in 2005. NO_2 and PM_{10} were monitored as indicators for traffic-related air pollution on the campuses and in classrooms. After controlling for the potential confounding factors, logistic regression analyses showed that participants living in the polluted area performed poorer on all neurobehavioral function testing than others.

Exposure level of PAHs among on-duty traffic police in Beijing was investigated during the summer of 2004 using a personal sampling technique in measuring both particulate and gaseous phase PAHs (Liu et al., 2007). Exposure levels to gaseous and particulate PAHs for the traffic police were found to be 1525 ± 759 ng/m^3 and 148 ± 118 ng/m^3, respectively, representing 2–2.5 times higher levels than those at the control sites. The daily inhalation exposure of the police was estimated to be 277 ng/kg/d. Most of the PAHs exposure came from the vapor phase. Based on calculated PAH diagnostic ratios, the major source of PAHs exposure was from vehicle exhaust.

2.4.2. Sand dust storm

Sand dust storms are common phenomena which occur with great frequency and magnitude over the arid and semi-arid regions of the earth's land sand surface, which is intensified in recent years in northern China (Chen et al., 2003). Airborne PM was very high during the dust events, causing an increasing concern in China from public health's perspective. Toxicological tests in Wuwei and Baotou indicated that sand dust $PM_{2.5}$ can increase in chromosomal aberration frequency, micronucleus induction, oxidative damage, and damage on alveolar macrophages (Geng et al., 2005; Meng and Lu, 2007; Wei and Meng, 2006). These findings suggest that the risk of health effects is likely to be greater during dust storms than other time simply because dust storm PM has a much higher mass concentration levels.

Several time-series studies were conducted in northern China to explore the health effects of dust storms. For example, to allow an opportunity to reduce confounding by anthropogenically derived PM, Meng and Lu (2007) evaluated the health effects of dust events in Minqin, a county where traffic and industry are underdeveloped and dust events are most frequent in China. The health outcome was daily counts of hospitalizations in Minqin (1994–2003) for respiratory and cardiovascular diseases. Dust events were found to be significantly associated with total respiratory hospitalization for both males and females, with RRs of 1.14 (95% CI: 1.01, 1.29) and 1.18 (95% CI: 1.00, 1.41), respectively. Dust events were significantly associated with upper respiratory tract infection (URTI) in males (RR 1.28; 95% CI: 1.04, 1.59), and were significantly associated with pneumonia in males, with an RR of 1.17 (95% CI: 1.00, 1.38). There was also a significant association between dust events and hypertension in males (RR 1.30; 95% CI: 1.03, 1.64). In the season-specific analyses, the associations between the dust events and respiratory and cardiovascular hospitalizations were stronger in spring and in winter, respectively. The observed health effects of dust events were consistent with recent animal and human data showing the cardiorespiratory effects of particulate matter (Brook et al., 2010).

2.5. Meta-analysis of exposure–response functions for health effects of ambient air pollution in China

Quantitative knowledge about the relationship between exposure to air pollution and health outcomes is crucial to assessing the health impact of air pollution and its implications in relevant policy-making. Several meta-analyses on exposure–response functions for acute health effects associated with short-term exposure to ambient air pollution based on Chinese epidemiological studies have been conducted (Aunan and Pan, 2004; Kan et al., 2005). For example, Aunan and Pan (2004) reported 0.3% and 0.4% increase in total mortality per 10 μg/m^3 increase of PM_{10} and SO_2, respectively. Kan et al. (2005) reported a 0.29% increase in total mortality for 10 μg/m^3 increase of PM_{10}. In contrast, the pooled risk estimates for developed countries are around the range of 0.35%–1.20% per 10 μg/m^3 increase of PM_{10} (Pope and Dockery, 2006; Stieb et al., 2002, 2003).

With some exceptions, Chinese studies report somewhat lower exposure–response coefficients per unit increase of pollutant concentrations as compared to studies in developed countries. This may be explained by the different characteristics of the study contexts, such as local air pollution level, population sensitivity to air pollution, age structure, especially components and toxicity of pollution mixture. Air pollution level in China is much higher than that in developed countries. At higher concentrations, the risks of death could be reduced because vulnerable subjects may have died before air pollutant concentrations had reached the maximum level. Also, the exposure–response curve of air pollution often tends to become flat at higher concentrations (Pope et al., 2009). In addition, the composition of the motor vehicle fleet in Europe and North America may differ from that in China. This, together with other differences as the widespread use of coal in China, implies that the air pollution mixture may differ between China and the areas where most air pollution health studies were conducted.

3. Health impacts of climate change in China

As in other parts of the world, China has experienced noticeable climate change over the past century (China National Development and Reform Commission, 2007). Annual average air temperature has increased by 0.5–0.8 °C during the past 100 years, which is slightly higher than the average global temperature rise. Most of the temperature rise was observed over the last 50 years. Regional distribution of temperature changes shows that the warming trend was more significant in western, eastern and northern China than in southern China. Seasonal distribution of the temperature changes shows that the most significant temperature increase occurred in winter. The trend of climate change in China is projected to intensify in the future.

The Chinese government has paid an increasing attention to climate change, but only limited engagement has been given to the health impacts so far. Evidence is mounting that climate change has already affected human health directly and indirectly in China, including mortality from extreme weather events; changes in air and water quality; and changes in the ecology of infectious diseases (Zhang et al., 2010a,b,c).

3.1. Health effects of temperature variation and weather extremes

The association between temperature and mortality has been observed extensively worldwide (Basu et al., 2005). As in other parts of the world, the observed relationship between temperature and daily mortality among Chinese residents was generally J-, V- or U-shaped, with mortality risk decreasing from the lowest temperature to an inflection point and then increasing with higher temperature (Kan et al., 2003; Chung et al., 2009). The pattern of this relationship may differ for areas with different weather patterns, latitudes, air pollution levels and prevalence of air-conditioning systems.

Various factors may modify the relationship between temperature and mortality risk. It is important to understand the characteristics of individuals who are vulnerable to temperature variation. In Shanghai, Ma et al. (2011) reported that age, but not gender or education level, could modify the association of temperature with cardiopulmonary mortality. Compared with the young people, the elderly (≥ 65 y) were more vulnerable to temperature variation.

Diurnal temperature range (DTR), defined as the difference between maximal and minimal temperatures within 1 day, is a meteorological indicator associated with global climate change and urbanization (Easterling et al., 1997). Large diurnal temperature change might be a source of additional environmental stress and therefore a risk factor for health. Kan et al. (2007b) examined the association between DTR and mortality outcomes in Shanghai, and found a strong association after adjustment for those potential confounders including time trend, day of the week (DOW), temperature, humidity, and outdoor air pollution. A 1 °C increment of DTR corresponded to 1.37% (95% CI: 1.08%, 1.65%), 1.86% (95% CI: 1.40%, 2.32%) and 1.29% (95% CI: 0.49%, 2.09%) increase of total non-accidental, cardiovascular, and respiratory mortalities, respectively. Consistent with Kan et al.'s findings, Tam et al. (2009) reported significant associations between DTR and cardiovascular mortality among the elderly in Hong Kong. In Taiwan, a significant positive correlation between DTR and COPD ER visits was also reported ($r = 0.90$); COPD ER visits increased by 14% when DTR was over 9.6 °C (Liang et al., 2009).

Heat wave and other extreme weather conditions have been associated with increased mortality risks in large Chinese cities such as Beijing (Li et al., 2009) and Shanghai (Huang et al., 2010). In 2003, Shanghai recorded the hottest summer in over 50 years. Huang et al. (2010) investigated the impact on the mortality of a heat wave in 2003 in Shanghai. The authors calculated excess mortality and RRs during the heat wave (July 19–August 6, 2003) compared to a summer reference (non-heat wave) period (June 28–July 9, and August 16–August 22); the RR of total mortality during the heat wave was 1.13 (95% CI: 1.06, 1.20), and the impact was greatest for cardiovascular (RR = 1.19; 95% CI: 1.08, 1.32) and respiratory (RR = 1.23; 95% CI: 1.02, 1.48) mortality. Gender did not modify the heat-wave impact. Elderly people (over 65 years) were most vulnerable to the heat wave. Elevated mortality during temperature extremes was mainly attributed to cardiovascular and respiratory diseases, especially among the elderly. However, little information is available in China on possible modifiers of the health impact of thermal extremes, such as preexisting health status and population demographic characteristics such as education, occupation and socioeconomic position.

It should be noted that an improvement of living conditions resulting from rapid economic development in China can reduce heat wave-related heath impact. In Shanghai, for example, heat waves in 1998 and 2003 both led to increased mortality (Tan et al., 2007). While the heat waves in these two years were similar in meteorological characteristics, elevated mortality was much less pronounced during the 2003 event, suggesting adaptations to climate change (such as increased use of air conditioners, larger living spaces, and increased urban green space, along with higher levels of awareness and the implementation of a heat warning system issued by local meteorological stations) can reduce health risks imposed on Chinese residents.

The health impacts of high temperatures and air pollution may interact and are thus worthy of attention because outdoor air pollution is one of the major environmental challenges for public health in Chinese cities. In Wuhan, an “oven” city because of its hot summers, high temperatures enhanced the effect of PM_{10} on total (p for interaction = 0.014), cardiovascular ($p = 0.007$), and cardiopulmonary ($p = 0.014$) mortality, even though PM_{10} concentrations were lower on the extremely high-temperature days than on the normal temperature and low-temperature days (Qian et al., 2008). Similar synergetic effects were also observed in Beijing (Wu and Zhang, 2009). Also, levels of some secondary air pollutants, such as O_3, are affected by temperature and tend to be higher on hot days. Epidemiological evidence from Chinese cities has indicated significant mortality risks of ozone associated with increasing temperatures (Zhang et al., 2006).

Climate change may increase the frequency, intensity and duration of extreme weather events in China, including blizzards, windstorms, typhoons, floods, drought, and landslides (China National Development and Reform Commission, 2007). The direct and indirect health impacts due to these extreme events are important, but are difficult to assess at present.

3.2. Climate change and infectious disease

Infectious diseases remain the major causes of morbidity and mortality in China despite substantial progress in disease control and risk management (Wang et al., 2008). China is also a major contributor to the worldwide infectious disease burden because of its population size. Climate change can affect China's climate-sensitive infectious diseases carried by animal hosts or vectors, including schistosomiasis (Zhou et al., 2008, 2010), hemorrhagic fever (Bi et al., 2005; Zhang et al., 2010a, b, c, Japanese encephalitis (Bi et al., 2003a), and malaria (Bi et al., 2005; Zhang et al., 2010a, b, c; Bi et al., 2003b). Appraisal of the present and future impact of climate change and climate variability on the transmission of infectious diseases is a complex but pressing public health issue in China.

Schistosomiasis is one of the recently neglected vector-borne diseases but the impact of climate change on its transmission has attracted attention and debate (Zhou et al., 2005; Liang et al., 2007). Zhou et al. (2008) developed a biology-driven model to assess the potential impact of rising temperature on the transmission of schistosomiasis in China. The authors reported a temperature threshold of 15.4 °C for development of Schistosoma japonicum within O. hupensis (the intermediate host of human blood fluke Schistosoma japonicum), a temperature of 5.8 °C at which half the snail sample investigated was in hibernation. The occurrence of O. hupensis was restricted to areas where the mean January temperature is above 0 °C. The combination of these temperature thresholds, together with predicted temperature increases in China of 0.9 °C in 2030 and 1.6 °C in 2050, forecasted an expansion of schistosomiasis transmission into currently non-endemic areas in the north, with an additional risk area of 783,883 km^2 by 2050, covering 8.1% of the surface area of China. These results call for rigorous monitoring and surveillance of schistosomiasis in a future warmer China. Similarly, a recent study indicated that as winter temperatures continue to rise due to global warming, O. hupensis may increase its range, thereby spreading schistosomiasis to the northern part of China (Zhou et al., 2010).

In Anhui Province, China, Bi et al. (2005) examined the relationship between monthly Southern Oscillation Index (SOI) and monthly incidences of hemorrhagic fever with renal syndrome (HFRS) and malaria, over the periods 1971–1992 and 1966–1987, respectively. The results indicated that the SOI had positive relationships with monthly incidences of malaria, and negative relationships with monthly incidences of HFRS. The SOI could thus be used as an index to study the association of climate variability with the transmission of HFRS and malaria, particularly over larger areas.

In northeastern China, Zhang et al. (2010a,b,c) examined the potential impact of climate variability on HFRS transmission and developed climate-based forecasting models for HFRS. Rainfall, land surface temperature, relative humidity, and multivariate El Nino Southern Oscillation (ENSO) index were found to be significantly associated with monthly HFRS cases with lags of 3–5 months, suggesting that climate variability plays a significant role in HFRS transmission in northeastern China.

In another study, Bi et al. (2003b) used data on monthly climatic variables and monthly incidence of malaria in Shuchen County, China, during the period 1980–1991. Monthly mean maximum and minimum temperatures, monthly mean relative humidity, and monthly amount of precipitation were found to be positively associated with the monthly incidence of malaria, though the associations were significant for monthly mean minimum temperature and total monthly rainfall only. Zhang et al. (2010a,b,c) conducted a similar study on climate variation and malaria in Jinan, a temperate city in northern China.

In Jieshou County of eastern China, Bi et al. (2003a) examined the impact of climate variability on the transmission of Japanese encephalitis. Maximum and minimum temperatures and rainfall were found to be associated with the transmission of Japanese encephalitis. Also, monthly mean minimum temperature and monthly precipitation had a significant relationship with the transmission of Japanese encephalitis, with a 1-month lag effect.

4. Air pollution health co-benefit studies of reducing GHG emissions

Climate change and air quality issues are linked in several ways. First and foremost, CO_2, the main GHG, and the major air pollutants (eg, PM, NO_2 and SO_2) stem from the same sources to a large extent. In addition to the source linkage between climate change and air quality issues, increasing evidence exists that well-known air pollutants, especially tropospheric O_3 and particles, play an important role in the climate system. Finally, climate change and air quality are linked through the chemistry of the atmosphere, as some air pollutants influence the lifetimes of GHGs.

Several studies carried out in China over the past decade have found that many measures aimed primarily at reducing local air pollution decrease GHG emissions as a co-benefit. This may be of special importance in areas of high urban population densities and high emission levels of air pollutants and GHGs (Aunan et al., 2006). One of the co-benefit analyses is the Integrated Environmental Strategies (IES) program initiated by the US Environmental Protection Agency in 1998 to help developing countries (including China) evaluate the public health, economic, and environmental benefits of integrated planning to address local environmental concerns and also reduce associated GHG emissions.

In Shanghai, Chen et al. (2007) investigated the potential public health and economic impact of ambient air pollution under various low-carbon energy scenarios. The analysis showed that ambient air pollution in relation to low-carbon energy scenarios could have a significant impact on the future health status of Shanghai residents, both in physical and monetary terms. Compared with the business as usual (BAU) scenario, implementation of various low-carbon energy scenarios could prevent 9870–23,100 PM_{10}-related avoidable deaths in 2020. The corresponding economic benefits could reach 2642–6192 million U.S. dollars in 2020. These estimates illustrate that a low-carbon energy policy will not only decrease the emission of GHGs, but also play an active role in the reduction of air pollutant emissions, improvement of air quality, and promotion of public health.

Pan et al. (2007) estimated the expected population exposure to air pollutants under various energy scenarios by the year 2010, 2020 and 2030, respectively, in the urban area of Beijing, China. The study population included 6,589,175 permanent residents living in the urban area. Compared with the BAU scenario, there will be, by 2020 and 2030, respectively, a decrease of 30–212 and 39–287 acute excess deaths; and 356–2529 and 462–3424 chronic excess deaths associated with the reduction of PM_{10} level; also a decrease of 285–371 and 400–554 short-term excess deaths associated with the decrease of SO_2 level. Meanwhile, the number of respiratory and cardiovascular hospital admissions, outpatient visits to internal and pediatrics departments, total emergency room visits and asthma attacks would be remarkably reduced with the reduction of air pollution. These results suggested that energy structure improvement could reduce ambient air pollution and produce substantial public health benefits in Beijing.

5. Summary and recommendations

In summary, accruing evidence shows that ambient air pollutants have a range of adverse health effects in China. The increased mortality or morbidity risks observed among the Chinese population are somewhat lower in magnitude for per unit increase in air pollution than the risks found in Europe and North America. However, the importance of these increased health risks is greater than in other parts of the world, because the air pollution in China is at much higher levels in general and China's overall population accounts for more than one fourth of the world's total. Most air pollution health studies in China were ecological in nature, thus limiting the power for causal inference. In addition, few published studies assessed the relation between air pollution and sub-clinical indicators. Future air pollution health research in China will need to clarify the life-time course of these effects (e.g. prospective cohort studies), to examine the relevance of cumulative exposure, as well as to identify the most susceptible time periods and population groups, genetic–environment interaction, and pathophysiologic link between air pollution and cardiopulmonary diseases in Chinese population.

Meanwhile, there is some evidence showing that climate change poses significant health risks to the population in China. Future climate change health research will need to build the capacity to adapt to climate change and evaluate the implementation of adaptation measures; to improve characterization of climate–health relationships (particularly at regional levels); to identify thresholds and particularly vulnerable groups; and to collect and enhance long-term surveillance data on possible health impacts of climate change (including excess mortality and morbidity due to weather extremes, vector-borne, food-borne and waterborne diseases, air quality, pollen and mold counts, and mental health impacts from extreme weather events).

China is striving to quadruple its GDP of 2000 by the year 2020, and consequently will face even more serious challenges in controlling emissions of both air pollutants and GHGs. If China acts to reduce the combustion of fossil fuels and the resultant air pollution, it will gain not only the health benefits associated with improvement of air quality but also with the mitigation of climate change. Therefore, these air pollution-related health benefits might be a strong inducement for the Chinese government to act to combat climate change. Finally, air quality, climate change and population health need to be taken into account simultaneously. Consideration of the health impacts of air pollution and climate change can help the Chinese government move forward towards sustainable development with appropriate urgency.

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